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Visual images in science education

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Visual images in science education

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Editorial: Visual images in science education

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Editorial on the Research Topic
Visual images in science education

Visual Images (V.I.) are integral in knowledge construction, thinking, and communicating in science. Similarly, science teaching and learning are increasingly discussed as multimodal processes, relying on a multitude of V.I. On the one hand, science teaching typically relies on V.I. to introduce, define, and explain scientific concepts and phenomena. On the other, scientific literacy, which involves competency in effectively communicating scientific ideas, requires a variety of representational abilities and is closely related to visual literacy, i.e., the ability to understand, interpret, think through, and create V.I. (Lemke, 1998; Ainsworth, 2008; Jewitt, 2008; Tang, 2023).

Science education has primarily been primarily dependent on verbal communication to investigate, mediate, and evaluate science-related meanings, largely overlooking the importance of images in constructing scientific meanings. Even when the importance of the visual mode in science teaching and learning was acknowledged, it has been misleadingly assumed that V.I. bear unambiguous meanings, that are self-evident to viewers. However, understanding, creating, and using images in the context of science education are challenging processes demanding targeted instruction (Kress, 2003; Glazer, 2011). Failing to recognize these requirements deprives students of critical competencies related to scientific (visual) literacy, particularly essential in an era dominated by visual communication.

Moreover, V.I. are complex constructs, often associated with viewers' emotions toward science (Christidou et al., 2021; Duan and Bombara, 2022). All these observations highlight the necessity for sophisticated and multidimensional instruments to investigate the role of V.I. in science education comprehensively. As a response to the need for science education to support students' scientific visual literacy, there has been a growing research interest in how V.I. can be meaningfully integrated into science teaching, how learners read and interpret V.I., or how they visually express their views about different science topics.

Attempting to address some of the aforementioned issues and contribute to the discussion on Visual Images in Science Education we invited valued and interested researchers to participate in this Research Topic. Twenty-five authors from 5 countries in Europe, North America, and Asia contributed 9 articles that cover a range of themes, which fall within two broad and interrelated clusters signified by different colors in Figure 1.

The first cluster (designated with blue in Figure 1) involves research with a primary focus on students, exploring how V.I. support students' meaning making in science, students' visual representations as evidence of their thinking and learning in science, students' difficulties in reading science images, emotional reactions induced by V.I., and students' images of scientists and science.

The focus of the second thematic cluster (designated with yellow in Figure 1) is on science teaching. Related themes examine the relations between V.I. and scientific literacy, the characteristics of V.I. in science teaching material, the use of multiple V.I. in science teaching and learning, ways of scaffolding students' scientific visual literacy, science teaching and learning as multimodal practices, and teachers' use of V.I. in science.

As Figure 1 illustrates, most articles relate more or less directly (indicated with continuous or dashed lines respectively) to a variety of themes pertaining to both clusters. Thus, Uchinokura and Koba explore primary students' visuospatial thinking skills and their use in domain-specific tasks requiring the interpretation of diagrams about solar cells.

Viewers' positioning regarding different V.I. designs is explored in two articles. Lenski and Großschedl investigate whether including emotional design illustrations in concept maps about the Lake Ecosystem is associated with students' affective state, cognitive load, and learning performance, while Höst et al. explore the effect of realism indicators in interactive science center exhibits on viewers' preferences, perceptions of the depicted biological entities as real, and desire for further exploration.

Adbo and AAkesson Nilsson indicate the potential of student-generated playdough models of atomic nuclei for exploring a range of challenges faced in understanding chemistry content that could be concealed in students' verbal explanations.

Chionas and Emvalotis expand the long research tradition of exploring students' images of scientists and science through drawings, by using an open-ended questionnaire. Their findings indicate some interesting deviations from previous studies based on visual data, namely an emphasis on scientists' personality traits instead of their skills, appearance, or specialty.

Christidou et al. make a case for using student-generated V.I. to explore their views on scientific issues by analyzing children's verbal comments and drawings about SARS-CoV-2 and COVID-19 preventive practices and exploring age- and mode-related differences.

After performing two studies to examine the role of representational competencies in students' learning from video games about astronomy, Herder and Rau suggest that representational competency supports designed for structured learning environments may not be effective for educational video games.

Pantidos et al. discuss how different types of V.I. with varying degrees of naturalism and abstraction can be amalgamated to support the formation of science concepts by connecting everyday and specialized visual codes in the context of multimodal science classroom communication.

Wright et al. propose the use of wildlife photographs in place-based education as a means for developing visual literacy, which they consider a powerful component of environmental literacy.

The diversity of themes, research questions, and methodologies addressed by the articles in this Research Topic indicates that integrating V.I. in science education constitutes a promising and multidimensional field to which this volume aspires to make a valuable contribution.

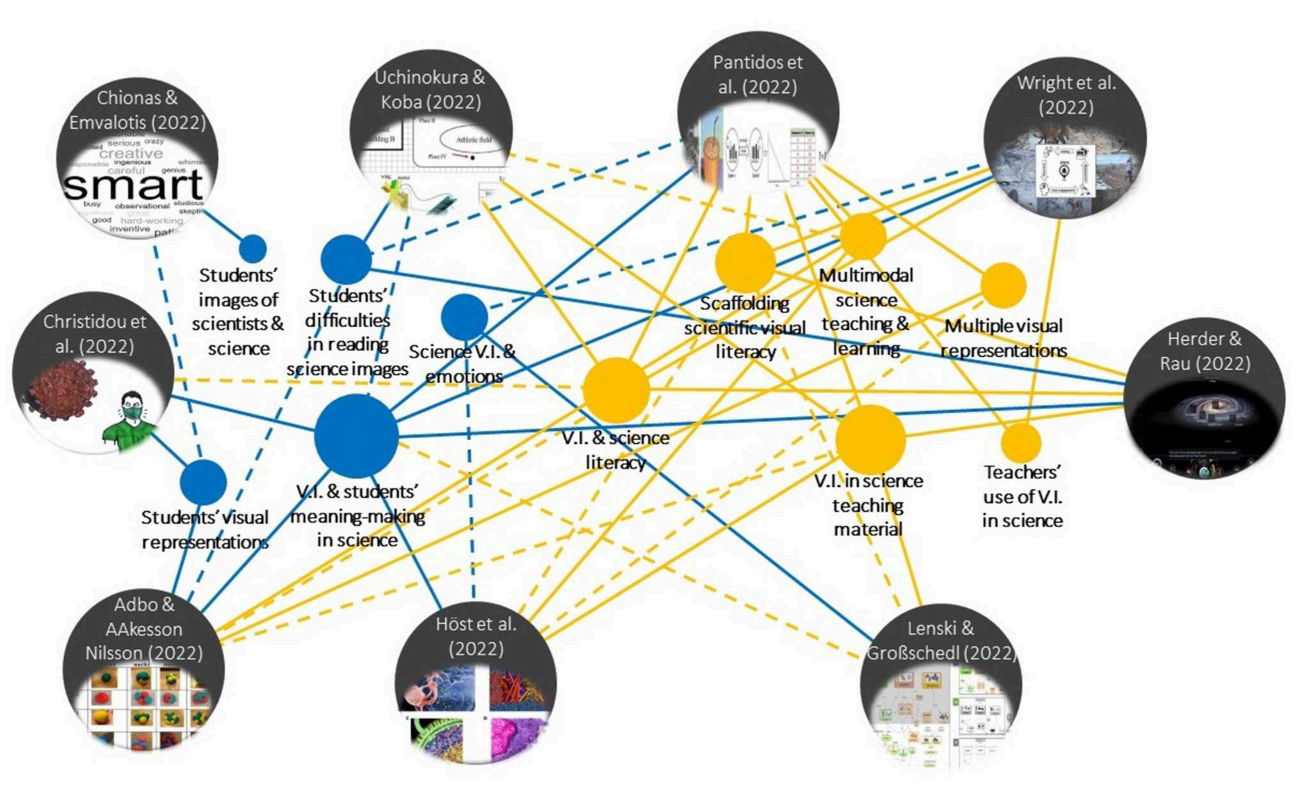

FIGURE 1
Themes covered by the articles in the "Visual images in science education" Research Topic.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
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Emotional Design in Concept Maps – No Support but Also No Burden

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A concept map is a powerful method that promotes meaningful learning and is highly recommended for use in biology classes. According to multimedia research, the effectiveness of concept maps could be improved by incorporating pictorial elements. Apart from using realistic images, a new field of research claims that specific design manipulations, including human-like features with appealing colors (*emotional design*), influence learners' affective state and improve learning. A positive affective state is assumed to evoke emotions and provoke deeper cognitive processing, which increases the cognitive resources available for a task. We conducted two experiments with a total of *N* = 249 junior high school students, comparing the effect of concept maps with emotional design illustrations (emotional design), with non-emotional design illustrations (neutral design), and without illustrations (control design). Experiment 1 examined the influence of these designs on students' *perceived affective state*, *perceived cognitive load (extraneous, intrinsic, and germane load)*, *perceived task difficulty*, and *learning performance* (*n* = 202), experiment 2 focused on the *perceived affective state* of the students (*n* = 47). We found that emotional design led to a significant decrease in *perceived task difficulty,* but we neither found an effect on *learning performance* nor the *positive affective state*. Learning with pictorial concept maps (in emotional or neutral design) reduced the *negative affect* compared to learning with control concept maps. Other than expected, the neutral design led to reduced *perceived extraneous* and *intrinsic cognitive load*. Consequently, in terms of learning, emotional design in concept maps did not hamper learning but did not foster it either.

Keywords: concept maps, multimedia learning, emotional design, anthropomorphisms, emotions

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INTRODUCTION

Modern and global society is exposed to various information that we must filter, evaluate, and interpret. Most of them can only be assessed correctly when relationships are understood. Understanding concepts and their relationships (*conceptual knowledge*) are essential in everyday life, especially in learning contexts. This poses a significant challenge for students, especially for the subject of biology (Schmid and Telaro, 1990), as it tries to elucidate how organisms in supersystems interact with or influence each other and their environment (Reiners et al., 2018). The complexity of the biological subject matter causes high element interactivity which means that different aspects highly interact and cannot be learned in isolation (Chen et al., 2015). To help students obtain the required conceptual knowledge and handle the high element interactivity (Williams, 1998), concept maps are recommended for biology classes (Kinchin, 2000).

Concept maps are graphical tools that make knowledge and relationships between different elements of a system visible (Novak, 1990) and can be used for various purposes (e.g., planning, teaching, learning, and diagnosing; Schroeder et al., 2018). For the study of concept maps, Blankenship and Dansereau (2000) found that learners could experience a so-called *map shock* characterized by "bewilderment of not knowing where to start or how to penetrate the topography of the map" (p. 294). Researchers assume that these cognitive challenges could produce an adverse affective reaction that demotivates and inhibits learning (Dees et al., 1994). A possible solution to this problem could be to enrich the text-based nodes of the concept maps with illustrations (Alpert and Grueneberg, 2001). According to the *cognitive theory of multimedia learning* (Mayer, 2001), the combined presentation of illustration and text can reduce cognitive load (e.g., Levie and Lentz, 1982).

A new research field assumes that distinct design manipulations (*emotional design*) influence learners' affective-motivational state (e.g., positive emotions in general, situational interest, intrinsic motivation, and enjoyment) and thereby foster learning (Um et al., 2012). Emotional design is characterized by human-like features, round shapes, and appealing colors. Several studies have been carried out to investigate the effect of emotional design on *learning*, *affective state*, and *mental effort* (Um et al., 2012; Plass et al., 2014; Park et al., 2015; Plass and Kaplan, 2016; Uzun and Yıldırım, 2018). Some findings support the assumption that emotional design evokes emotions and enhances learning (Um et al., 2012; Mayer and Estrella, 2014; Brom et al., 2018; Tien et al., 2018; Wong and Adesope, 2020), while other findings showed that emotional design did not impact emotions and learning (Park et al., 2015; Münchow and Bannert, 2019; Stárková et al., 2019). Overall, the meta-analysis by Brom et al. (2018) showed that emotional design improves *retention*, *comprehension*, and *transfer*. Furthermore, a reduced *perceived task difficulty*, a weak effect for *positive affect*, and no significant impact on *mental effort* were found. A recent meta-analysis supported these findings (Wong and Adesope, 2020). In emotional design research, mainly the positive scale of the positive and negative affect scale (PANAS) was used to investigate the affective impact of emotional design. Several other authors presume that the effect of emotional design can vary and may be dependent on factors such as context, learning domain, learning time, nature of the presentation, intensity of manipulation, or grade level (e.g., Münchow and Bannert, 2019; Stárková et al., 2019; Wong and Adesope, 2020).

The emotional design applied to concept maps has so far been little investigated. Tien et al. (2018) examined the effects of multidimensional concept maps (digital concept maps where videos, pictures, or sounds are linked to the concepts) on learning and the affective state in college students. They found that colorful and animated multidimensional concept maps lead to "higher learning well-being" and better learning than achromatic multidimensional concept maps (Tien et al., 2018, p. 1). However, it should be noted that Tien et al. (2018) interpreted the emotional design differently than Um et al. (2012). Rather than using anthropomorphisms, they applied daily-life advertisement music, animations, and images to induce emotions. Thus, it is unclear whether emotional design features in concept maps (incorporation of colorful and anthropomorphized images into the concepts) increase the learning efficiency of concept maps or whether it increases cognitive load and impairs learning.

We examined whether concept maps in emotional design reduce inhibitory *perceived cognitive load*, influence the *perceived affective state,* and thereby improve *learning* of junior high school students in an authentic learning environment. The present study was designed for junior high school students as there is a discrepancy between the evidence-based potential of concept maps to improve students' learning and the actual use in schools (Kinchin, 2001).

THEORETICAL FRAMEWORK

Concept Maps

A concept map is a graphical tool that represents knowledge in adomain (Novak, 1990; see **Figure 1** for examples). External information (e.g., learning text and teaching) or own knowledge (retrieval practice; Blunt and Karpicke, 2014) guide the construction of a concept map. A concept map consists of textual elements (concepts) connected by labeled links that define their relationships. Arrowheads indicate the reading direction at one or both ends of the links. Combining at least two concepts connected via a link is called *proposition* and forms a meaningful unit (Novak and Gowin, 1984). If the concepts "chlorophyll" and "leaf pigment" are connected via the labeled arrow "is," the proposition "chlorophyll is (a) leaf pigment" can be formed. The number of propositions of a concept map is unlimited, but fifteen to twenty-five concepts are usually necessary to create a (good) concept map (Novak and Cañas, 2008). Novak and Cañas (2008) recommend structuring concept maps hierarchically. The concepts are sorted according to their relevance and essential terms at the top and more specific terms below in the concept maps (**Figure 1**).

To explain why the construction and the study of concept maps are effective for learning, Schroeder et al. (2018) classified three reasons: (1) concept maps promote meaningful learning, (2) concept maps reduce extraneous cognitive load, and (3) concept maps do both.

While learning with concept maps, existing knowledge structures are modified and linked with new information (*elaboration*), a fundamental component of *meaningful learning* (Renkl, 2010). According to Großschedl and Tröbst (2018), concept maps help organize new information and promote metacognitive learning. Metacognitive learning is encouraged since concept maps help to reflect individual learning progress and identify knowledge gaps (Mintzes et al., 1997). For studying concept maps, it is assumed that learners adopt the (experts'/teachers') knowledge structure and integrate the information of the concept map into their knowledge (Gehl, 2013). The learning effectiveness of concept maps of both

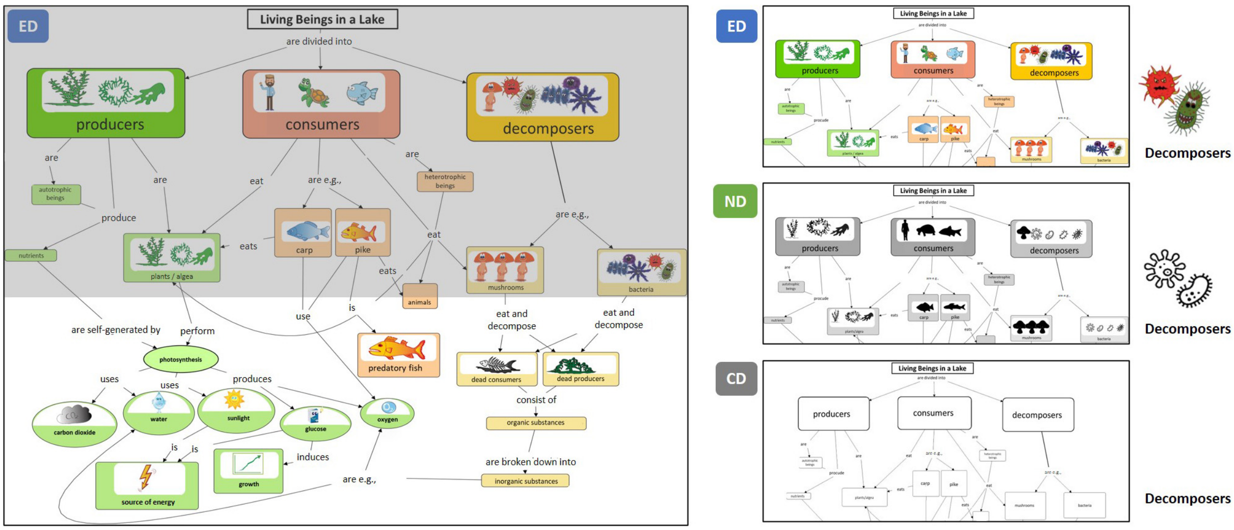

FIGURE 1 | Concept map for "Living Organisms in a Lake" (translated from German) in emotional design (ED) **(left)**. Gray area of the concept map is displayed enlarged **(middle)** for the emotional design, the neutral design (ND), and the control design (CD). The concept "Decomposers" is shown in detail **(right)**.

processes (constructing and studying) has been empirically confirmed by meta-analyses (Horton et al., 1993; Nesbit and Adesope, 2006; Schroeder et al., 2018).

Emotions, Emotional Design, and Learning

There are two opposing hypotheses about the possible effects of emotions on learning: the *emotions-as-facilitator-of-learning hypothesis* and the *emotions-as-suppressor-of-learning hypothesis* (Um et al., 2012). The emotions-as-facilitator-of learning-hypothesis suggests that experiencing positive emotions can enhance learning performance. According to Um et al. (2012), "experiencing positive emotions during the learning process can enhance learning outcomes, either through direct impact and learning or through mediating variables, such as interest and motivation." Furthermore, (design) elements that elicit positive activating affective states are assumed to provoke deeper cognitive processing and thereby increase the cognitive resources dedicated to a task (see Stárková et al., 2019 for an explanatory graphic). By increasing available cognitive resources, aspects like affect and motivation can mediate the learning process at a higher level.

On the contrary, the emotions-as-suppressor-of-learning hypothesis postulates an impairing effect on learning. In this case, emotions are presumed to distract students from a task by, for example, processing information about one's emotional state or other task-irrelevant thinking. This additional process competes for the limited capacity of the working memory (see Plass and Kalyuga, 2019 for a recent overview of the effect of emotions on cognitive processes).

Since studies on emotional design focus on the learners' general emotional state rather than specific types of emotions, in this study, the generic term "affect" is used to refer to emotion and mood (for a similar approach, see Plass et al., 2014; Park et al., 2015; Uzun and Yıldırım, 2018). According to the *circumplex model of affect* by Russell (2003), emotions can be categorized in a two-dimensional system with *valence* as a continuum from positive to negative (affect) as one dimension and *activation* as a continuum from activated to deactivated as the other. Activating emotions are *enjoyment* or *curiosity* (positive) and *anger* (negative). Deactivating emotions include *relaxation* (positive) and *sadness* (negative; Pekrun et al., 2006) and are mainly related to an impairment of learning (e.g., Aspinwall, 1998). Empirically, positive affect is typically found to increase interest and motivation to learn, while negative affect is mainly shown to impair learning [see meta-analysis by Barroso et al. (2021)]. On the contrary, beneficial effects on learning for some negative emotions and inhibitory effects for positive affect has been found (Münchow and Bannert, 2019). In a recent study by Mensink (2021), positive affect negatively predicted learning performance, while negative affect positively affected learning. In line, learners in a negative affective state before learning outperformed those in a positive affective state (Knörzer et al., 2016). Positive activating emotions are suspected of distracting from the learning material and acting detrimentally. Pekrun (2021) concluded that the type of effect (beneficial or inhibitory) of different emotions depends on, for example, the situation, the kind of task, and personal traits. Also, Knörzer et al. (2016) suspected that moderating trait variables are responsible for the inconsistent results. Beyond, it was found that the experience of multiple emotions (here, joy, anger, confusion, and frustration) could distract and negatively impact learning (Dever et al., 2021). The authors suspect that the processing of emotions causes additional cognitive load, reducing cognitive resources available for the learning task.

For multimedia designs, the effect of a design on the viewer [(visual) *appeal*], has been found to influence the affective state (Capota et al., 2007). Emotional design manipulations are developed based on this assumption, however, their effect on appeal has been little investigated so far (Mayer and Estrella, 2014). Contrary to expectations, learning material in emotional design was not perceived as more appealing compared to non-emotional design material (Mayer and Estrella, 2014). Besides examining the affective parameter *enjoyment*, Mayer and Estrella (2014) also assessed the *desire for additional lessons of a similar nature* which served as a proxy for positive affect. No difference between emotional design and non-emotional design material was found here either.

Cognitive Load and Multimedia Learning

In emotional design research, different theories are used to explain how emotional design influences learning and cognitive processes. Central to learning is the *cognitive load theory* (Sweller, 2005). It is assumed that the amount of information that can be processed simultaneously is restricted while different aspects can increase a person's cognitive load (*limited capacity assumption;* Mayer, 2001). Sweller (2005) distinguishes between three types of cognitive load, i.e., intrinsic, extraneous, and germane load. The intrinsic load is caused by the task or learning material and depends on the complexity of these and the learners' expertise. Consequently, it cannot be manipulated directly by instructional design. Germane load refers to the resources that learners invest in their learning process. In contrast, the extraneous load is not conductive for learning and arises from a poor learning material design (e.g., unsuitable design). A *seductive detail*, for example, is assumed to impose extraneous cognitive load and can impair learning by competing with the learning object for cognitive resources (Harp and Mayer, 1997; Lenzner et al., 2013).

According to the *dual-channel assumption* by Paivio (1986), information is processed in verbal and visual channels. Based on this assumption, the c*ognitive theory of multimedia learning* (Mayer, 2001) was developed, which describes multimedia as any material that consists of a combination of text and illustration elements. It is assumed to improve learning by reducing extraneous cognitive load. The text can be written or spoken, and illustrations are understood to include static pictures (e.g., illustrations, graphics, and photos) and moving pictures (e.g., videos and animations). The cognitive theory of multimedia learning is mainly focused on cognitive processes, but it was shown that emotional and motivational aspects and cognitive processes are inextricably linked (Plass and Kalyuga, 2019). The *cognitive-affective theory of learning with media* was established to extend the previous theory with non-cognitive elements (emotional and motivational aspects) which can influence the learning process (Moreno and Mayer, 2005, 2007; Moreno, 2006). It presumes that affect and motivation can mediate the learning process by manipulating the cognitive resources available for a specific task.

Two competing views exist regarding emotional design and its influence on extraneous cognitive load. As stated in section "Emotions, Emotional Design, and Learning," emotions induced by emotional design could cause extra processing. This process is not considered relevant for the learning goal, it can be classified as extraneous cognitive load (Plass and Kalyuga, 2019). Another potential source of extraneous cognitive load is that to achieve an emotional design, certain features must be added to the learning material. According to the *coherence principle* by Mayer and Fiorella (2014), design elements that are described as interesting and entertaining but irrelevant in terms of content could cause extraneous cognitive load. However, this applies primarily to seductive details (*seductive detail effect*, Park et al., 2011), which does not include the emotional design according to Um et al. (2012). The emotional design does not consist of irrelevant, decorative elements. Instead, elements of the learning material are equipped with emotional features (Um et al., 2012). Thereby unnecessary extraneous cognitive load should be avoided. In addition, the emotional design is not expected to increase the extraneous cognitive load, as it is assumed that it increases the cognitive resources that are made available for a task (as stated in section "Emotions, Emotional Design, and Learning"). Another aspect suggests that emotional design does not increase the extraneous load but even reduces it. This is because emotional design is supposed to guide attention (Park et al., 2015; Le et al., 2021; Peng et al., 2021). Search processes in a learning task are one source of extraneous cognitive load (Plass and Kalyuga, 2019), which can be reduced by guiding learners' attention. Supporting this, students perceived the learning material adopting emotional design features to be less complicated (lower *perceived task difficulty*) than differently designed material [see meta-analysis by Brom et al. (2018)]. The *perceived task difficulty* represents a persons' estimation of effort needed to manage a certain task (Schneider et al., 2021). For emotional design features, a low perceived task difficulty is expected as they are supposed to "being perceived by the students as *easy to learn* because of their *entertaining appearance*" (Uzun and Yıldırım, 2018, p. 125).

In contrast, incorporating emotional design elements should not affect intrinsic cognitive load. Since the different design features are not presumed to affect aspects directly related to the complexity of the learning content. However, Le et al. (2021) reported that the emotional design decreased intrinsic load. Emotions, in general, could either increase or reduce the intrinsic cognitive load, which is context-dependent, according to Plass and Kalyuga (2019).

Regarding the germane cognitive load, it can be presumed that the emotional design, which potentially increases cognitive resources and lowers extraneous cognitive load, could increase the resources available for meaningful, effective learning (increase germane cognitive load).

HYPOTHESES

This study examined the influence of emotional design on learning performance, cognitive load, and affective state in a two-experiment approach. As part of **experiment 1**, the effect of emotional design on junior high school students' learning performance, different dimensions of *perceived* cognitive load (e.g., in the form of *task difficulty*), and *perceived* affective state (e.g., *appeal*, *enjoyment*, and *desire for additional tasks of a similar nature*) were investigated. In **experiment 2**, the change of the *perceived affective state* was investigated in more detail.

Concept maps with (1) bright and saturated colors as well as anthropomorphisms (emotional design, ED), (2) grayscale coloring and non-anthropomorphic illustrations (neutral design, ND), and (3) without pictorial elements (control design, CD) were used.

Based on the theoretical foundation and previous research, the following hypotheses arise:

> We expect students who study with concept maps in emotional design to outperform students of the other conditions in terms of *learning performance* (**H1**). We further assume that students in the emotional design condition experience lower *extraneous cognitive load* (**H2.1**) and higher *germane cognitive load* (**H2.2**) compared to the other conditions. No difference is expected for the *intrinsic cognitive load* (**H2.3**). We presume students in the emotional design condition to experience a lower *task difficulty* (**H2.4**) and rate the *appeal*, *enjoyment,* and *desire for additional tasks of a similar nature* as higher (**H3.1**) than the other conditions. In terms of affect, we assume concept maps in emotional design to induce a rise in *positive affect* and a decrease in *negative affect* (**H3.2**).

GENERAL METHOD

Two experiments were carried out in students' regular classrooms. For all experiments, the same learning material was used, and all students underwent concept map training to ensure comparable knowledge in the use of concept maps. Two investigators carried out the studies, one presenting the instruction and the other providing individual support if needed. Teachers were welcome to attend the lessons. All students were informed about the aims and course of the investigation, the option to stop participating at any time, guaranteed protection of data privacy, and the no-risk character of study participation. Written consents from parents and school principals were obtained before the study. During the experiments, we comply with the requirements of the school law, which, for example, determines that the learning material corresponds to the teaching specifications and does not promote a discriminatory understanding of the students (North Rhine-Westphalian Ministry of Education Science and Research, 2020) and followed the ethical principles and guidelines for the protection of human subjects of research (World Medical Association, 2001).

Learning Material

The learning material covered the topic ecosystem and consisted of three double pages (DIN A3) presented in a study book. The ecosystem is a central topic in biology lessons (Lohmar and Eckhardt, 2014) and is well suited for the use of concept maps due to many possible interrelationships. Each double-page of the study book contained one of three concept maps referring to the aspects "Living Organisms in a Lake," "Zones of a Lake," and "Limnetic Zones in a Lake." These concept maps followed the general principles of Novak and Cañas (2006), were hierarchically structured, and consisted of 16–25 concepts and 28–36 propositions. *CmapTools* software was used to construct the concept maps (available at https://cmap.ihmc.us/). Three study books were developed, each of them applied specific design principles (i.e., emotional, neutral, or control design) to the concept maps (see **Figure 1**).

The concept maps in the emotional design condition were constructed using bright and saturated colors and illustrations with anthropomorphisms based on the cognitive-affective theory of learning with media and along the lines of previous studies (e.g., Mayer and Estrella, 2014). Additionally, semantically related concepts were visually grouped by color (see *signaling principle*; Mautone and Mayer, 2001; for a similar approach see Nesbit and Adesope, 2011). For example, all concepts related to the main concept "Producers" (e.g., "Photosynthesis," "Plants/Algae," and "Sunlight") were colored green. Illustrations without emotionally relevant design features were incorporated for the neutral design condition, and monochromatic grayscale was used to group related concepts. Plain concept maps without any illustrations or design manipulations served as control design.

The conditions did not differ in content or structure (e.g., the number of objects shown, their orientation, location, or size). To avoid attention being divided (see *split-attention effect*; Mayer, 2001) for the neutral and emotional design concept maps, the illustrations were always presented in close spatial proximity to the textual element. Complete concept maps on "Living Organisms in a Lake" are available as supporting information (see **Supplementary Learning Material**).

Concept Map Training

As training is recommended for the correct handling of concept maps (e.g., Holley and Dansereau, 1984; Allen and Tanner, 2003), we implemented a concept map training (135 min; Lenski et al., in preparation[1]) before learning with concept maps. First, declarative knowledge about concept maps was conveyed (e.g., "What are concept maps?," "What can they be used for?," "What elements are concept maps made of?"). Learners were then provided with procedural knowledge. The training material was not specific to any school subject and covered various topics (e.g., "National Economy" and "Different States of Water").

Data Analysis

Normal distribution was identified visually and tested statistically using histograms and Kolmogorov–Smirnov tests. Levene's tests or Box's *M* tests were conducted to check for homogeneity of variances. Unless stated otherwise, all assumptions were met in the respective analyses. Parametric and non-parametric techniques were implemented, and if not otherwise specified an alpha significance level of 0.05 was set for all analyses and hypothesis testing.

[1] Lenski, S., Elsner, S., and Großschedl, J. (in preparation). *Comparing Construction and Study of Concept Maps – An Intervention Study on Cognitive, Metacognitive and Emotional Effects of Training and Learning.*

EXPERIMENT 1

Method

Design and Procedure

An experimental intervention study was implemented with a pre- and post-test design. The study consisted of six lessons (á 45 min) delivered over 3 weeks (two lessons a week). In the first lesson, *prior knowledge*, *reading fluency*, and *demographic data* (age, gender, and grade in biology) were determined by questionnaires (45 min). In the following three lessons, the students received training in concept maps (see section "Concept Map Training"). In the learning phase (45 min), study books in the emotional design, neutral design, or control design were randomly distributed among the students (see section "Learning Material"). The students were told they would be tested on the material's content afterward and were instructed to study each concept map carefully. After the learning phase, *cognitive load, task difficulty, appeal, enjoyment*, and *desire for additional tasks of a similar nature* were assessed by self-rate questionnaires included in the study books. Puzzles were handed out to those who completed their learning phase early to avoid disturbing others. In the following lesson, learning performance was measured using a post-test questionnaire (45 min).

Sample

An *a priori* power analysis was performed for sample size requirements. Based on the findings of former studies (d_{recall} = 0.32, $d_{transfer}$ = 0.33, $d_{perceiveddifficulty}$ = −0.21; Brom et al., 2018), we expected a medium effect (cf., Cohen, 2013) of our treatment on our primary dependent measure (*learning performance*). Power analysis was conducted using *G*Power 3.1.9.2* with the assumed medium effect (f = 0.28) and an alpha level of 0.05 at a power of 0.95. The result showed that a total sample of 223 students is required. In this context, Cunningham and McCrum-Gardner (2007) recommend estimating the drop-out rate in advance and adjusting the sample size. As to our knowledge, there are no benchmarks available on drop-out numbers from multi-day intervention studies in schools, we assumed a drop-out rate of about 15% based on previous studies of similar manner.

A total of 257 8th-grade students were recruited from four different German high schools and N = 202 students completed the entire experiment (47% female; age: M = 13.18, SD = 0.49; maximum classroom size: 33 students). All classes received 50 euros as compensation. Students who did not attend the training, the learning phase, or the post-test were excluded in further analyses (for detailed information, see the flowchart of participants in **Figure 2**).

Instruments

Reading Fluency

As reading fluency was identified as a predictor for successful reading (National Institute of Child Health Human Development, 2000) and is known to influence learning performance (Bigozzi et al., 2017), we captured students' reading fluency by the *Salzburg Reading Screening SLS 2-9* (Wimmer and Mayringer, 2014), a classroom-administered standardized reading speed task [test-retest reliability for normative sample (grade 8) r = 0.87].

Prior Knowledge

Since prior knowledge can account for a large portion of a students'learning performance (Shapiro, 2004), we controlled for prior knowledge on "Ecosystems" (including "The Lake Ecosystem"). Prior knowledge was measured by a pre-test questionnaire consisting of 30 items that include general items about ecosystems and specific questions about the lake ecosystem. A general item deals, for example, with the question of why photosynthesis is important for humans (see **Supplementary Tests**, p. 2, item 3). An item focusing on the lake ecosystem covers, for example, the role of decomposers in the ecosystem lake (see **Supplementary Tests**, p. 6, item 14). Three of the items in the pretest were taken from the third International Mathematics and Science Study TIMSS (Harmon et al., 1997; Baumert et al., 1998), as the items fit thematically well and have been validated for the 8th grade (see **Supplementary Tests**, items taken from the TIMSS study are marked accordingly). Nine items were excluded due to low items' discrimination <0.20 (Durrheim and Tredoux, 2004). The remaining 21 items are single choice (13 items), multiple choice (4 items), and matching tasks (4 items). The complete questionnaire is available as supporting information (see **Supplementary Tests)**. One point for each correct answer and zero points for incorrect answers were awarded; hence, the students' total scores obtained could range from a minimum score of zero to a maximum score of 21 points (Cronbach's α = 0.72).

Perceived Cognitive Load

Regarding cognitive load, mostly the self-rating items on *perceived effort* (Paas, 1992) and *perceived (task) difficulty* were used in previous studies. According to Brom et al. (2018), these are proxies (subcomponents) of cognitive load and may not be suitable for this purpose. Therefore, contemporary cognitive load questionnaires are highly recommended for future emotional design research (Brom et al., 2018). Based on this, we decided to use the first version of the *naïve rating questionnaire* by Klepsch et al. (2017) to measure the three types of cognitive load separately (seven items). The items were not modified from the original except for the replacement of "the task" with "the concept map." Items were rated on a 7-point Likert scale from "*not at all true*" to "*very much true*," with only the ends of the scale being labeled. Two items assessed the intrinsic cognitive load ("For this concept map, many things needed to be kept in mind simultaneously"; "This concept map was very complex"; Cronbach's α = 0.51). The germane cognitive load was assessed by two items as well ("For this concept map, I had to engage myself highly"; "For this concept map, I had to think intensively about what things meant"; Cronbach's α = 0.67). The extraneous cognitive load was investigated by three items ("When looking at concept maps, it was exhausting to find the critical information"; "The design of the concept map was very inconvenient for learning"; "When looking at concept maps, it was difficult to recognize and link the crucial information"; Cronbach's α = 0.77).

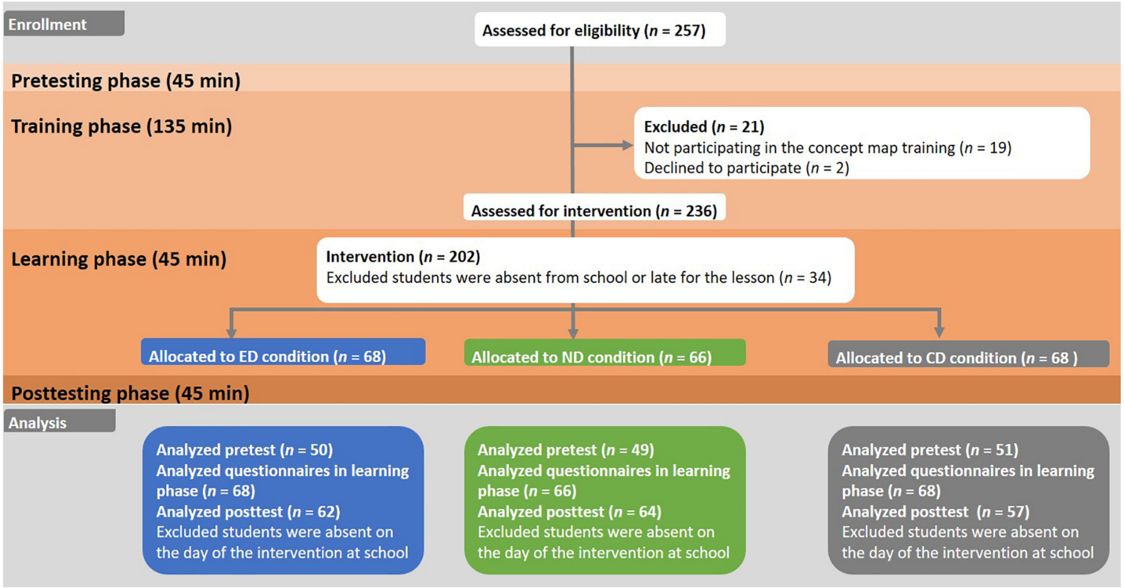

FIGURE 2 | Flow of participants through **experiment 1** according to the criteria recommended in the CONSORT guidelines (Moher et al., 2012).

Perceived Task Difficulty

To determine the *perceived task difficulty*, a single item was applied, which was used in previous studies (Um et al., 2012; Mayer and Estrella, 2014; "Please rate how difficult the concept maps were for you."). This item was rated on a 5-point Likert scale from "*very easy*" to "*very difficult*."

Self-Assessed Handling of Concept Maps

To determine whether all students had successfully passed the concept map training, they were asked to assess their handling of concept maps during the learning phase. The questionnaire was developed based on a self-regulation questionnaire in the context of a computer-based concept map training program for 10th-grade students (den Elzen-Rump and Leutner, 2007). It consists of four items on a 3-point Likert scale (e.g., "Did you look carefully at the arrow directions in the concept map?" on a scale from "*seldom*" to "*very often*"; Cronbach's $\alpha = 0.70$). As the original questionnaire was designed for a construction task, the items were modified for an observation-based task (e.g., "arrows drawn" was replaced with "looked carefully at the arrow directions"). Moreover, the emoticon-based rating scale was replaced by a number-based Likert scale. According to Pollock et al. (2018), emoticons should be used with caution in rating scales due to possible interpretation problems.

Perceived Appeal, Enjoyment, and Desire for Additional Tasks of a Similar Nature

To investigate affective parameters, we followed the approach of Mayer and Estrella (2014). They used a five-item questionnaire on *task difficulty*, *mental effort appeal*, *enjoyment*, and *desire for additional tasks of a similar nature* on a 5-point Likert scale. As in the present study a questionnaire on cognitive load is applied, only the four items covering appeal, enjoyment, and desire for additional tasks, and perceived task difficulty (see section "Perceived Task Difficulty") were adopted. The question on mental effort was excluded to avoid redundancies. All items were translated into German and the term "the lesson" was replaced by "the concept maps" (*appeal*: "Please rate how appealing the concept maps were for you" on a scale from "*very unappealing*" to "*very appealing*"; *desire for additional tasks of a similar nature*: "I would like to learn from more concept maps like these" on a scale from "*strongly disagree*" to "*strongly agree*"; *enjoyment*: "I enjoyed learning from concept maps" on a scale from "*strongly disagree*" to "*strongly agree*").

Knowledge of the Lake Ecosystem (Learning Performance)

Learning performance was measured by a 21-item post-test focusing on the "Lake Ecosystem." Items were taken from the pre-test with two items slightly changed. Three items were excluded due to poor item parameters (items' discrimination <0.20; Durrheim and Tredoux, 2004). The final version of the questionnaire includes 15 single choice items and three matching items. The full questionnaire is available as supporting information (see **Supplementary Tests**). The maximum score on the pre-test was 18 points (Cronbach's $\alpha = 0.78$).

Results

Preliminary Analyses

We checked whether the three conditions (emotional design, neutral design, and control design) differed in *age*, *reading fluency*, *prior knowledge* about ecosystems, *grades in biology*, and *gender* distribution. Since we assume that the null hypothesis is true for preliminary analyses, an alpha level of $\alpha = 0.10$ is set to increase test power and reduce the probability of committing a type II error (Döring and Bortz, 2016). One-way analysis of variance (ANOVA) did not result in any statistically significant differences between conditions in *age*, $F(2,161) = 0.23$, $p = 0.798$, *reading fluency*, $F(2,151) = 1.38$, $p = 0.255$ or *prior knowledge* about ecosystems, $F(2,151) = 1.38$, $p = 0.255$. A chi-squared test revealed no statistically significant differences in *gender*, $\chi^2(4) = 6.23$, $p = 0.182$. Kruskal–Wallis tests showed that students did not differ referring to *self-assessed handling of concept maps*, $\chi^2(2) = 0.55$, $p = 0.761$, and *grades in biology,* $\chi^2(2) = 2.02$, $p = 0.364$. For descriptive data, see **Supplementary Table 1**. No unusual data distribution or outliers were observed.

Hypothesis Testing

Knowledge of the Lake Ecosystem (Learning Performance; H1)

We assumed that students in the emotional design condition outperform students in the neutral and control design conditions in terms of learning performance. A one-factorial analysis of covariance (ANCOVA) showed that, after adjustment for *prior knowledge* and *reading fluency* as covariates, the design conditions had no influence on *knowledge of the lake ecosystem* tested by means of a post-test, $F(2,141) = 0.23$, $p = 0.796$ (lack of support for **H1**). **Table 1** displays mean values and standard deviations.

Cognitive Load and Task Difficulty (H2.1–2.4)

We expected the emotional design to affect the *perceived cognitive load*. The results of a bivariate correlation between all dependent variables showed moderate correlations between the cognitive load subscales (*intrinsic, extraneous,* and *germane load*) and *task difficulty* [bivariate correlation is available as supporting information (see **Supplementary Table 2**)]. The results together with the classification of task difficulty as a proxy for cognitive load (Brom et al., 2018), a one-way multivariate analysis of variance (MANOVA) was conducted. *Design* was set as independent variable and the *cognitive load* subscales as well as the *perceived task difficulty* as dependent variables. MANOVA assumptions were met, except for the multivariate assumption of normality. Since MANOVAs are robust with respect to those deviations from normal distribution (Olson, 1974), we use the original MANOVA (for a similar argumentation see Stárková et al., 2019). Although *prior knowledge* correlates significantly with cognitive load, it was not found to be a significant covariate [Wilks' Lambda = 0.96, $F(2,159) = 1.91$, $p = 0.13$]. Thus, the variance analysis was performed without any covariate. A significant effect for design [Wilks' Lambda = 0.90, $F(2,201) = 2.60$, $p = 0.009$, $\eta^2_p = 0.051$] was accompanied by significant effects using univariate variance analyses (ANOVAs) on *extraneous cognitive load*, $F(2,181) = 3.89$, $p = 0.022$, $\eta^2_p = 0.038$; *intrinsic cognitive load*, $F(2,201) = 4.162$, $p = 0.017$, $\eta^2_p = 0.040$; *germane cognitive load*, $F(2,201) = 3.16$, $p = 0.045$, $\eta^2_p = 0.031$, and *task difficulty*, $F(2,201) = 4.32$, $p = 0.015$, $\eta^2_p = 0.042$.

Bonferroni *post hoc* analyses were conducted. In the neutral design, intrinsic cognitive load was lower compared to the emotional design, $p = 0.050$ ($M_{Diff} = 0.56$, 95%-CI [1.12, 0.00]), and compared to the control design condition, $p = 0.031$ ($M_{Diff} = 0.60$, 95%-CI [1.16, 0.04]; lack of support for **H2.2**). See **Table 1** for mean values and standard deviations. The *extraneous cognitive load* was significantly lower in the neutral condition compared to the control design condition, $p = 0.018$ ($M_{Diff} = 0.72$, 95%-CI [1.34, 0.09]; lack of support for **H2.1**). The same pattern was observed for the *germane load,* $p = 0.049$ ($M_{Diff} = 0.61$, 95%-CI [0.00, 1.22]; lack of support for **H2.3**). The *perceived task difficulty* was highest for the control design condition and lowest for the emotional design condition, $p = 0.015$ ($M_{Diff} = 0.49$, 95%-CI [0.07, 0.91]; support for **H2.4**).

Appeal, Enjoyment, and Desire for Additional Tasks of a Similar Nature (H3.1)

Independent Samples Kruskal–Wallis tests showed that the students' perceived *appeal* (of the concept maps), $H(2,199) = 1.09$, $p = 0.58$, *enjoyment,* $H(2,201) = 1.99$, $p = 0.37$, and *desire for additional tasks of a similar nature,* $H(2,200) = 0.71$, $p = 0.70$ did not differ significantly between conditions (lack of support for **H3.1**; see **Table 1**).

EXPERIMENT 2

Method

Design and Procedure

To investigate whether concept maps in emotional design influence *positive affect*, an experimental intervention study with a pre- and post-test design was conducted. First, demographic data (age, gender, and biology grade level) were determined, and students completed a questionnaire on positive and negative

TABLE 1 | Means and standard deviations of dependent variables.

	Emotional design		Neutral design		Control design	
Dependent variables	***M***	***SD***	***M***	***SD***	***M***	***SD***
Knowledge of the lake ecosystem (learning performance)	11.58	3.17	11.50	3.24	10.86	2.85
Appeal[A]	3.33	1.10	3.11	1.15	3.11	1.17
Enjoyment[A]	3.23	1.21	2.97	1.12	3.08	1.27
Desire for additional lessons of a similar nature[A]	3.12	1.09	3.05	1.17	2.97	1.29
Task difficulty[A]	2.61	1.05	2.71	0.90	3.08	1.05
Intrinsic cognitive load	4.92	1.28	4.36	1.31	4.96	1.42
Extraneous cognitive load	3.41	1.51	2.98	1.34	3.70	1.60
Germane cognitive load	4.32	1.42	3.86	1.41	4.48	1.56

[A] *Variables are based on a single-item measures.*

affect for the first time. Each student was then randomly assigned to one of the three study books implementing emotional, neutral, or control design (see section "General Method"). In a learning phase, students were asked to study the concept maps carefully.

Sample

An *a priori* statistical power analysis using *G*Power 3.1.9.2* was performed for sample size requirements. For studies by Um et al. (2012) and Plass et al. (2014), large effect sizes of $d_{PositiveAffect}$ = 0.79 and $d_{PositiveAffect}$ = 0.88 were reported but in the meta-analysis by Brom et al. (2018) a marginal effect for positive affect ($d_{PositiveAffect}$ = 0.11) was found. Since in the meta-analysis by Brom et al. (2018), studies were included in which only the color of a learning environment was varied, we consider the effect sizes gained by Um et al. (2012) and Plass et al. (2014) to be a better guide value for our study. A compromise was chosen, and a medium average effect size (f = 0.30) was anticipated. Accordingly, a total sample of 48 students was required for repeated measures ANOVA at a significance level of α = 0.05 at a power of 0.95. A total of 54 students (grade 9) were recruited from a German high school. Since n = 7 were excluded because they missed the concept map training, N = 47 students were assigned to the treatment conditions (47% female; age: M = 14.34, SD = 0.56).

Instrument

The Positive and Negative Affect Scale (*PANAS*; Watson et al., 1988) was used in the German version (Breyer and Bluemke, 2016) to measure affect. For *positive affect*, ten different emotions related to positive affect (interested, excited, strong, enthusiastic, proud, alert, inspired, determined, attentive, and active) were presented to the students (Cronbach's α = 0.79). For *negative affect*, ten different adjectives describing negative affect (distressed, upset, guilty, scared, hostile, irritable, ashamed, nervous, jittery, and afraid) were presented (Cronbach's α = 0.87). Each subscale was rated on a 5-point Likert scale from "*not at all*" to "*very much*." Ratings are averaged by mean as recommended by Breyer and Bluemke (2016).

Results

Data were analyzed using *IBM SPSS Statistics* (version 26) and *nparLD R* software package (The R Foundation for Statistical Computing, Vienna, Austria).

Preliminary Analysis

Prior to hypothesis testing, the three conditions (emotional design, neutral design, and control design) were checked for differences in *age*, *grades in biology*, and *gender distribution*. As described earlier, for preliminary analyses, an alpha level of α = 0.10 is set as recommended by Döring and Bortz (2016). A chi-squared test revealed no statistically significant results for *gender distribution*, $\chi^2(2) = 0.83$, p = 0.659. Furthermore, it was shown by means of Kruskal–Wallis tests that students in all conditions did not differ in terms of *grades in biology*, $H(2) = 2.31$, p = 0.891, or *age* $H(2) = 0.02$, p = 0.990. No unusual data distribution or outliers were observed.

Hypothesis Testing

Affective State (H3.2)

We expected students to experience more *positive affect* and less *negative affect* when learning with the emotional design compared to the neutral or the control design. As the data were not normally distributed, a non-parametric counterpart of the repeated measures analysis of variance was conducted [rANOVA; nparLD R package; see Noguchi et al. (2012) for more information] with *design* as an independent variable and *positive affect* as a repeated measures variable. Descriptive statistics are shown in **Table 2**. We found no significant main effect for *time of measurement* (pre vs. post), $F(1,47) = 0.01$, p = 0.921. Also, no significant difference for the *design* could be determined, $F(2,47) = 2.45$, p = 0.087. Furthermore, *time of measurement* and *design* did not interact with each other, $F(2,47) = 1.11$, p = 0.325. To examine differences in the experienced *negative affect*, a rANOVA was calculated with *design* as an independent variable and *negative affect* as a repeated measures variable. No significant effect for the *time of measurement*, $F(1,47) = 1.00$, p = 0.315 and non for the interaction (*time of measurement*: *design)* was observed, $F(1,47) = 0.55$, p = 0.577. However, a significant main effect for the *design* could be found, $F(1,47) = 4.82$, p = 0.009. *Post hoc* analyses (Bonferroni) showed that learning with concept maps in the control design led to higher negative affect compared to concept maps in emotional design, $F(1,47) = 4.36$, p = 0.037 and neutral design, $F(1,47) = 7.59$, p = 0.006 (partly support for **H3.2**).

GENERAL DISCUSSION

The purpose of this research was to examine the effect of emotional design in concept maps on junior high school students' *learning performance*, *perceived cognitive load,* and *perceived affective state*. The concept maps covered the biological topic of the lake ecosystem.

Learning Performance

Based on the cognitive-affective theory of learning with media and previous findings (e.g., Um et al., 2012), we assumed concept maps with emotional design to influence learners' affective-motivational state and thereby foster learning. Contrary to our assumption, emotional design did not foster learning performance. Our results contradict previous findings (Um et al., 2012; Mayer and Estrella, 2014; Brom et al., 2018; Tien et al., 2018; Wong and Adesope, 2020) but as current results in emotional design research are heterogeneous, our results complement other findings showing that emotional design did not influence recall, transfer, or comprehension (Park et al., 2015; Uzun and Yıldırım, 2018; Stárková et al., 2019). There are several possible reasons to explain conflicting results in the field. Varying intensity of emotional design could be one possible cause (Park et al., 2015) as features of emotional design could include variations in shape, color, and sound, as well as the use of anthropomorphic graphics. So far, studies that incorporate only one design feature (e.g., color; Heidig et al., 2015) and those applying various, potentially more intensive manipulations

TABLE 2 | Means and standard deviations of the positive and the negative affect.

	Emotional design		Neutral design		Control design	
	M	***SD***	***M***	***SD***	***M***	***SD***
Positive affect pre	2.99	0.64	2.71	0.79	3.13	0.80
Positive affect post	3.02	0.59	2.59	1.03	3.13	1.17
Negative affect pre	1.58	0.59	1.39	0.37	2.07	0.98
Negative affect post	1.51	0.60	1.69	0.82	2.10	1.12

such as sounds, animations, and anthropomorphisms (Uzun and Yıldırım, 2018; Bülbül and Abdullah, 2021) are summarized under the umbrella term emotional design. Furthermore, the different ways in which the learning material is presented (e.g., paper-based or computer-based) must be considered. Previous studies were mainly computer-based (Um et al., 2012; Münchow et al., 2017; Münchow and Bannert, 2019; Stárková et al., 2019; Shangguan et al., 2020). Another aspect which needs to be considered is whether the learning material is animated or static (*nature of presentation*; Wong and Adesope, 2020). A meta-analysis by Berney and Bétrancourt (2016) revealed that animated graphics were more beneficial for learning compared to static graphics. Since our study was conducted in an authentic learning environment, the paper-based study books could not include sounds or animations. The resulting emotional design might, therefore, be "weaker" compared to computer-based (animated) designs [see the emotional designs applied in Uzun and Yıldırım (2018) or Bülbül and Abdullah (2021)]. Another aspect could be the learning topic. In our study we used the topic of the lake ecosystem because it is well suited for the use of concept maps. However, the effect of emotional design manipulations could vary depending on the topic, which still needs to be investigated further.

Furthermore, although in the emotional design research a direct effect of emotions on learning is assumed (Um et al., 2012), there is evidence to question this direct connection (e.g., Linnenbrink, 2006). In fact, a large body of research supports the assumption that emotions influence learner's self-regulation, interest, intrinsic motivation, and their use of learning strategies and thereby "exerting positive effects on overall performance" (Pekrun, 2017, p. 151). To further illustrate the complexity of the relationship between learning and emotions, it has to be mentioned that it is assumed that not only emotions can influence for example motivation and achievement but they in turn influence emotions (*reciprocal influence*; Pekrun, 2017).

As stated earlier, the cognitive theory of multimedia learning (Mayer, 2001), presumes that learning material providing both, pictures and text, should be more efficient for learning than material consisting only of pictures or only of texts. Therefore, concept maps with picture-text combinations (emotional design and neutral design) should have been more effective for learning than text-based concept maps (control design) which we could not observe in our study neither.

Cognitive Load

We expected emotional design manipulations to influence different types of perceived cognitive load. Other than expected, emotional design did not lead to significant differences in the perceived extraneous cognitive load compared to the non-emotional designs. This finding is in line with the results of previous studies (Plass et al., 2014; Park et al., 2015). Other than the emotional design, we found the neutral design leading to a significantly reduced extraneous cognitive load compared to the control design. Emotional design features could impose more extraneous cognitive load than neutral design features since emotional designs come with additional seductive details, whereas neutral designs are – in the most literal sense – reduced to essentials. The findings support assumptions posed by the cognitive theory of multimedia learning and the emotions as extraneous cognitive load hypothesis but contradict the cognitive-affective theory of learning with media (Um et al., 2012).

Intrinsic cognitive load was presumed to be unaffected by design manipulations. Other than expected, the intrinsic load was reportedly lower in the neutral design condition compared to the emotional design and the control design condition. One potential source of intrinsic cognitive load can be lack of prior knowledge (Sweller, 2005). However, as the experimental conditions did not differ in terms of prior knowledge or the self-assessed handling of concept maps (see preliminary results, **experiment 1**), differently perceived complexity cannot be due to different degrees of familiarity with concept maps or different levels of prior knowledge. A possible explanation could be that learners were unable to distinguish between sources of extraneous cognitive load and sources of intrinsic cognitive load (Klepsch and Seufert, 2020). As students perceived lower levels of extraneous load, the intrinsic load of the learning material is felt less complex because more cognitive resources are available to cope with it (Klepsch and Seufert, 2020). For the settings where intrinsic cognitive load and extraneous cognitive load may merge, Klepsch et al. (2017) recommend using complex instruments to uncover underlying processes. It is also worth noting that the scale for intrinsic load had limited reliability in our experiment ($\alpha = 0.51$), consequently the results need to be interpreted with caution.

For germane cognitive load, we expected the emotional design to increase the perceived germane load compared to the other conditions. Contrary to these expectations, our results do not indicate such an effect. This is in line with the findings of several studies (Um et al., 2012; Mayer and Estrella, 2014; Park et al., 2015; Navratil et al., 2018; Uzun and Yıldırım, 2018). An explanation why emotional design does not lead to higher germane load invested in a task is offered by Uzun and Yıldırım (2018). They draw the conclusion, based on Pintrich et al. (2000)

that emotional design elements could give the impression that the learning material is less difficult, resulting in less effort devoted to the task. Supporting this, the students' ratings of the perceived task difficulty in our study were significantly lower in the emotional design condition, compared to the control condition (Le et al., 2018).

Finally, methodological differences make it difficult to interpret the cognitive load results within the group of emotional design research. The self-rating questionnaire created by Paas (1992) has predominantly been used in emotional design research to measure mental effort. While, in some studies, mental effort is regarded as germane load (Um et al., 2012), in others it is equated with intrinsic load (DeLeeuw and Mayer, 2008). The same applies to task difficulty. Um et al. (2012) use this to measure extraneous load, whereas DeLeeuw and Mayer (2008) assign it to germane load. Thus, direct comparison of the results in emotional design research is difficult.

Affective State

In contrast to the cognitive-affective theory of learning with media and respective previous findings (e.g., Um et al., 2012), we did not find emotional design to induce a *positive affective state* (see section "Experiment 2"). Furthermore, no difference was found for other affective variables like self-report ratings on how well the students enjoyed the learning phase, desired additional lessons of a similar nature, or found the learning material appealing (see section "Experiment 1"). These results are in line with findings by many other studies which also found no influence of the emotional design on positive affect (e.g., Heidig et al., 2015; Park et al., 2015; Münchow and Bannert, 2019).

However, both the neutral and the emotional design led to lower *negative affect* compared to the control design. Studying concept maps can be overwhelming for learners (*map shock*; Dansereau et al., 1994). The excessive demand could lead to an affective reaction characterized by frustration and results according to Blankenship and Dansereau (2000) in a loss of motivation. The findings of the present study suggest that adding (emotional or neutral) images to concept maps could help learners overcome negative feelings while studying concept maps.

According to the cognitive-affective theory of learning with media, learning is influenced by emotions. Thus, it is reasonable to assume that an emotional design that does not induce emotions may also be unable to influence learning performance. Stark et al. (2018) raised the question whether changes in the emotional state of learners need to be proven when classifying an applied design as emotional. However, they note that if a change in an emotional state is required for a design to be designated as emotional design, many studies that have been carried out so far could no longer be assigned to this research field. Heidig et al. (2015) and Münchow and Bannert (2019), for example, found that emotional design influenced learning performance even though their design did not induce positive affect. Stárková et al. (2019) suspected that the affective influence of emotional design is generally small and difficult to detect [supported by the meta-analysis by Brom et al. (2018)]. It must be noted that even replication studies using the same learning material and instruments yielded contradicting results for affect (Plass et al., 2014; Park et al., 2015; Navratil et al., 2018). This suggests that the perceived affective state and learning performance could be influenced by other variables which still need to be identified.

Münchow and Bannert (2019) for example observed a time-dependent effect, whereby, after 10 min of learning time, higher (albeit not statistically significant) positive emotions were found among students who learned with emotional design material compared to students who learned with a neutral design. After another 10 min of learning, this was no longer observed. The authors concluded that emotional design, at least for the first 10 min of learning, can prevent the reduction of positive emotions. In support of this observation, many of the studies that found a positive effect on emotional state, were based on a short learning time ($\leq$15 min). Consequently, extended learning time (e.g., 20 min, as in our study) could cause these effects to fade. Wong and Adesope (2020) support these findings in their meta-analysis and suspect that "novelty of learning with emotional designs was most beneficial between short and moderate lengths of instructional time" (p. 24).

LIMITATIONS

When measuring affective parameters using the self-reporting method, study participants may not be conscious of their current emotional state (Damasio, 2000), and even if they are, they may encounter difficulties assigning it to specific categories (Salovey and Mayer, 1990). Since our study was carried out on junior high school students rather than college students (as in most studies), the students in this study might had problems answering the items on the PANAS scale. One possible reason for the failure to find any effects on for example, *appeal*, *enjoyment* or *perceived cognitive load* is that the concept maps provided in the form of study books may have been more elaborate than everyday worksheet-based learning material, and as the students only learned with one of the three designs, they lacked a direct comparison. Supporting this, Navratil et al. (2018) showed that an intended negative emotional design was only perceived as more negative when students had the opportunity to compare it directly with different designs.

CONCLUSION AND OUTLOOK

Our research pioneered to investigate the question of whether emotional design in paper-based concept maps improve learning for junior high school students. Together, these results indicate no superiority of emotional design over non-emotional design concept maps. However, the use of emotional design seems to reduce the perceived task difficulty. The current state of research suggests that in the best-case scenario, emotions are triggered by an emotional design and learning is improved while, in the worst-case scenario, it has no effect on emotions and learning. As suggested by several authors, we agree that the effect of emotional design features could depend on factors like learning context, intensity of the design manipulation, the age of the learners or in which way the learning material is presented (e.g., Münchow and Bannert, 2019; Stárková et al., 2019; Wong and Adesope, 2020). The present study was conducted for a biological topic (as most studies in this field). Therefore caution is needed when interpreting the results, and more research is required to transfer them to other cognitive domains or different learning conditions. To allow an assessment of the generalizability of our findings, we recommend broad and systematic examinations on emotional design in concept maps for other (biological) topics.

Furthermore, to make specific statements about the use of emotional design in concept maps, more basic research on emotional design manipulations is needed. From our point of view, this research should involve the following aspects.

Reliable measuring instruments for determining emotional influence should be established. We recommend more objective approaches (Brom et al., 2018), for example, heart rate variability or electrodermal activity measurements as implemented by, e.g., Lenski and Großschedl (submitted)[2]. Furthermore, the two dimensions of emotions (arousal and valence) should be examined differentially (Lenski and Großschedl, submitted[2]) as it is suspected that the learning performance is especially affected by arousal (Schneider et al., 2019; Irrazabal and Burin, 2021). Additionally, further research is needed to identify the conditions in which emotional design manipulations successfully evoke emotions (see also Heidig et al., 2015). If the basis for objective measurement and emotional induction is established, effects of those emotional design features on learning performance and emotions can be analyzed and new insights gained. These insights could have a major impact on the design of learning material and learning success in general. Since learning success could be influenced by other factors, such as time spent with the learning material, personal characteristics like cultural background (Stárková et al., 2019) or different perceptions of aesthetics (Heidig et al., 2015), uncovering these aspects should be focused on. As already stated, a large proportion of studies assume that emotions affect learning indirectly, which should also be reflected in emotional design research. Finally, the practicability of successful emotional design manipulations should be evaluated. If time-consuming and artistic manipulations are necessary to evoke emotions and influence educational variables, the use in everyday school life may be restricted (Lenski and Großschedl, submitted[2]).

[2] Lenski, S., and Großschedl (submitted). Emotional design pictures –pleasant but too weak to evoke arousal and attract attention? *BMC Psychol.*

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.807627/full#supplementary-material

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Children's Views of SARS-CoV-2 and COVID-19 Preventive Practices: Comparing Verbal and Visual Empirical Evidence

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Despite the growing body of research on the consequences of the COVID-19 pandemic on children's wellbeing, few studies so far have explored children's points of view, while the majority were based on data collected during the first year of the pandemic. The present study attempted to capture children's views 1 year after the beginning of the pandemic, and to this end, data were collected during Spring 2021 in Greece. Specifically, by combining verbal and visual data, the study attempted to explore children's views of SARS-CoV-2 and COVID-19 preventive practices. Participants involved 320 children, ranging in age from 4 to 12 years, who were asked to verbally describe and draw (a) Coronavirus and (b) the preventive measures adopted to mitigate the pandemic. Data analysis indicated that overall, children's views involve elements of scientifically appropriate information since from an early age they are able to describe and depict SARS-CoV-2 in ways that reflect the abundance of available verbal and visual information in the public sphere. Moreover, children recommended suitable COVID-19 preventive practices since their verbal and drawing responses included references to both the Hygienic and Social preventive practices that prevailed during the time of data collection. Age-related differences in children's views, as well as differences between the two data collection techniques, were also found. Results also showed that children who described SARS-CoV-2 as a virus or a germ tended to report more hygienic practices than those who failed to describe the term appropriately. The findings shed light on the way children form their views of the novel coronavirus and COVID-19 and raise research educational implications.

Keywords: children, COVID-19, drawings, SARS-CoV-2, preventive practices

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INTRODUCTION

Since the emergence of COVID-19, an abundance of information about infection and transmission risks and related measures to contain the pandemic has been addressed to the public, including children (Provenzi et al., 2020; Thompson et al., 2021; Zou and Tang, 2021). Most countries have imposed restrictive measures and broadcasted campaigns involving visual and verbal slogans to promote citizen observance of safe behavior (Berasategi et al., 2020; Bray et al., 2021a). It has been argued (Assante and Candel, 2020; Idoiaga et al., 2020) that this storm of information might have embedded children in social representations (Moscovici, 1984) of COVID-19. The available social representations might have facilitated their effort to transform scientific knowledge into everyday thinking, to become familiar with this unknown and dangerous phenomenon, to regulate the negative emotions it aroused, and finally to understand it (Moscovici, 1988).

Research has shown that the pandemic abruptly disturbed children's daily lives that have impacted their physical and mental health, wellbeing, and education (Assante and Candel, 2020; Garcia de Avila et al., 2020; Valadez et al., 2020; Berasategi Santxo et al., 2021; Bray et al., 2021a; Spiteri, 2021). These findings indicate the need to support children, who will probably face similar emergencies later in life, in understanding SARS-CoV-2 and its resulting disease (Manches and Ainsworth, 2022). Consequently, it is essential to scaffold children's understanding of COVID-19 and assist them in coping with this unpredictable condition, to empower their responsible participation in mitigating the pandemic (Garcia de Avila et al., 2020; Provenzi et al., 2020; Maftei et al., 2022; Manches and Ainsworth, 2022; Rydström et al., 2022), and to prevent traumatic effects (Assante and Candel, 2020; Idoiaga et al., 2020).

However, how the public discussion and the available information on SARS-CoV-2 and COVID-19 are conceptualized by children has not been fully explored thus far. For any teaching intervention or information campaign to be meaningful to them, it is crucial that it starts from their point of view. It is therefore of great importance to gain insight into children's understanding of the novel coronavirus and ways of responding to the crisis (Thompson et al., 2021). Such insight would allow the selection and formulation of age-appropriate and accurate explanations and representations that they could meaningfully handle. This, in turn, would make learning about viruses relevant to children and support them in preserving their overall wellbeing (Assante and Candel, 2020; Berasategi et al., 2020; Garcia de Avila et al., 2020; Idoiaga et al., 2020; Majid et al., 2020; Bray et al., 2021b; Manches and Ainsworth, 2022).

Few studies so far have investigated children's views of the pandemic (Idoiaga et al., 2020; Thompson et al., 2021; Rydström et al., 2022), although a rapidly growing body of research related to COVID-19 and its consequences on children's wellbeing has evolved during the last 2 years (e.g., Garcia de Avila et al., 2020; Valadez et al., 2020). Interestingly, despite the previously documented lack of appropriate understanding of infectious diseases and prevention practices in non-experts (Jee et al., 2015), recent studies report high levels of awareness of COVID-19 even in young children (Rydström et al., 2022), and their sensitivity in perceiving and adopting adults' reactions to the pandemic (Valadez et al., 2020; Thompson et al., 2021). This awareness has been revealed in children's ability to distinguish SARS-CoV-2 (cause) from COVID-19 (result); to name common symptoms of the disease (for instance cough, fever, or sneeze); to understand the possibility of asymptomatic infection; to recognize the necessity of preventive and mitigation practices such as social distancing or handwashing; to describe airborne transmission and high contagiousness of the virus (Idoiaga et al., 2020; Bray et al., 2021b; Christidou et al., 2021; Martinerie et al., 2021; Thompson et al., 2021; Bonoti et al., 2022; Maftei et al., 2022; Rydström et al., 2022).

In their attempt to understand this unprecedented phenomenon, children might have been facilitated by depictions of SARS-CoV-2, its transmission, and pertinent mitigation measures which have dominated public discourse during the COVID-19 pandemic. Nowadays, visual images are increasingly used to convey information and support meaning-making (Avgerinou and Ericson, 1997), especially in the realm of science, where communication and meaning-making are inherently multimodal (Lemke, 1998; Givry and Pantidos, 2012). Furthermore, images are particularly valuable when invisible entities are at play (Lemke, 1998; Jewitt, 2008; Coleman et al., 2011; Jarman et al., 2012; Manches and Ainsworth, 2022), all the more so in crisis circumstances (Höijer, 2010; Alcibar, 2018; Stark and Stones, 2019).

Therefore, in the context of COVID-19, visual images have become powerful communication means with the potential to convey meanings more effectively than verbal communication by rendering complex information accessible to non-experts (Joubert and Wasserman, 2020). Besides, images, as socio-cultural mediating tools, apart from representing scientific information touch upon social, emotional, or cultural facets of the pandemic (Delicado and Rowland, 2021; Zou and Tang, 2021). Publicly available images of SARS-CoV-2 typically involve (a) the morphology of the virus, emphasizing its sphere-like shape and the spikes on its surface (Delicado and Rowland, 2021) and (b) anthropomorphic elements, echoing a tendency to assign human features, like eyes, mouth, facial expression, or human-like limbs to the virus (Joubert and Wasserman, 2020; McGellin et al., 2021). This is no surprise since anthropomorphic representations are commonly used when representing entities inducing uncertainty and fear, as in the case of SARS-CoV-2 (de Rosa and Mannarini, 2020). On the other hand, visual representations of mitigation measures and illness have been more realistic and straightforward, since they typically depict real-life, observable situations. These mainly involve (a) visualized instructions on protective measures (e.g., mask-wearing, hand washing, covering the mouth, and nose when coughing), (b) COVID-19 symptoms; (c) iconic symbols of different levels of medical intervention, namely, testing, treatment (e.g., hospitals, medicines), or vaccination; and (d) depictions of the social aspects of the pandemic [e.g., lockdown, deserted streets, business, and school closures (Bray et al., 2021b; Delicado and Rowland, 2021)].

Visual communication is particularly popular among children, who typically resort to drawing to express their ideas, emotions, and experiences (Brechet et al., 2009; Cox, 2005; Misalidi and Bonoti, 2014). In this sense, children's drawings are seen as documentations of how they understand and interpret scientific concepts. Thus, they become valuable tools for exploring students' science ideas and their evolution as their learning progresses (Jewitt, 2008; Brooks, 2009; Ainsworth et al., 2011). More particularly, when engaged in the act of drawing children are also engaged in meaning-making by creating multimodal artifacts that can be regarded as inscriptions of their mental images. In this way, children express and communicate their knowledge with others (Matloob Haghanikar and Leigh, 2022). In addition, inviting students to express their views of a scientific issue visually engages them in relating sociocultural to scientific knowledge (Smith and Joffe, 2013; Zou and Tang, 2021; Bonoti et al., 2022). This allows them to communicate scientific meanings without relying on specialized vocabulary, while it offers a more wide-ranging picture of their understanding and experiences compared to verbal communication alone (Kress and van Leeuwen, 1996; Jewitt, 2008; Jolley, 2010; Mutonyi and Kendrick, 2011).

Acknowledging the multimodal character of perceiving SARS-CoV-2 and COVID-19 and that much of the public information about these issues has been visually communicated, previous studies (Bray et al., 2021a; Christidou et al., 2021; Martinerie et al., 2021; Thompson et al., 2021; Rydström et al., 2022; Bonoti et al., 2022) have exploited the potential of children's drawings to capture their views when combined with verbal tasks (Driessnack and Gallo, 2013). Children's drawings of SARS-CoV-2 vastly replicated the visual representations widely available in the media, i.e., its sphere-like shape with spikes (Martinerie et al., 2021; Thompson et al., 2021; Bonoti et al., 2022), while instances of anthropomorphic depictions were also common (Martinerie et al., 2021; Bonoti et al., 2022). These findings are also in line with previous research on children's representations of micro-organisms, depicting them in regular geometric shapes (e.g., circles), or with anthropomorphic characteristics including physical (e.g., hands, and legs), or mental features, such as intentionality (Nagy, 1953; Byrne et al., 2009; Byrne and Grace, 2010; Byrne, 2011; Jee et al., 2015; Prokop et al., 2016). Furthermore, in some cases, SARS-CoV-2 was depicted as animal-like or as an aggressive monster (Thompson et al., 2021; Bonoti et al., 2022). Some children have also expressed visually their understanding of the process of transmission (Bray et al., 2021a; Martinerie et al., 2021; Thompson et al., 2021; Bonoti et al., 2022). Moreover, their depictions of COVID-19 preventive measures have been found to emphasize advisable hygienic practices, such as handwashing, social distancing, or wearing a mask (Bray et al., 2021a; Christidou et al., 2021; Martinerie et al., 2021; Thompson et al., 2021; Rydström et al., 2022).

As the pandemic and related research on children's views is still in progress, questions that merit more systematic investigation arise. Data in most studies to date (Assante and Candel, 2020; Berasategi et al., 2020; Idoiaga et al., 2020; Valadez et al., 2020; Bray et al., 2021a,b; Christidou et al., 2021; Martinerie et al., 2021; Thompson et al., 2021; Bonoti et al., 2022; Matloob Haghanikar and Leigh, 2022; Rydström et al., 2022) were collected during the first year of the pandemic, in 2020, when restrictions and preventive measures were novel. By examining children's views during the second year of the COVID-19 pandemic, namely 1 year after its outbreak, this study could provide insight from a different angle. More specifically, such an exploration would capture the accumulated experience of a long-term, ongoing, and continuously evolving crisis (Thompson et al., 2021), which probably implies rapid changes in children's understanding of viruses and infectious diseases (Manches and Ainsworth, 2022).

Furthermore, existing studies, have only shed light on some aspects of children's understanding of SARS-CoV-2 and COVID-19, while the development of this understanding has not been fully explored (Christidou et al., 2021; Martinerie et al., 2021; Bonoti et al., 2022). However, it has been suggested that it is important to investigate children's understanding of health information from a developmental point of view (Velardo and Drummond, 2017; Rydström et al., 2022). Thus, it would be valuable to determine whether the development of children's views follows the major changes observed in their overall biological knowledge around the age of 7 (Duschl et al., 2007), or if their progression toward more scientifically appropriate views is less straightforward.

In the present study, 4-to-12-year-old children in Greece were invited to express both verbally and visually their views of SARS-CoV-2 and COVID-19 preventive practices during the second year of the pandemic in an attempt to investigate the extent to which these views involve elements of scientifically appropriate information. To attain this aim, the following research questions were investigated:

1. What are children's views of SARS-CoV-2?
2. Do children's views of SARS-CoV-2 differ between age groups and data collection techniques?
3. What types of measures do children recommend to protect themselves from the disease and mitigate the pandemic?
4. Do the proposed types of measures vary with age and between the two data collection techniques?
5. Do the types of recommended preventive measures relate to children's views of SARS-CoV-2?

MATERIALS AND METHOD

Participants

A total of 320 children (140 boys and 180 girls) ranging in age from 4 to 12 years participated in the study. The sample was distributed in three age groups: (a) 4-to-6-year-olds (n = 107, 48 boys and 59 girls, M = 66.78 months, SD = 9.96), (b) 7-to-9-year-olds (n = 114, 51 boys and 63 girls, M = 101.43 months, SD = 10.85), and (c) 10-to-12-year-olds (n = 99, 41 boys and 58 girls, M = 133.67 months, SD = 10.18).

A snowball sampling procedure (Parker et al., 2019) was adopted to approach children from different cities in Greece. Specifically, researchers used their social networks to invite families to participate in the study, who in turn suggested other potential participants. Parents were informed about the purpose of the study, and they provided their written consent. The children's willingness to participate in the study was also obtained and they were informed that they could quit the process at any time.

The study has achieved the approval of the Ethics Committee of the Department of Early Childhood Education/University of Thessaly (18/26.02.2021), affiliation of the second author during the design and implementation of data collection.

Procedure

Data were collected during the second year of the COVID-19 pandemic (March–April 2021) through electronic platforms due to the restrictions imposed by the Hellenic Ministry of Health. Precisely, during that period the following governmental measures were adopted to mitigate the spread of the pandemic: (a) stay-at-home suggestions (b) social and physical distancing guidelines (c) closure of schools and non-essential businesses (d) movement and traveling restrictions, (e) night curfew (f) mandatory use of mask, (g) gradual vaccination of the population (optional), and (h) implementation of teleworking. To ensure measure observance by the citizens an automated service through SMS messages on mobile phones was initiated, instantly granting permission to phone holders to go out for specific reasons apart from professional ones (e.g., visiting a doctor, shopping for essential goods, or physical exercise).

To eliminate physical contact between researchers and participants, each child was tested individually while being in his/her home through a video call. His/her parents were asked to recommend the electronic platform in which they had access and to propose a suitable time for them to arrange an appointment. Researchers made the video call at the present time, while parents were prompted to not intervene in the process but to offer their help in case the child could not cope with the technical requirements of the procedure. Each video call lasted 10–20 min.

Overall, children were asked to answer a couple of simple questions and to produce two drawings. They were also advised to use two sheets of white paper, and colored pencils or crayons. Initially, children were asked to describe verbally SARS-CoV-2 (*"Do you know what coronavirus*[1] *is?"*) and then produce a picture of it (*"Would you like to draw coronavirus?"*). Subsequently, they were prompted to mention the preventive measures they followed (*"Please tell me, what do you do to protect yourself from the coronavirus disease?"*) and then to create a picture *"showing what you do to protect yourself from coronavirus."* After the completion of each drawing, children were asked to describe what they had included in them.

Children's verbal descriptions were transcribed verbatim, while photos of their drawings were emailed to the researchers by themselves or their parents.

Coding of Verbal and Visual Data

Coronavirus

Children's verbal descriptions and depictions of SARS-CoV-2 were coded as Adequate, Partially Adequate, and Inadequate, depending on the degree to which they involved elements of scientifically appropriate terminology and imagery (Bonoti et al., 2022). Specifically, verbal descriptions were classified as Adequate when they referred to a virus or a germ, as Partially Adequate when there was an explicit connection of SARS-CoV-2 with a health issue or the pandemic, but no reference was made to micro-organisms, and as Inadequate when they incorporated mythical or irrelevant elements. Respectively, children's drawings were characterized as Adequate when they portrayed the virus in a circular shape with or with no spikes, as Partially Adequate when they involved both appropriate and inappropriate elements (e.g., a circular virus enriched with symbolic or anthropomorphic elements like a crown, or frown eyes) and as Inadequate when the drawing included mythical (e.g., depictions of coronavirus as a monster) or irrelevant elements (e.g., the coronavirus as an animal). In a next step, two female coders, trained students of an Educational Department in Greece, who were unaware of the aims of the study, were asked to rate data by assigning a score of 3 to the adequate, a score of 2 to the partially adequate, and a score of 1 to the inadequate verbal and drawing responses. Interrater reliability in assessing the verbal descriptions and the visual representations of coronavirus was satisfactory since intraclass correlation coefficient (ICC) values were 0.89 and 0.92, respectively.

Preventive Measures

Quantitative content analysis has been applied in children's quotes and drawings of preventive measures since this method is considered appropriate for analyzing both verbal and visual data (Stemler, 2000; Krippendorff, 2018). This analysis revealed two main themes, namely the Hygienic and the Social. Analytically, the Hygienic theme included verbal or drawing indices of (a) wearing a mask, (b) washing hands, (c) sanitizer use, and (d) medical care (hospital, medical staff, vaccines, and rapid, or self-testing). The Social theme included indices of (a) social/physical distancing (avoiding crowded or indoor places and intimacy such as hugging or kissing), (b) staying at home, (c) governmental restrictions (remote schooling/teleconferences, curfew, requirement for permission for any outdoor activity through SMS messages, restrictions on travel/movement between regions) and (d) lack of interaction with significant others (such as peers or grandparents). In the next step, the two independent coders mentioned above were asked to review the transcripts and the drawings by giving a score of 1 for the presence of each of the aforementioned indices and a score of 0 for its absence. Inter-coder agreement in identifying the indices included in participants' verbal responses and drawings ranged from 89 to 98% and divergences between coders were resolved after discussion. **Figure 1** illustrates the categories of the Hygienic and Social themes.

Data Analysis

Initially, descriptive statistics have been used to summarize collected data. In order to examine whether children's views of SARS-CoV2 and preventive measures relate to their age and the data collection technique we performed mixed Analyses of Variance with repeated measures, while a series of chi-square tests was applied to detect possible age differences in the incidence of each preventive measure. Finally, to examine whether children's views of SARS-CoV-2 as expressed in their verbal descriptions and their drawings differentiate children's recommendation of Hygienic vs. Social practices to mitigate the spread of COVID-19, a series of Analyses of Variance was applied

[1] During data collection, the term "coronavirus" was used to denote SARS-CoV-2, as has been typically the case in public discourse since the beginning of the COVID-19 pandemic.

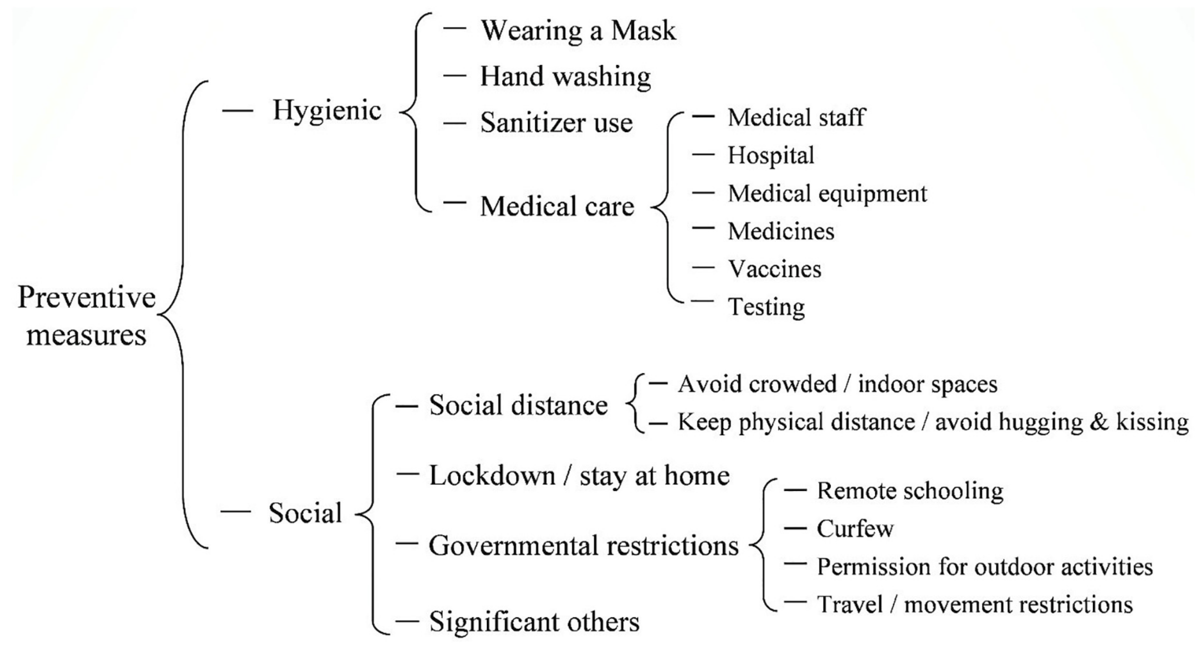

FIGURE 1 | Categories of hygienic and social preventive measures proposed by children.

using children's verbal and drawing scores about SARS-CoV-2 as the independent factor.

RESULTS

Results are presented in accordance with the research questions as follows: Firstly, children's views of SARS-CoV-2 and whether these vary according to age and mode of expression are presented. Secondly, analyses related to children's views of preventive measures and their variation with age and between data collection techniques are described. Finally, the relation between children's views of SARS-CoV-2 and prevention measures is reported.

Children's Verbal Descriptions and Drawings of SARS-CoV-2

First, the children's verbal descriptions and pictorial representations of SARS-CoV-2 were examined. Precisely, the analysis showed that the majority of children provided adequate responses and mentioned viruses or germs ($n = 190$, see Example 1), while fewer children gave partially adequate responses, for instance by connecting coronavirus to illness ($n = 99$, see Example 2). A small number of children responded inadequately and included mythical or other inappropriate elements in their answers ($n = 31$, see Example 3).

Example 1 (12-year-old boy):

> Coronavirus is a virus that is circular and it has little prickles. (. . .) it looks, if we see it from above, it will look like a crown,[2] and that's why they named it coronavirus. There are many coronaviruses. This particular (coronavirus) that's hitting us is called SARS-COVID-2. It's bad because a lot of people are dying from it.

Example 2 (10-year-old boy):

> It's an illness like all others but it's very contagious and this illness can easily kill you if you are old. And if you have not been vaccinated, then it is even easier for it to kill you.

Example 3 (5-year-old boy):

> Coronavirus is that people should not go out.

When asked to draw coronavirus most children produced either an adequate ($n = 145$) or a partially adequate representation ($n = 158$), as in **Figures 2** and **3**, respectively. Fewer children portrayed coronavirus including mythical or irrelevant elements in their drawings ($n = 17$, see **Figure 4**). The vast majority of children ($n = 298$) included spikes in their -either adequate or partially adequate- depictions.

In order to examine whether children's scores related to SARS-CoV-2 vary as a function of age and mode of expression we performed a 3 (*age group:* 4–6, 7–9, 10–12) X 2 (*mode of expression*: verbal, drawing) mixed ANOVA with repeated measures on the last factor. The analysis revealed a significant effect of age group, $F_{(2,317)} = 15.89$, $p < 0.001$, indicating that children's scores improved with age, with older children providing more adequate responses. *Post hoc* Tukey HSD comparisons revealed that statistically significant differences were observed between the 4–6-year-olds and the 7–9-year-olds ($p < 0.05$), between the 4–6-year-olds and the 10–12-year-olds ($p < 0.01$), as well as between the 7–9-year-olds and the 10–12-year-olds ($p < 0.05$). Furthermore, a significant main effect of mode of expression was found, $F_{(1,317)} = 5.03$, $p < 0.05$,

[2] In Greek, the word "corona" means "crown."

FIGURE 2 | A 9-year-old boy's adequate drawing of SARS-CoV-2.

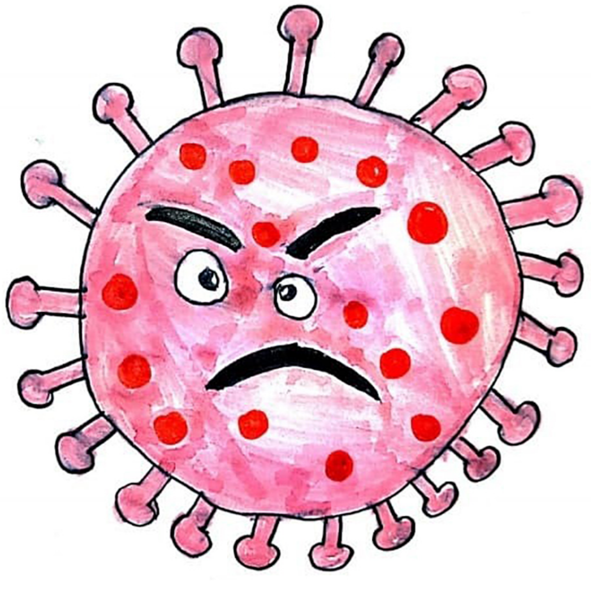

FIGURE 3 | An 11-year-old girl's partially adequate drawing of SARS-CoV-2 with anthropomorphic features.

since children's scores while verbally describing SARS-CoV-2 (M = 2.50) were higher than their scores while drawing it (M = 2.40). Finally, the interaction between age group and mode of expression was also found statistically significant, $F_{(2,317)} = 6.54$, $p < 0.05$. This interaction was investigated further by a series of ANOVAs, which showed that age group differentiated significantly participants' verbal descriptions of SARS-CoV-2, $F_{(2,319)} = 19.81$, $p < 0.001$, but not their drawing representations. As presented in **Table 1**, which summarizes the mean scores of children's responses by age group, even the younger age group seems to provide a partially adequate verbal description of coronavirus, while older children present higher

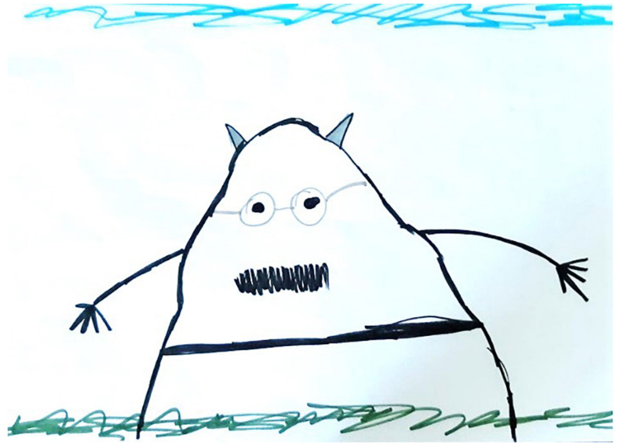

FIGURE 4 | A 6-year-old girl's inadequate drawing representing SARS-CoV-2 as a monster "with big hands because he reaches everything and eyeglasses because he sees everything."

TABLE 1 | Mean scores (and standard deviations) of children's verbal descriptions and drawings of coronavirus by age group.

	Verbal descriptions	Drawings
Age groups	***M (SD)***	***M (SD)***
4–6 years	2.22 (0.78)	2.35 (0.62)
7–9 years	2.51 (0.59)	2.35 (0.56)
10–12 years	2.78 (0.46)	2.52 (0.58)
Total	2.50 (0.67)	2.40 (0.59)

scores than the younger ones. On the contrary, mean scores of the drawing representations were at similar levels for all age groups.

Children's Verbal Descriptions and Drawings of COVID-19 Preventive Measures

In a next step, we attempted to identify the preventive measures proposed verbally and visually by participants to mitigate the spread of COVID-19. Overall, children mentioned equally Hygienic (n = 586) and Social (n = 585) measures. On the contrary, they included more Hygienic (n = 386) than Social (n = 218) measures in their drawings. **Table 2** presents the frequencies with which each preventive measure appeared in both modes of expression. Analytically, in their verbal descriptions children referred more often to Wearing a Mask (n = 276), Governmental Restrictions (n = 200), the need for Social/physical distancing (n = 191), Handwashing (n = 163), and use of Sanitizer (n = 112). Example 4 is indicative of participants' verbal responses. On the other hand, Wearing a Mask (n = 243, see **Figure 5**) and Staying at home (n = 105) were the most often depicted measures in children's drawings.

Example 4 (8-year-old girl):

> We can take the vaccine, wear a mask, use antiseptic and be cautious in general. We can't go out; they have limited us. We are

TABLE 2 | Frequencies (and %) of preventive measures in children's verbal descriptions and drawings by age group.

Preventive measures	Verbal descriptions				Drawings			
	Age groups							
	4–6 years	7–9 years	10–12 years	Total	4–6 years	7–9 years	10–12 years	Total
Hand washing	55 (51.4)	60 (52.6)	48 (48.5)	163 (50.9)	14 (13.1)	22 (19.3)	16 (16.2)	52 (16.3)
Sanitizer	33 (30.8)	48 (42.1)	31 (27.7)	112 (35.0)	18 (16.8)	31 (27.2)	29 (29.3)	78 (24.4)
Mask	84 (78.5)	103 (90.4)	89 (89.9)	276 (86.3)	74 (69.2)	83 (72.8)	86 (86.9)	243 (75.9)
Medical care	14 (13.1)	13 (11.4)	8 (8.1)	35 (10.9)	4 (3.7)	4 (3.5)	5 (5.1)	13 (4.1)
Social distance	46 (43)	72 (63.2)	73 (73.7)	191 (59.7)	5 (4.7)	19 (16.7)	27 (27.3)	51 (15.9)
Stay at home	27 (25.2)	37 (32.5)	29 (29.3)	93 (29.1)	34 (31.8)	40 (35.1)	31 (31.3)	105 (32.8)
Restrictions	55 (51.4)	74 (64.9)	71 (71.7)	200 (62.5)	9 (8.4)	30 (26.3)	15 (15.2)	54 (16.9)
Significant others	33 (30.8)	41 (36.0)	28 (28.3)	102 (31.9)	2 (1.9)	4 (3.5)	2 (2.0)	8 (2.5)

FIGURE 5 | A 6-year-old boy's drawing of his family members wearing masks.

> not allowed to go out without sending an SMS. When we don't send an SMS, they check us and put a fine.

In order to analyze the data presented in **Table 2**, we created two composite scores for each mode of expression (verbal vs. drawing) by summing up the measures of Hygienic and Social categories (range 0–4). These data were analyzed by a 3 (*age group*: 4–6, 7–9, 10–12) X 2 (*type of measures*: hygienic, social) X 2 (*mode of expression*: verbal, drawing) mixed ANOVA with repeated measures on the two last factors. The analysis showed that the main effect of age group was statistically significant, $F_{(2,317)} = 13.94$, $p < 0.001$, showing that with age participants tended to introduce more preventive practices in their responses. The mean scores were 1.18, 1.49, and 1.49 for the younger, the middle, and the older group, respectively. *Post hoc* Tukey comparisons revealed significant differences between the 4–6-year-olds and the 7–9-year-olds ($p < 0.001$), as well as between the 4–6-year-olds and the 10–12-year-olds ($p < 0.001$). Examples 5 and 6 and **Figures 6** and **7** are indicative examples of older participants' attempts to include a variety of preventive measures in their verbal and drawing representations.

Example 5 (9-year-old girl):

> To protect ourselves from COVID-19 we should all wear masks, use antiseptics, and try to keep distance measures so that we don't catch it. These footprint stickers they have in supermarkets and department stores are good. (You) can't… contact people you don't know… You see, you are negative, OK? You don't know the other one doesn't have it. And the other one is also negative or has not had any symptoms, but we can both have (COVID-19) and not have any symptoms. That's why it is good to be cautious even without having the coronavirus and keep distances. This is the best. And (wearing) masks. As for hugs, I would suggest no.

Example 6 (10-year-old boy):

> We should take all necessary protection measures, that is mask, 2-m distance, frequent handwashing, antiseptic, and even the vaccine. We can't be in our homes forever, away from our friends and the people we love, e.g., grandpa, grandma.

Moreover, a significant main effect of mode of expression, $F_{(1, 317)} = 401.33$, $p < 0.001$ was recorded, since children included more preventive measures in their verbal descriptions ($M = 1.83$) than in their pictorial representations ($M = 0.94$). The main effect of type of practices was also found significant indicating that children overall reported more Hygienic ($M = 1.52$) than Social ($M = 1.26$) practices. Additionally, a statistically significant interaction was found between mode of expression and type of practices, $F_{(1,317)} = 33.53$, $p < 0.001$, suggesting that drawings included more Hygienic ($M = 1.21$) than Social practices ($M = 0.068$), while verbal descriptions included equally Social ($M = 1.83$) and Hygienic ($M = 1.82$) practices.

Finally, the interaction between age group, mode of expression, and measures was also found significant, $F_{(2,317)} = 3.18$, $p < 0.05$. This interaction was investigated further by a series of ANOVAs, which showed that the effect of age-group was statistically significant in reporting Social measures [$F_{(2,319)} = 8.36$, $p < 0.001$] and in drawing Hygienic [$F_{(2,319)} = 4.22$, $p < 0.05$] and Social measures [$F_{(2,319)} = 7.2$, $p < 0.001$]. Subsequent *post hoc* analyses revealed that the younger group verbally reported fewer social measures than the

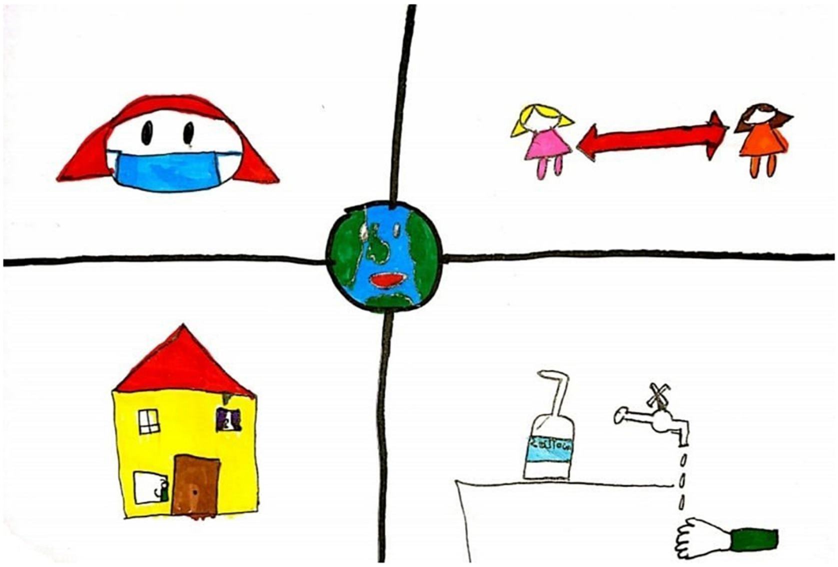

FIGURE 6 | An 11-year-old girl's drawing portraying a variety of COVID-19 preventive measures: Wearing a mask, keeping distance, staying at home, and washing hands.

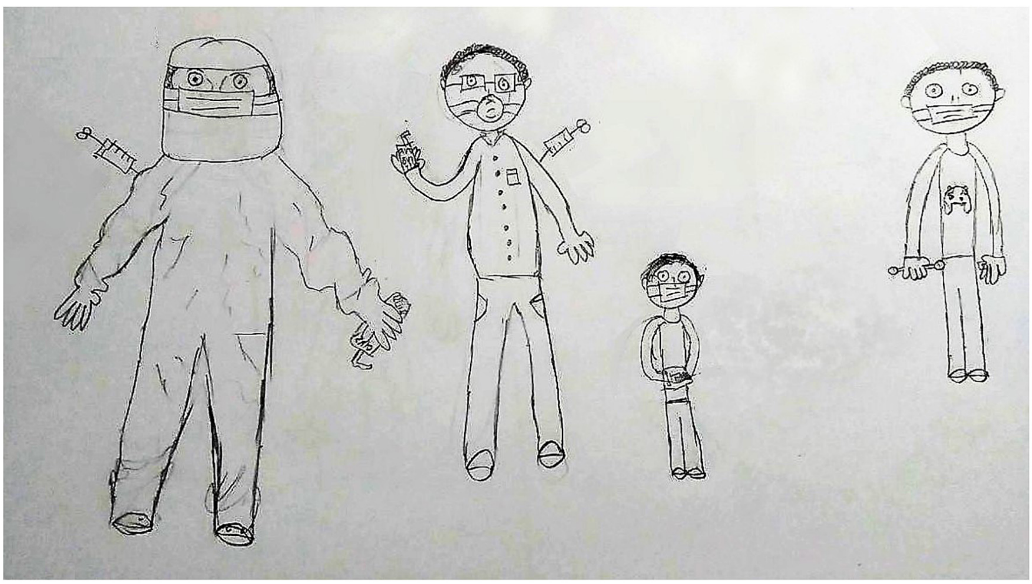

FIGURE 7 | A 10-year-old girl's drawing of her family taking preventive measures: masks, hospital uniform, vaccines, antiseptics, and self-tests.

middle and the older group, drew fewer hygienic measures than the older group, and fewer social measures than the middle and the older group (all *ps* < 0.05).

Regarding the emergence of each preventive measure between age groups, the crosstabulation of data presented in **Table 2** showed significant differences in (a) Wearing a Mask [χ^2(2, $N = 320 = 8.14$, $p < 0.05$ for verbal descriptions), χ^2(2, $N = 320 = 9.78$, $p < 0.05$ for drawings)] (b) Social/physical distancing [χ^2(2, $N = 320 = 21.09$, $p < 0.001$ for verbal descriptions), χ^2(2, $N = 320 = 17.67$, $p < 0.001$ for drawings)] and (c) Governmental restrictions, [χ^2(2, $N = 320 = 9.49$, $p < 0.05$ for verbal descriptions), χ^2(2, $N = 320 = 12.92$, $p < 0.05$ for drawings)]. Specifically, the analysis showed that the youngest age group tended not to mention wearing a mask or governmental restrictions, while they referred to social/physical distancing less frequently than expected. Consistently, this group drew keeping social/physical distances and governmental restrictions less frequently than expected. Furthermore, the 7-to-9-year-old group drew governmental restrictions more frequently than expected, while 10-to-12-year-olds emphasized social/physical distancing both verbally and visually more frequently than expected and tended not to draw masks. No statistically significant age differences were noticed regarding the emergence of Handwashing, Use of antiseptic, Staying at home, Medical care, and Lack of significant others either in verbal descriptions or drawings.

Relation Between Children's Views of SARS-CoV-2 and the Proposed Preventive Measures

The analysis performed to investigate the relation between children's views of SARS-CoV-2 and the proposed preventive measures showed that children's verbal references to Hygienic practices varied according to their verbal score concerning SARS-CoV-2 [$F_{(2, 319)} = 3.07$, $p < 0.05$]. Specifically, children who explicitly referred to a virus or a germ tended to verbally report more Hygienic practices ($M = 1.92$) than those who provided more generic descriptions of the novel coronavirus connecting it with illness ($M = 1.75$) or gave inappropriate answers ($M = 1.51$). *Post hoc* comparisons showed that statistically significant differences emerge between those children who offered an adequate and an inadequate description ($p < 0.05$). On the contrary, the adoption of social preventive practices did not seem to differ according to children's scores reflecting their verbal descriptions of Coronavirus. Finally, children's drawing scores of SARS-CoV-2 had no effect on either type of measures.

DISCUSSION

The present study aimed to explore children's views of SARS-CoV-2 and COVID-19 preventive practices during the second year of the pandemic in Greece. To attain this aim children aged 4–12 years were asked to verbally describe and draw the terms under investigation. In general, our results support previous findings suggesting that even from the beginning of the pandemic children have formed a significant level of understanding of COVID-19 related issues (Christidou et al., 2021; Bray et al., 2021a,b; Bonoti et al., 2022; Rydström et al., 2022). However, interesting differences emerged as a function of children's age or the data collection procedure.

Regarding children's views of the novel coronavirus, our data indicate that the majority of participants provided adequate responses by recognizing that SARS-CoV-2 is a virus or a germ. Fewer children seem to confuse SARS-CoV-2 with COVID-19 and other health issues or provide inappropriate answers. Similarly, their drawings mostly include either adequate or partially adequate representations, a finding which possibly reflects children's exposure to an abundance of publicly available images of SARS-CoV-2 which include its morphological characteristics, namely its circular shape and spikes (Delicado and Rowland, 2021; Martinerie et al., 2021), oftentimes with anthropomorphic elements (Martinerie et al., 2021; McGellin et al., 2021).

Remarkably, developmental differences in children's views of SARS-CoV-2 were evident only in their verbal descriptions, but not in their drawings. In other words, our results showed that children's verbal descriptions of coronavirus improve with age since as they get older, they express views more compatible with scientific knowledge. More precisely, analyses revealed significant differences between the younger and older participants, possibly indicative of the reported major changes in their overall biological knowledge taking place at around the age of 7 years (Duschl et al., 2007).

On the other hand, the lack of developmental differences in children's drawings of coronavirus verifies findings from the first year of the pandemic (Martinerie et al., 2021; Bonoti et al., 2022) and can be interpreted by the emphasis given on visual images of SARS-CoV-2 in information and health promotion campaigns since the beginning of the pandemic. Visual images of the SARS-CoV-2 morphology were abundant in these campaigns (Delicado and Rowland, 2021), quite often with anthropomorphic attributes (de Rosa and Mannarini, 2020; Joubert and Wasserman, 2020; McGellin et al., 2021). Therefore, representing a circular virus with spikes, and occasionally with malevolent intentions to indicate its menacing character was a well-established and easy-to-follow meaning-making device, even for the younger participants (Martinerie et al., 2021). Besides, anthropomorphic views of micro-organisms are readily adopted by students (Vasquez, 1985; Byrne and Grace, 2010; Byrne, 2011; Ruiz-Gallardo and Paños, 2018). Although anthropomorphic perceptions of microbes seem to decline with age, they can persist even among older students, who rather acknowledge it as an explanation tool than a literal description of reality, but continue to use it to explain abstract or invisible concepts (Byrne and Grace, 2010; Byrne, 2011). Yet, in the case of microbes, anthropomorphism often also entails anthropocentrism: viewing a virus as a hostile creature intending to harm people, can obscure biological knowledge and hamper children from neutrally considering the viruses' role as microorganisms within wider ecosystems (Gelman and Kremer, 1991; Byrne et al., 2009; Manches and Ainsworth, 2022).

The overwhelming majority of children who –irrespective of age– included spikes in their circular representations of SARS-CoV-2 (Martinerie et al., 2021; Bonoti et al., 2022) reveals that the visual mode constitutes a privileged field for conveying meanings about the novel coronavirus (Joubert and Wasserman, 2020) -even considering the limitations of its anthropomorphic and anthropocentric representations undermining and obscuring critical aspects of its biology (Manches and Ainsworth, 2022). This is particularly obvious, taking also into account that public verbal communication did not concentrate on descriptions of SARS-CoV-2 *per se*, but rather on its transmission, the resulting disease, and preventive measures.

The results also suggest that children are well informed about the preventive practices implemented to mitigate the spread of COVID-19 (Bray et al., 2021a; Christidou et al., 2021; Thompson et al., 2021; Rydström et al., 2022). In other words, their verbal and drawing responses include references to both the Hygienic and Social preventive practices which prevailed during the second year of the COVID-19 pandemic. This finding seems to be in line with previous research (Jones and Rua, 2008) indicating non-experts' awareness of critical aspects of infectious diseases based on their relevant experiences. Overall, Hygienic practices seem to emerge more often than Social ones, although this tendency is obvious only in children's drawings. In line with previous studies these findings reveal that children conceptualize COVID-19 as a multidimensional concept with hygienic and social facets, as has been the case with illness in general (Nagy, 1953; Schmidt and Frohling, 2000; Myant and Williams, 2005; Piko and Bak, 2006; Zaloudikova, 2010; Mouratidi et al., 2016; Prokop et al., 2016; Bonoti et al., 2019). Our results are also indicative of children's sense of emergency, responsibility, and readiness to take action toward protecting their families and the community (Bray et al., 2021a; Thompson et al., 2021).

When asked to describe verbally appropriate preventive measures, children report more practices, than those they include in their drawings. Although verbal responses seem to be richer than drawings, the two data collection techniques seem to provide similar information and act complementarily (Avgerinou and Ericson, 1997; Jewitt et al., 2001; Unsworth, 2004; Coleman et al., 2011; Matloob Haghanikar and Leigh, 2022).

Overall, although children tended to report more preventive measures with age, significant differences seem to emerge between the younger and the two older age groups, confirming that around the age of 7 years, children seem to be able to grasp a greater variety of measures that should be followed (Duschl et al., 2007). Moreover, from the age of 7 years onward, measures concerning governmental restrictions and instructions of social distancing tend to appear more frequently either in verbal or in drawing responses of older participants.

Interestingly, children who can describe SARS-CoV-2 as a virus or a germ, seem to report more hygienic practices than those who do not provide an appropriate description of the term. This finding supports Manches and Ainsworth's (2022) claim that a greater understanding of SARS-CoV2 assists children to differentiate the virus from the disease, to cope with the consequences of the pandemic, and finally to adopt positive health attitudes and behaviors. On the contrary, children's understanding of the term did not seem to differentiate their report of social preventive practices. Whether this finding indicates children's difficulty to relate the significance of the imposed social measures with the interception of the disease remains a question to be answered.

Limitations

Recruiting a wide age range of participants can be considered an advantage of the present study since this permitted exploration of possible age differences in children's views of SARS-CoV-2 and related mitigation measures. However, the adoption of a less-structured approach would permit to establish the level of their biological knowledge concerning SARS-CoV-2 and ultimately their degree of understanding of the term. Respectively, although our findings suggest that children present a remarkable awareness of the appropriate COVID-19 preventive measures, it should be noted that these data emerged from their self-reports, so one cannot conclude whether they actually adopted them to confront the threat of the pandemic. An in-depth interview, as well as the reports of their parents, could elucidate the degree of adoption of the aforementioned practices. Moreover, the imposed restrictions during the phase of data collection inevitably led to several limitations of the adopted procedure. For instance, the sampling method used as well as the implementation of data collection through video calls, which did not allow face-to-face communication with participants and did not exclude their parents' presence, might have had an impact on the reported results. Moreover, this remote communication and interaction did not facilitate to obtain data concerning parents' socio-economic and educational background which might have influenced children's expressed views; future studies should attempt to cover this challenging research question.

Implications for Science Education and Research

By combining verbal and visual data, this study has revealed aspects of children's views of SARS-CoV-2 and COVID-19 that could not have become apparent through language-based elicitation tools alone. The combination of two data collection techniques resulted in a more comprehensive understanding of the participants' perspectives that would not emerge otherwise (Pfister et al., 2014).

Future research could involve a more in-depth exploration of children's understanding of the biological aspects of SARS-CoV-2, such as its structure, its replication, and how it is related to infection, immune system response, and the emergence of symptoms. Furthermore, a more systematic investigation of how children associate the biological and the social aspects of COVID-19 could also provide valuable results, given that the current pandemic may be significantly influencing children's knowledge about viruses that has not been recorded by research in the previous years (Manches and Ainsworth, 2022).

Also, it would be valuable to compare research data on children's emerging views of SARS-CoV-2 and COVID-19 collected at different phases of the pandemic, to capture the changes they undergo amid the evolution of the crisis. Being part of a broader and ongoing project, this study has focused on data from the second year of COVID-19. Data collection and analysis are continuing during the current, 3rd year, which will enable useful comparisons between different time spots of the pandemic and provide insight on the implications of experiencing this long-term phenomenon on children's related views.

Considering children's verbal and visual responses regarding SARS-CoV-2 and COVID-19 preventive measures could serve as a starting point for designing appropriate teaching material and interventions to scaffold their rapidly developing understanding of the topic, and potentially of similar future pandemics. Visual representations would expectedly be a critical component in such endeavors, since they provide a powerful means for meaning-making in the case of viruses and infectious diseases (Mutonyi and Kendrick, 2011; Joubert and Wasserman, 2020; Manches and Ainsworth, 2022). Furthermore, having students read and create visual images of SARS-CoV-2, could scaffold their construction of more appropriate views as is the case with other concepts in science (Jewitt, 2008; Britsch, 2013) and engagement in relevant COVID-19 prevention and mitigation practices that could be applicable in future crises (Mutonyi and Kendrick, 2011).

Moreover, as Manches and Ainsworth (2022) suggest, learners' difficulties in understanding viruses do not originate so much from inherent cognitive limitations but are also highly dependent on how they are represented during teaching. Thus, the publicity of the novel coronavirus and the resulting COVID-19 pandemic might provide an appropriate context for children to become engaged in learning about the biology of viruses.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of the Department of Early Childhood Education/University of Thessaly. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

VC, FB, and PP were collaboratively involved in designing the study and in data collection. PD was involved in data collection and coding. VC and FB performed data analysis and were involved in manuscript preparation. PP and VH contributed in the theoretical and methodological underpinnings of the study, interpretation and discussion of results, and manuscript editing. All authors contributed to the article and approved the submitted version.

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Inscriptions in Science Teaching: From Realism to Abstraction

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This article attempts to highlight inscriptions, i.e., photographs, drawings, diagrams, or graphs as autonomous carriers of meaning that can illuminate the different dimensions of a scientific concept. In addition, the article examines the inherent potential of diverse types of inscriptions to be combined with each other creating conceptual sequences and thus, crafting a narrative for the formation of a concept. For the formation of conceptual sequences the proper synthesis of both naturalistic and abstractive inscriptions that hold different types of information and complement each other is suggested. That is, inscriptions such as photographs that hold morphological relevance with their referent describing at the same time the everyday knowledge, as well as inscriptions such as graphs or equations that, from a morphological perspective, have a no linear connection to their referent and are related to the typical visual code of school knowledge. Thus, existing, transformed, or novel inscriptions can create conceptual continuums offering logical connections between visual codes from everyday experience and the codes of diagrams, graphs, and equations. From both the teachers and the students, when inscriptions cooperate with the human body, oral language, and other elements of the space, constitute a critical aspect in multimodal communication within school classrooms.

Keywords: inscriptions, realism, abstraction, science education, semiotics

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INTRODUCTION

Research in human learning has shown that the type of "text" for the representation of scientific entities in the material world affects the meaning-making process in a unique way (Kress and Bezemer, 2015; Gillies and Baffour, 2017). Although there are different ways of representing a scientific concept, from mathematical equations to graphic representations, or language, at the interpretation level, the meanings are not the same. Each mode, as a vehicle of signs, communicates and might orient the receivers to diverse types of meanings (Lemke, 1998a; Fernández-Fontecha et al., 2019; Yeo and Nielsen, 2020). Thus, although for example a graph and a word text may refer to the same concept, their conceptual content is not equivalent and this has as a result being complementary to each other in the meaning-making process (Hubber et al., 2010; Lopes et al., 2014; Hand et al., 2016). Within this framework, the two-dimension spatial representations constitute "texts" that have a dynamic role in the learning process as a type of language that in some cases has an advantage against other types of representation (Gilbert et al., 2007; Hubber et al., 2010; Kress and van Leeuwen, 2020; Xiao, 2020).

Lemke (n.d.) argues that the dynamics of visual information are vast, and this is highlighted in everyday life since for example we may choose a text with figures rather than a verbal one or choose the navigation in a website rather than a printed text. Especially in the public understanding of science visual modes such as graphs or drawings are mainly used (Moriarty, 2004; Bucchi and Saracino, 2016; Christidou et al., 2016). In learning environments where mechanisms (e.g., pulleys) and constructions have a central role, students' actions and thinking are conceptually related to the rest elements that constitute the perceptual data, such as the lexicogrammatical texts, graphs, and drawings (Kirsh, 2010; Newcombe, 2016). Each two-dimensional depiction, no matter the abstraction level of the content, requires the reader to create conceptual bridges between the depiction and its referent in the physical space. For example, understanding a mechanical design requires knowing the symbols that constitute a special language that has transformed the three-dimensional objects (mechanisms, parts) into two-dimensional graphic representations (Miller and Halpern, 2011; Hegarty, 2014). Especially in the science textbooks, the visual code is a key element and several studies describe its role from a social-semiotics and pedagogical perspective (Carvalho et al., 2011; Anagnostopoulou et al., 2012; Ge et al., 2018).

In the present article, the term inscription is used. The term was introduced by Latour (1987), to describe contents that can be written on a surface (i.e., paper, computer monitor). Alternatively, several researchers have used terms such as visual or graphic representation, image, and document for some types of inscriptions (i.e., Colin et al., 2002; Stylianidou et al., 2002; Cook, 2006; Kress and van Leeuwen, 2020). In line with Pozzer-Ardenghi (2009), we prefer to use the term inscription instead of representation avoiding any connection with the term mental representation, that is, a distinct concept identifying conceptual entities. Inscriptions are spatial forms in two dimensions, in some cases with perspective (depth) as well as with other visual codes (e.g., colors on maps, symbols in mechanical designs). The term inscription refers to figures/entities/elements included in photos, maps, drawings, graphs, diagrams, tables etc., and differs from simulations and moving pictures. In this article, emphasis is given to inscriptions that appear to represent diverse aspects of the concepts and the phenomena of the natural and technical world and the interrelations between them.

Regarding the interrelation between inscription and referent, photos capture the referent as it is, drawings usually capture referents keeping morphological shapes and, in some cases, are abstractive to some extent. Diagrams document conceptual interrelations using at the same time visual and verbal codes. Graphs (including charts etc.) refer to an abstractive version of the description of a situation or a change in the characteristics of a natural phenomenon. Tables and equations are also considered inscriptions. **Figure 1** is an example of various types of inscriptions containing a photo of expanded train tracks (A), a drawing with refraction-apparent elevation (B), a diagram of a model of energy transfer between two systems (C), a speed-time graph in smoothly decelerating motion (D), a temperature - volume value table (E), and an equation of velocity in linear smoothly accelerating motion (F). Varga-Atkins and O'Brien (2009) mention that drawings mainly depict salient features are less abstractive, do not require knowing conventions or notations, and visual code is foregrounded to verbal. However, diagrams can communicate complex ideas and are quite abstractive while knowing specific conventions and notations is required to understand them. Diagrams are the most conceptually complicated inscriptions, either concrete or abstract, structured by nodes connected by visual code (i.e., lines, text) that states causal, analogical, spatial, and temporal relations. Nodes can include icons, symbols as well as drawings, photographs, equations, etc. (Gilbert, 2005).

The present article seeks to unpack and highlight the critical role of inscriptions in science education. It begins with an overview of the literature about diverse forms of inscriptions and their role in the process of teaching and learning. This is followed by a discussion about the degrees of realism and abstraction that could be seen in diverse forms of inscriptions. How different degrees of realism and abstraction affect students' understandings of science are also discussed through empirical examples. The article suggests five key points for creating amplified conditions for students' learning and development in science through the use of inscriptions: (a) the introduction and use of multiple and diverse forms of inscriptions into students' learning experiences, (b) the organization of inscriptions into meaningful sequences, (c) the conceptual continuum and consistency between naturalistic and abstract forms of inscriptions, (d) the use of inscriptions that promote the dialectical interrelation between everyday life and school knowledge, and (e) the supplementation of inscriptions by a multimodal framework that includes dynamic elements such as human body, verbal communication, and space. Taken together, the outcomes of the article inform practice by providing a pedagogical framework for the dynamic and multimodal introduction and use of inscriptions in science teaching and learning in educational settings.

THE ROLE OF INSCRIPTIONS IN TEACHING AND LEARNING

The contribution of inscriptions to learning and teaching science is systematically explored in contemporary research in the field (Kim and Roth, 2018; Xiao, 2020). As modes of meaning, inscriptions interact with other semiotic systems, such as speech and gestures, and communicate aspects of scientific concepts (Xu et al., 2021). Photographs, drawings, diagrams, graphs, tables, and equations are not just mediators of information but, factors that co-shape meanings (Pozzer-Ardenghi and Roth, 2019). The discussion that follows focuses mainly on drawings and diagrams and less on graphs since drawings constitute tools to think with, that is, means that allow the clear documentation of students' transforming thinking. In addition, the same feature is seen in several diagrams that are based on drawings where words and symbols are added to express conceptual interrelations.

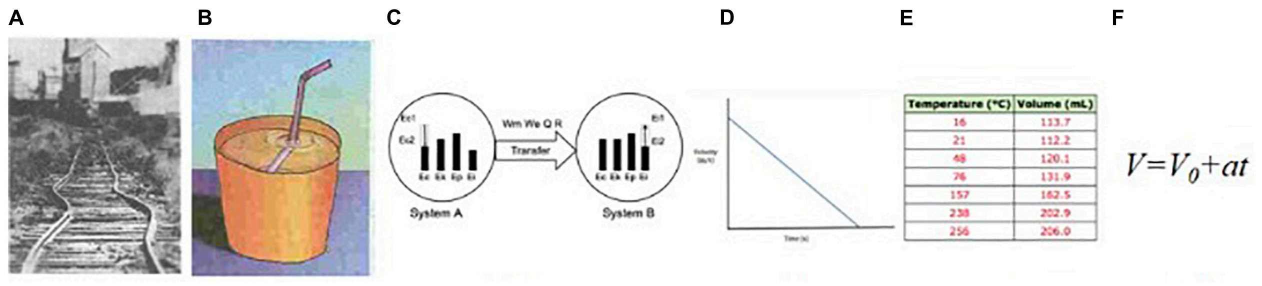


FIGURE 1 | (A–F) Types of inscriptions.

FIGURE 2 | Two snapshots assigning Earth's rotation.

Photographs capture their referent in a realistic way but, in some cases, prevent students from making transitions to more abstractive forms related to the concept that is explored (Pintó and Ametller, 2002). Diagrams and drawings that include topological and geometrical elements support problem-solving processes, especially those related to mechanics providing a kind of external support in working memory, and facilitating the formation of mental models (Larkin and Simon, 1987). Diagrams, when incorporated into specific tasks, minimize info searching on behalf of the student, contribute to the easiest identification of the information, and facilitate the process of concluding (Larkin, 1989). This makes diagrams more comparable in learning processes to verbal text because they present information in a conceptually more explicit way (Cheng and Gilbert, 2015). However, a precondition for diagrams to act as conceptual tools is that the students will approach and develop abstractive competencies, and this is usually developed at the later educational levels (Booth and Koedinger, 2012). In general, inscriptions can promote imagination, especially in the field of science and mathematics (Hegarty and Just, 1993; Stieff, 2011; Hay et al., 2013). In the framework of visual semiotics, every inscription is a figure that the receiver can extract denotations and connotations (van Leeuwen, 2001; Moriarty, 2004). Especially, asking students to interpret sequences of photographs or drawings that describe the historical/morphological transformation of entities stimulates their imagination (Pantidos et al., 2022). For example, by watching the two snapshots of the system Sun-Earth in **Figure 2**, one can ascertain that Earth has light at different parts. The lower left corner of **Figure 2** depicts Earth, while the upper right corner shows the Sun. Situations like these that suggest the concept of change in space and time promote the development of imaginative thinking (Pantidos, 2017). In an appropriate learning environment, the question "what caused the change you notice" could be posed to the viewer giving this way the opportunity for predictions to be made and actions to be planned for checking the hypotheses. In a framework like that, photographs and drawings are not just informative means but, contribute to wondering and exploration that are critical points for science learning (Pantidos, 2017; Hadzigeorgiou and Schulz, 2019).

However, it should be noted that the diagrams, due to the degree of abstraction they carry, and also the abstractive drawings can lead students to different interpretations from the one that the inscription suggests (Colin et al., 2002). Moreover, Ametller and Pintó (2002) argue that several times the caption is not read by the students, except when they are asked to do so. However, in case it is read, it offers possibilities for a clearer interpretation of the inscription. This means that illustrative ways of highlighting the relationship between the inscription itself and the caption should also be sought. The above researchers note that students ignore any lexicographic information contained in an inscription when it is not understood. In addition, they note that when it comes to inscriptions that are interconnected in any way (e.g., lexicographic elements, arrows) and form a whole, it is advisable to be particularly careful to fit into the teaching framework that is formed each time. In that way, the interpretation of an abstractive inscription (e.g., diagram, graph), is significantly assisted by its spatial interconnection with a

FIGURE 3 | Transformation and/or transfer of energy.

corresponding with realistic style (e.g., photo, drawing) but with the risk of transferring the function of the realistic elements of everyday life that compose the second, to that which has the abstract content (Pintó and Ametller, 2002).

On a similar issue, Pantidos and Givry (2021) state that written text or speech can, in synergy with the content of an inscription, remove possible ambiguities arising from its very content. For the energy section in a textbook they studied, they mention that inscriptions sometimes create de facto ambiguities between the transformation and transfer of energy, because the content of the inscriptions does not separate the physical systems that participate in the processes. It is noted that the identification, and therefore the separation of physical systems, is a prerequisite for the conceptual distinction of transfer from the transformation of energy. **Figure 3** is a drawing morphologically showing similarity to a corresponding photograph that is, a girl pulling a suitcase. It is an example of "text"; that is an inscription, which can lead to two different meanings, depending on the interpretive framework used by the reader. The drawing in this form creates a conceptual blending between the transformation and transfer of energy. If the reader considers the human-suitcase as one system, then the message conveyed by the drawing refers to transformations of energy within the system. But if the girl is considered to be system A and the suitcase is system B, then it could be understood that it is a case of energy transfer from system A to system B. In the case that the identification of the physical system(s) is not taken into account as an initial condition then the inscription creates ambiguities regarding the transfer and transformation of energy. Graphically, the removal of these ambiguities could be achieved either by adding an explanatory text to the caption or through a diagram that will also contain semantic clarification elements such as the diagram in **Figure 1C**.

Drawings are traditionally a means of exploring students' thinking and are considered appropriate for describing precursor models of young children for concepts and phenomena from the natural world. Precursor models are conceptual constructions (concepts, models, processes etc.) created within educational contexts. They constitute molds for later intellectual constructions that would be hard or impossible to be constructed without them. In precursor models, the elements and the interrelations between them are compatible with the ones found in the scientific models used in teaching and learning science nowadays. At structural and functional level, they connect individual structures in students' thinking about natural phenomena with school knowledge and can serve as a basis for the formation of more complex models (Ravanis and Boilevin, 2009; Delserieys et al., 2017, 2018; Ravanis, 2020). The precursor models are conceptually reflected both in the morphological characteristics of the actual content of a drawing, as well as in its change, recording development in students' thinking. This is because, in line with oral speech, drawings have the ability, like diagrams, to produce autonomous thinking so that they can share unique meanings (Cabello et al., 2021; Cabello, 2022). Chachlioutaki et al. (2016) showed that preschool children, after a relevant didactic intervention on the phenomenon of earthquakes, improved their conceptions by improving, among other things, their drawings for some aspects of the phenomenon. That is, their drawings were carriers of an exclusive improvement of their thinking about aspects such as the place where earthquakes and tectonic plates take place. A similar conclusion was reached by the study of Herakleioti and Pantidos (2019). It showed that preschool children's drawings are a means of improving their thinking about the day/night alternation phenomenon regarding the size of the Earth and the sun and the regions of the Earth having day and night. On the other hand, drawings may work restrictively, sometimes presenting difficulty in conveying entities and their properties, usually when they are related to motion or three-dimensional entities (e.g., the shape of the Earth) (Siegal et al., 2004). For example, regarding the Earth's self-rotation, during a drawing activity young children prefer to activate their body to represent its motion and rarely attribute it through helical lines (Papandreou and Terzi, 2011; Galperin and Raviolo, 2015), while sometimes, even though they have the knowledge of sphericity, they draw a circle (Nobes and Panagiotaki, 2007). In general, in preschool education, drawings are considered an early stage of writing which gradually evolves into the written language (Wright, 2007; Robbins, 2009). It is a means of visualizing thinking, which helps in the interpretation of a problem, while many times children draw symbols that are either suggested to them, or they produce them themselves, and then think through them (Papandreou, 2009).

In addition to the content of a drawing itself, the process of the activity in which the drawing is produced plays an important role. In this context, various semiotic modes are activated along with the drawing for the students to express their ideas with the physical expression having a dynamic presence (Einarsdottir et al., 2009; Chang, 2012; Fragkiadaki and Ravanis, 2021). Verbal discourse and vocal and non-vocal sounds constitute components of the acoustic semiotic system. Inscriptions and material objects are components of the spatial semiotic system. Gestures, facial expressions, and movements in the space are part of the kinesics semiotic system. Taken together, the above components are vehicles of meaning activated during communication. Sometimes students use deictic gestures to signify something that is not yet drawn, while generally gestures are typically used when pointing to an element of the drawing when answering a question. Moreover, students use iconic gestures, first representing in the air an entity that has not been drawn yet and then drawing it. Sometimes, they depict something with their body that already exists in the drawing. In other cases, the gesture has different information from the drawing, while many times physical expression and painting function complementary (Hall, 2009; Papandreou and Terzi, 2011).

Since students are able to create diagrams by incorporating in their initial drawings arrows or words to indicate the direction of movement of the material components of mechanical systems, this creates more usable mental animations (Hegarty and Just, 1993; Hegarty, 2014). Drawings, sketches, and diagrams, which for engineers are fundamental elements in the organization of technological design (e.g., aircraft construction), also give a social dimension to knowledge. Each member of a group of people co-constructs drawings or diagrams capturing and documenting his/her knowledge and thinking. Through these, as well as all the other inscriptions, the whole design program is distributed and organized in groups and the result is that the construction of knowledge takes place through shared cognitive processes, both at interpersonal and group level (Henderson, 1991; Johri et al., 2013). Highlighting here the collective character of the construction of knowledge is critical in understanding inscriptions as socially and culturally oriented products that are historically developed and transformed.

Graphs have a high degree of abstraction and are used to show relationships and correlations between variables while being a common visual code in natural sciences. In school textbooks, the high degree of abstraction of graphs can also create difficulties for students when trying to interpret them (Planinic et al., 2013; Bollen et al., 2016). Pozzer-Ardenghi and Roth (2010) state that in school textbooks, when there is textual information about graphs that helps the student to understand the content of the graph, then the student acquires the ability to read and learn scientific inscriptions. The difficulties that students have in reading graphs are also related to the fact that they have not been involved in the processes that led to their production (Roth, 2003). Experts (scientists), when they face difficulty in meaning-making, usually repeat the reading of the graph, try to connect it with more complex conclusions, formulate thoughts and check if these thoughts match the graph's characteristics, and design versions of it under different conditions (Roth and Bowen, 2003). In addition, the interpretive difficulties that appear in such readings by experts still exist even when the graphs are contained in an introductory textbook of their field (Roth and Lawless, 2002). In general, the understanding of a graph, as for any sign, is related to the preparation of students in the relationships that exist and develop between the signifier, the referent, and the signified. The referent is that for which someone "talks" about and refers. The signifier is the content of the representation of the referent in the material world. The signified expresses the mental construction of the referent, that is, how one - has formed the referent in his/her mind. Testa et al. (2002) referring to real-time graphs note that the actual form of these graphs - the "whole" - sometimes traps the student's attention, overshadowing the other information provided by the graph and the caption, making it work positively or negatively in meaning-making. Also, the relative spatial arrangement of two graphs, the scale on each axis, their size, as well as the way they are graphically correlated, are elements that strengthen the relationship between them. It is noted that, although real-time graphs, as products of measurements in an experimental process, approach a phenomenon more fully, they contain more irregularities than ideal graphs, that is those that are usually the school version of scientific knowledge.

FROM REALISM TO ABSTRACTION

Every inscription, as a signifier, holds some similarity, analogy, relevancy, and correspondence to the concept or the phenomenon that it refers to. However, in most cases, the kind of relationship is not obvious, for example when inscriptions are mathematical codes (e.g., "F = ma" is not obviously related to the way trolleys are moving in a supermarket). Regarding the degree of abstraction, inscriptions from a morphological perspective could be placed in between the duality of naturalism and abstraction. On one side, could be placed inscriptions that approach with accuracy the form of the referent and are related to photorealism, that is, the most precise representation of a photograph's content (e.g., a photograph of a glass or its drawing). On the other side, can be placed inscriptions with a high degree of abstraction that holds no linear morphological interrelation to the referent. For example, something that can stand for a glass or can narrate in a symbolic way an aspect of a glass's history e.g., pairs of values of velocity-time representing the free fall of a glass presented in a table.

Moreover, at the above criterion can be added the criterion of the proximity or not to familiar everyday codes. Thus, naturalistic inscriptions represent or express knowledge that the student is familiar with and at the same time, in line with realism, have some similarity or relevance to the referent. On the contrary, abstractive inscriptions are relevant to school knowledge and have a distance from the form of action or of the object that they refer to. In this framework, photographs and drawings are considered naturalistic inscriptions that are close to everyday knowledge and at the same time approach in a realistic way the referent while graphs, tables, and equations are considered abstractive inscriptions (see **Figure 4**). Drawings, no matter how realistic they are, are considered abstractive inscriptions when bearing knowledge from school science. This is different from the knowledge coming from experts that is experiential and scientific at the same time. For example, an expert can directly translate meteorological phenomena to thermodynamic changes and thus,

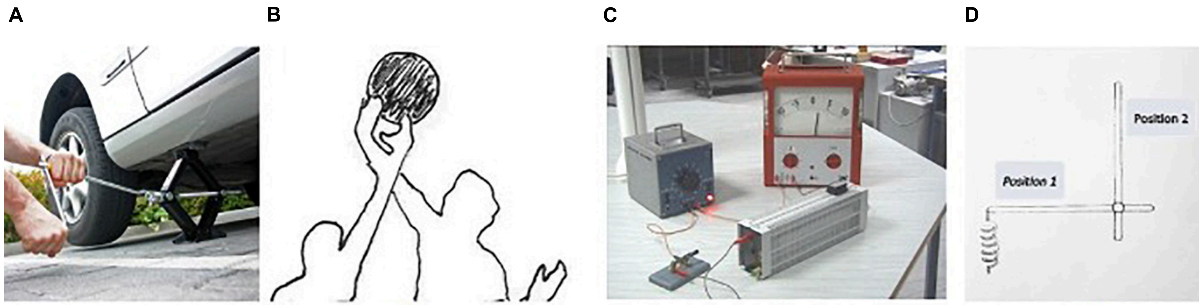


FIGURE 4 | (A–D) Naturalistic and abstractive inscriptions.

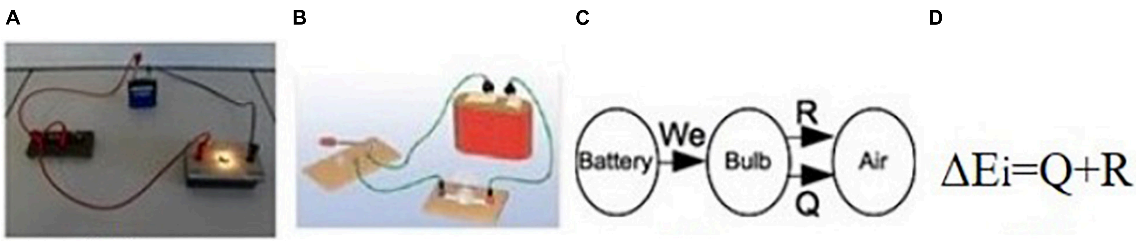


FIGURE 5 | (A–D) Conceptual completions of each inscription type regarding energy transfer.

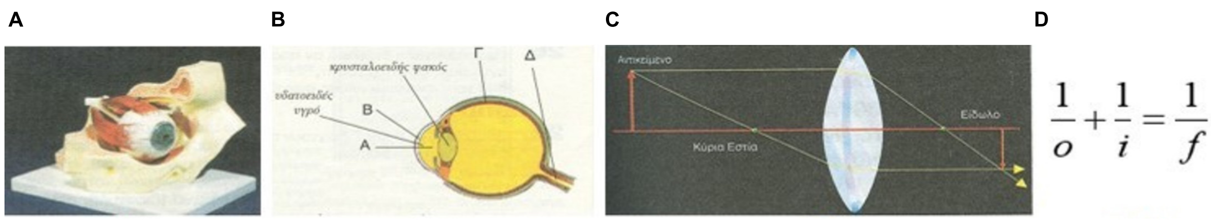


FIGURE 6 | (A–D) The synergy of inscriptions for storytelling the eye as a lens.

can interrelate the image of the sky at a particular point of time with a pressure-temperature graph.

On the left side of **Figure 4**, the first photo (A) refers to the application of a hydraulic press and is a naturalistic inscription as it morphologically accurately captures in two dimensions the referent "applying a jack to a car" which constitutes everyday life knowledge. We use everyday life knowledge as the informal knowledge that is developed in contexts outside school and differs from the school knowledge that has transformed characteristics of the scientific knowledge and the students experience within educational settings. Similarly, the drawing (B), which holds as a referent "the contest of the ball by two basketball players," morphologically maintains lines with what it represents and obviously constitutes everyday knowledge too. In contrast, the next picture (C), while morphologically accurately captures the "electrical circuit" and maintains an explicit morphological relationship with its referent, it signifies school instead of everyday life knowledge, as it presupposes knowledge of a specific code for reading and conceptualizing it. Similarly, the last entry (D) of **Figure 4**, which is registered as a diagram due to the combination of textual and graphic code, is abstract because one does not encounter such an arrangement in everyday life, although morphologically maintains a relationship of similarity with the three-dimensional referent, i.e., a beam-and-spring system, imaginary though. In general, graphs, tables, and equations are considered abstract inscriptions since they do not correspond to a linear mapping with the referent due to their morphology and their conceptual structure, while their conceptualization requires the knowledge of specialized code from the viewer. The characteristic of abstract inscriptions is that they depict or represent entities that require familiarization with the code to be understood.

MAKING CONCEPTUAL SEQUENCES IN SCIENCE TEACHING

From a semiotic point of view, the question that arises is that of evaluating the information *per se* that each inscription carries. **Figure 5** is an example of expressing aspects of "transfer of

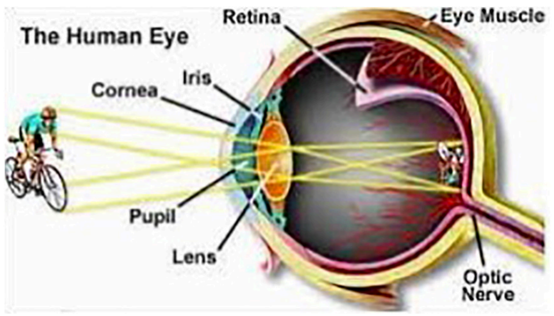


FIGURE 7 | A diagram that comprises both realistic and abstract elements.

energy" through various inscriptions and one can identify that each mode conveys a different meaning (Givry and Pantidos, 2015). Photograph (A) contains information about both the wiring of an electrical circuit (its parts are connected through contact) and the parts of which it is composed, while the drawing (B) adds the information that in a simple electrical circuit the lamp does not shine in the case the switch is off. In addition, diagram (C) describes the conceptual relationships among electrical work (W_e), radiation (R), and heat (Q) as mechanisms of energy transfer from the battery to the bulb and from the bulb to the air respectively, indicating in this way three distinct systems (battery, bulb, air). That is, the diagram indicates, using arrows, We, R, and Q as mechanisms of energy transfer from one system to another. Finally, equation (D) stands as an application of the conservation energy principle. So, for example, as far as air is concerned, it indicates that the change in its internal energy was caused by the imbalance in the "air" system, which is due to the heat and radiation transfer mechanisms caused by the "bulb" system. Equation (D) states that the change in the internal energy of the "air," in the region where the event occurs, is equal to the sum of the radiation and the heat transferred from the bulb. On the basis, therefore, that different types of inscriptions have conceptual autonomy concerning the same scientific concept or physical phenomenon, it is possible to create, in the school context, narratives and "stories" referring to scientific concepts along with their characteristics. In other words, teaching practices can be enriched by a series of both authentic or contextually constructed, diverse types of inscriptions that refer either to the scientific concept itself or to a context of related interdependent concepts. This can help to mitigate the conceptual confusion created by the use of individual inscriptions as independent conceptual entities.

It is, therefore, possible, in the axis of both everyday life and school knowledge, to construct sequences with realistic and non-realistic entries for a scientific concept, even at a pre-instructional level. Certainly, these refer to a pre-expressive context from the learners' point of view, as this analysis has more of a semiotic character than a character of evidence-based pedagogical knowledge. However, we hold the view that it has epistemological validity to discuss inscriptions as tools of meaning. That is, we consider that the discussion in this article has value for science eduaction since inscriptions are examined as semiotic modes that can naturally create a context of meaning, independent from the learner at a first level. Thus, criteria are used that are not related in the first instance to students' interpretations such as the proximity to the scientific code, the relevance of the inscription to the form of the referent, and the relevance between two "forms," e.g., two inscriptions (Dimopoulos et al., 2003; Hegarty, 2011; Kress and van Leeuwen, 2020). The difficulty of synthesizing everyday and school knowledge through inscriptions lies mainly in the fact that abstract inscriptions (e.g., equations, graphs) do not show similarity or relevance relations with the external form of the referent. Instead, they are mainly related to the abstract scientific code. So, for example, the inscription "$V = V_0 + at$" is abstract and may have the "motion of a car" as its real-world referent. While the same referent can also be seen in a photograph containing a car in motion, or even in a speed-time graph, there still exists a major difference. Specifically, their difference lies in the fact that the photo of the car, maintains a clear similarity relation with the referent, while both the inscription "$V = V_0 + at$" and the graph do not. It is therefore obvious that abstract inscriptions are highly related to the specialized code they carry.

In **Figure 6A** could be considered a naturalistic inscription given the relevance to everyday knowledge and the form of

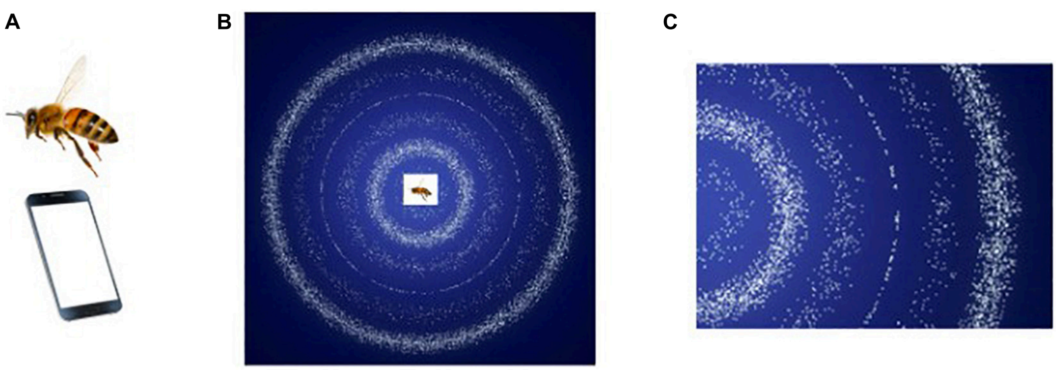


FIGURE 8 | (A–C) Regions with high, medium, and low molecular density.

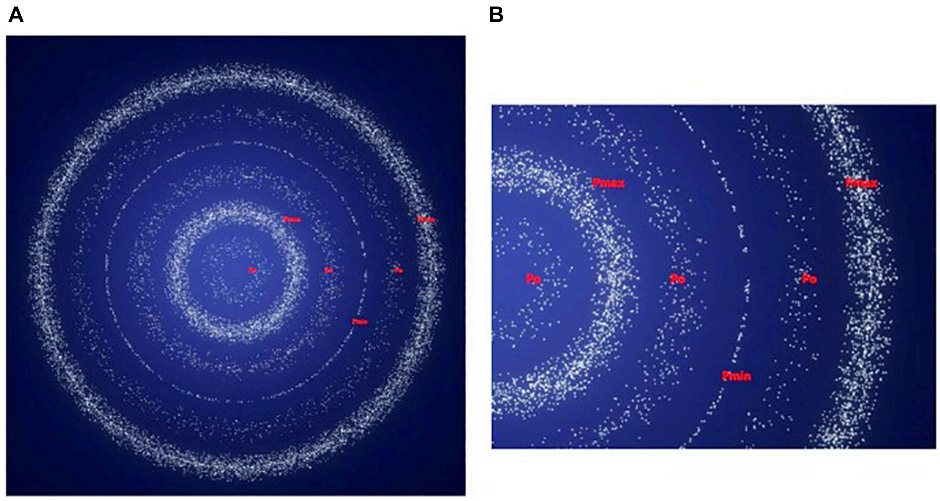


FIGURE 9 | (A,B) High, medium and low molecular density (and pressure) associated with the symbols p_{max}, p_0 and p_{min} respectively.

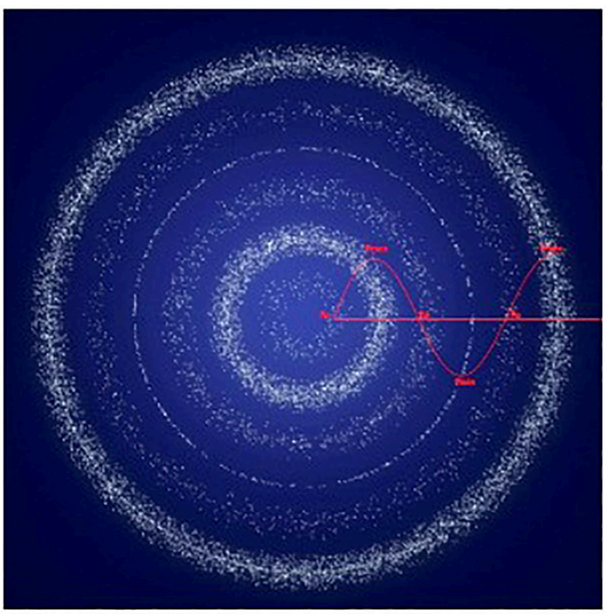
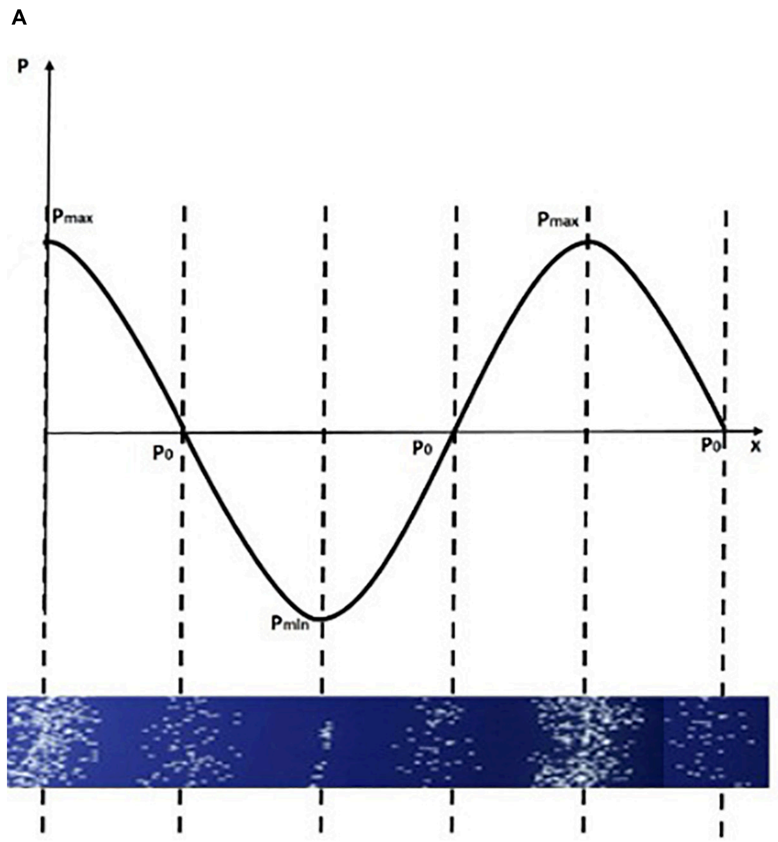


FIGURE 10 | A sinusoidal curve joining points and relating to the different values of pressure p_{max}, p_{min} and p_0.

the referent "eye." On the other hand, (B) is considered an abstract inscription, although it is related to everyday knowledge to a greater extent since it refers to a type of "eye" that is part of everydayness but, morphologically differs from the object "eye" since the visual code that it carries is specialized and does not refer directly to an "eye." (C) contains in its center an ellipsoidal depiction, representing a converging lens, an upright and an inverted arrow referring to the object and the image respectively, while the paths of the light rays are drawn according to the converging lens refraction rules. (D) contains the algebraic relation for the distances among object, image, and focus. (C) and (D) are directly characterized as abstract inscriptions, not only because they refer to contents of school knowledge e.g., "convergent lens" but mainly because morphologically there is a great distance from the "converging lens," but also from the "eye," especially in the case of (D). Moreover, in terms of relevance between two "forms," the morphological-conceptual distance between the photograph of eye model (A) and the diagram based on a drawing of the eye in two dimensions (B) is smaller than the distance between (B) and the diagram of the function of the eye as a lens (C) or (B) and the equation (D). Moreover, from (B) onwards, it is possible to "place" several different abstract contents. Therefore, the point is to conceptually bridge the morphologically "dissimilar" inscriptions and thus connect everyday knowledge with school knowledge.

Conceptual incoherence draws from the fact that the learner has to make conceptual leaps in order to read and interpret the "story" of the eye as a lens, and more specifically to access the inscriptions that carry a specialized visual code. As mentioned above, transmission between everyday and school knowledge should be sought through the inscriptions that each one is represented (naturalistic and abstract). As Roth (2001) states, this is after all the function of science; to enable, through the construction of knowledge, to move from the real world to the world of signs. The teaching process operates in a similar context, which of course aims to construct or reconfigure, pre-existing mental representations compatible with scientific models. Concepts are contained in a cognitive system with specific structures, processes of "processing and mapping." In this kind of system, the term "mental representations" is considered more appropriate, as it approaches not only the entities but also the structural as well as functional associations of a larger system (Hubbard, 2007).

Spatial isomorphism describes the similarity between students' mental animations and the physical processes of a mechanical



B

$$\Delta P = \Delta P_{max} \cos(kx - \omega t)$$

FIGURE 11 | (A,B) A harmonic curve P(x) associated with the concentrations of air particles in space.

system (Hegarty et al., 1991; Hegarty, 2011). Essentially it refers to the morphological similarity between the image of a piece of the physical world and its mental image. In terms of learning, diagrams function in a more effective way when they carry elements of spatial isomorphism compared to diagrams whose elements are linked by conventional relationships with their referents (Cheng and Gilbert, 2015). Bringing the above into the general context of inscriptions, spatial isomorphism describes the structural similarity relations, which are also morphological relations, between the pure content of the inscription and that to which the inscription refers. Thus, the resemblance of an inscription to its referent in the material world could facilitate learners in approaching its conceptual content. Developing this argument a little further, this could also apply to a set *of* inscriptions. The creation/selection of groups of inscriptions that show visual affinity could develop a conceptual continuum. Thus, both visual and conceptual reading can start from a realistic inscription that is spatially isomorphic to its referent in the material world and be followed by inscriptions that while being more abstract, hold elements of spatial isomorphism with each other. For example, with regard to the didactic approach of **Figure 6** inscriptions, it is a learning demand to mitigate the conceptual and morphological difference between (B) and (C). To achieve this goal, a semantic and visual intermediate hybrid inscription could be developed e.g., a diagram, which in terms of spatial isomorphism incorporates in the realistic entities "lens of the eye" and "object" abstract elements such as light rays and reflection (see **Figure 7**).

Essentially the inscription of **Figure 7** can be placed between (B) and (C) of **Figure 6** by clarifying the symbolic entities "object" and "image." This can be achieved by depicting realistic material objects, e.g., a bicyclist, which are not symmetrical in the up-down direction, and thus the viewer can perceive the inversion of the image. The conceptual bridging of **Figure 7** with the equation (D) of **Figure 6** can be achieved as long as the equation is a derivative of computational or conceptual realization by learners. That is, the result of a teaching process in which learners could be either measuring the distances o, i, and f in **Figure 7** and thus lead to the relationship among them as described by equation (D) of **Figure 6** or can deduce it exploratively through the experimental realization of the phenomenon.

Therefore, appropriate additions at specific points in a conceptual sequence of inscriptions, either by constructing original inscriptions or selecting inscriptions generated through the dynamics of the teaching process, can create conceptual bridges through mitigating conceptual discontinuities. **Figures 8**, **9**, 10, 11 narrate the "story" of sound propagation through inscriptions acting as an example, which contains

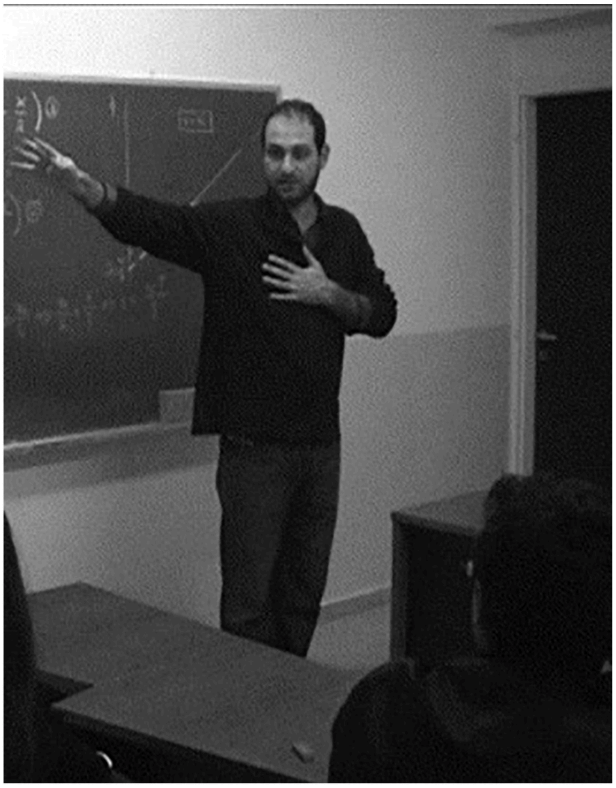


FIGURE 12 | Teacher as a particle in space.

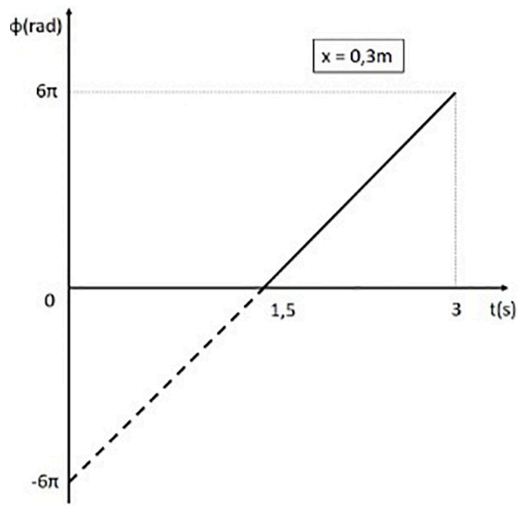


FIGURE 13 | Phase-time graph for molecule-teacher.

a conceptual sequence of inscriptions that meets the criteria of the existence of naturalistic and abstract inscriptions, the distinct information of each inscription as well as the conceptual bridging between inscriptions. It concerns the synthesis of the conceptual dimensions of the propagation of a longitudinal sound/mechanical wave in atmospheric air. The direction of a longitudinal wave is the same as the direction of oscillation of the molecules of the elastic medium. The "story" told by the inscriptions links the entities "air molecules" to the concepts of "pressure" and "pressure change." Particularly, sound is produced because an object moving through the air causes the air molecules to oscillate, creating regions of many, medium and few molecules. Thus, if one could see the space in which a bee's buzz is propagating, one would see the bee in the center of at least three concentric circles. A circle with many molecules, a circle with a moderate amount of molecules, and a circle with fewer molecules at their circumference (see **Figures 8A–C**). These three different regions correspond to three characteristic pressure values: high pressure, medium pressure and low pressure. The concentrations of the molecules determine how high the pressure is (see **Figures 9**, **10**). Quite importantly, the variation of the number of molecules in space is not proportional to the distance from the sound source. Instead it is harmonic, as the air molecules are subject to a restoring force, causing them to oscillate and move in space with varying accelerations. Therefore, the way the pressure changes is harmonic too (see **Figure 10**), which constitutes the harmonic equation as the proper equation to describe the change (see **Figure 11**).

In **Figure 8**, image (A) refers to two specific sound sources, a mobile phone, and a bee. While not explicitly connected to each other, these two entities create in space, as long as they are vibrating (or a part of them), structurally corresponding disturbances in air molecules. It should be noted that we are unable to perceive this characteristic by solely focusing our attention on the pictures (A), even if we recall from our memory daily experience with these sounds. Image (B) visualizes both the invisible molecules of the atmospheric air and the effect of the oscillation of the mobile phone or the bee's wings in space. A close look at (B) shows that there are areas with more and fewer air molecules, which in each case form groups of molecules that form imaginary concentric circles. One can identify three characteristic different regions based on the density of molecules. Regions with high, medium, and low molecular density. Image (C) makes it clearer what is happening with the air molecules, and in particular magnifies in one direction the regions of high, medium, and low molecule concentrations, indicating high, medium, and low pressure respectively. In **Figure 9** image (A) and a closer look of it (B) are nodal inscriptions as they comprise elements of greater abstraction. They are inscriptions that combine elements of realistic representation with elements of abstraction, linking the symbols p_{max}, p_{min}, and p_0 to what actually takes place in space, i.e., the regions of high, low, and atmospheric (normal) pressure. It should be noted that there are air molecules between these characteristic regions. However, we chose not to draw them so that these three different concentrations of molecules would be visually distinct to the reader.

Lemke (1998b) states, the making sense of scientific concepts is a process that is not exclusively linked to the spoken word. While it is associated with actions such as manipulating devices, making measurements and with a set of embodied actions, it is also linked with more symbolic means such as diagrams, graphs and equations. That is, concepts are mentally created through the interaction of students' actions and their realization of symbolic representations. Thus, concepts cannot "speak" and "narrate" their "story" unless they are approached as conceptual constructions with past, present, and future. In **Figure 10** this is attempted to be resolved, at least at a morphological level, by introducing the entry **Figure 10** which has a visual affinity with (A) and (B) of **Figure 9** by additionally containing a curve joining points located in an imaginary direction and relating to the distinct values of pressure p_{max}, p_{min} and p_0. In particular, in entry **Figure 10**, the sinusoidal curve introduces the notion of harmonicity by stating that the alternations between the different values of pressure, for each region of space, take place in a harmonic way. The harmonicity refers to the values of pressure and not to the displacement of each molecule, which has also a harmonic character but is not discussed here. It should be noted that the harmonic curve in **Figure 10** enters the sequence of inscriptions as prior knowledge and does not emerge through the visual reading of the prior inscriptions in **Figures 9**, **10**. Obviously, the sensing of a harmonic movement in visual or even bodily terms is quite difficult to be explored by learners in an inquiry based context, and usually, regardless of the pedagogical context, it enters the educational process in a declarative way. Nevertheless, we consider that this curve cooperates with the other entities of the inscription **Figure 10**, as it conveys the information of the way the concentrations of molecules in space change as soon as they receive a sonic disturbance. In this context, we can morphologically be led to the world of abstraction; that is, in a world of symbols described by inscriptions (A) and (B) (see **Figure 11**). This world cannot be "forcibly" introduced into the learners' mental world without taking into account the history of its constitution and the process of its symbolization.

The conceptual bridging among the inscriptions, is not only achieved by constructing appropriate sets of existing inscriptions or by constructing new inscriptions that serve the conceptual needs of each situation. In contrast, by approaching meaning-making as a process occurring in space and time, conceptual bridging across a series of inscriptions can be achieved in a multimodal context, where inscriptions collaborate with both the human body and the spoken word as well as the three-dimensional elements of space in order to produce meaning. Pozzer-Ardenghi and Roth (2005) note that teachers and learners place deictic and iconic gestures as interpretive filters over the photos. Roth (2000) states that deictic gestures disclose some specific feature, while iconic gestures depict entities and/or actions that the spoken word several times fails to convey.

Figure 12 is an example where spoken language and bodily expression work along with a graph to construct some aspects of the mechanical wave. Specifically, during a lesson about the propagation of sound waves, the teacher stands at the front of the class as a particle of the elastic medium which receives the disturbance. On the blackboard at the background of **Figure 12** is depicted the phase-time graph φ(t) for a given point in space (one dimension) $x = x_1$, which indicates the time that the molecule started to move as well as the fact that it continues to move. **Figure 13** depicts more clearly what the teacher had drawn on the board behind him at the time he represented the molecule.

The teacher mentions: "I am the particle at a distance of x = 0,3 m from the source [. . .] after a certain period of time from the initiation of the disturbance, it reaches me." Particularly, the teacher activates physicality in his attempt to clarify the graph in terms of his body. His left hand that shows himself is equal to the utterance "I am the particle," while the act of extending the right arm denotes the direction from which something – the wave disturbance – is coming. However, it is important that along with bodily expression the particle entity appears in physical space, ready at some point to begin moving. Roth and Lawless (2002) consider that the speaker's gestures, particularly iconic ones, transfer the viewer from the material place in which the inscription is contained (e.g., a drawing) to the place of narration. It should be noted that the narrative space is a mental "there" that differs from "here" where actions take place (Pantidos et al., 2010). In **Figure 12**, "there" refers to the air molecules that oscillate when, for example, a ship whistles and the sound reaches the passengers in the port. "Here," however, refers to the physical space created by the abstractive/encoded phase-time graph inscribed on the board, along with the teacher declared as a molecule and anything else that is uttered and displayed in that room. Often, when the speaker refers to a photograph or map located in the physical space, the salient features of the inscription guide the use of the speaker's gestures and "lock" the viewers' gazes on them. When speakers refer to entities that are not directly contained in the inscription and at the same time move away from the images to "unhook" from their content while turning toward the audience, they use both hands in gestural representation, and their enunciated speech refers semantically to the specific entities rather than to the inscription as a whole (Roth and Lawless, 2002). For example, in a speed-time graph depicting a complex movement, the speaker explains by pointing to the straight lines what is happening. That is, pointing to each line on the graph indicates the type of motion, e.g., uniform linear motion, accelerated motion. However, as long as the speaker turns to the audience to represent with his/her hands the track of the moving object itself instead of the lines, the discussion may take on a different dynamic. Actually, the discussion moves away from the lines of the graph which represented the movements and shifts to the human body that describes them (e.g., the hand first moves at a constant speed and then accelerates), along with the spoken word.

CONCLUSION

The theoretical analysis of inscriptions presented in the current paper showed that the conceptual continuity and the bridge between naturalistic and abstract inscriptions act as a prerequisite for bringing together everyday with school knowledge. The selection of individual inscriptions, the modification of existing ones, or the construction new inscriptions, which aim to create a series of inscriptions that narrate aspects of the "story" of a concept in the dipole of everyday and school knowledge, provides meaningful connections between the visual codes of everyday experience and the code of diagrams, graphs, and equations. This conceptual "welding" of naturalistic and abstract entries creates the conditions for a material-contextual component of students' thinking grounded both in their culture and experiences, which according to Greco et al. (2018) leads to the removal of misunderstandings.

The discussion concerning the rhetoric of inscriptions is not merely morphological. It highlights their potential for visualizing the conceptual features and relations between the conveyed entities. This contributes, along with other spatial and non-spatial means of representation [e.g., written or spoken text, moving image (video), material objects, gestures], to the multimodal expression of concepts in space, which improves students' spatial reasoning and enhances their kinesthetic perception (Kim, 2015; Ghisio et al., 2017). Although traditionally inscriptions, due to their content, have been perceived as isolated elements of meaning, teachers and learners should realize the dynamic role of inscriptions in space and time, since working together with various semiotic modes they constitute teaching and learning an active and multimodal process. Moreover, learning environments that activate thinking through action on the inscriptions enhance collaboration among learners and develop their ability to judge, evaluate and make meaning through problem-solving, even when it comes to learners who do not have an appropriate mathematical background (Verner, 2004; Medina and Suthers, 2013). According to some researchers, learners have different learning styles, i.e., they choose different ways to perceive and process information and therefore visual, auditory, read/write and kinesthetic aspects of a teaching environment have different effects on individuals' learning (Dobson, 2009). Although this view has been challenged (Riener and Willingham, 2010), inscriptions should be considered part of learners' multimodal thinking (Gillies and Baffour, 2017).

Encouraging students to use more visual elements in their "texts" requires a corresponding adaptation in the way of teaching, which in turn demands appropriate training and preparation of teachers in visual language as well (Pintó and Ametller, 2002). Undoubtedly, the non-preparation of students, as non-experts, in the conventions that form the visual codes used to write any inscriptions related to school knowledge might create problems of inscriptions interpretation. Consequently, learners are expected to appreciate the limitations of the visual code carried by a particular inscription i.e., which elements of the referent are not represented or cannot be represented or are represented implicitly. The current paper has attempted to mitigate limitations related to the conceptual relationship among real entities (e.g., air molecules) and their symbolic representations (e.g., graph of the change of pressure of air molecules in space) and thus to the connection between everyday with school knowledge, by proposing conceptual sequences of naturalistic and abstract inscriptions that narrate the "stories" of scientific concepts and physical phenomena.

The article adopted a semiotic approach that identifies inscriptions as intrinsic agents of meaning. The preceding analysis made it possible to depict the different types of inscriptions as autonomous meaning-making agents that can signify the different dimensions of a concept (Pozzer-Ardenghi, 2009). This is precisely what enables inscriptions to be combined to create conceptual sequences and thus tell a kind of story about a scientific concept (Ochs et al., 1994; Pantidos, 2017). In a science teaching perspective, semiotic analysis, through considering inscriptions as vehicles of signs, identifies an autonomous conceptualization framework that can be integrated into any learning context regardless of its pedagogical orientation. For this reason, the discussion of inscriptions has been localized to morphological issues concerning their proximity to the scientific code, the relevance of their content to the referent form as well as the morphological relevance among them (Hegarty, 2011; Kress and van Leeuwen, 2020). These issues have to do not only with the degree of abstraction of the visual code that each type of inscription carries, but also with the ability of the visual code to approximate or not everyday and school knowledge. The above discussion could act as a starting point for the systematic and efficient introduction and use of inscriptions as semiotic modes in science teaching and learning across school life from early childhood settings till high school.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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Wildlife Photographs: Seeing, Caring, and Learning Through Place-Based Education

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INTRODUCTION

To ensure global sustainability, the next generation must care about environmental systems, assess environmental problems, and make informed decisions (Monroe and Krasny, 2016; Fang, 2020). Unfortunately, the level of environmental literacy in the United States is still surprisingly low (McBeth and Volk, 2009; Plutzer et al., 2016). Without higher environmental literacy, pressing sustainability challenges (e.g., climate change, pollution, and inequitable distribution of resources) will continue (Kinslow et al., 2019). American teachers are expected to meet national and regional academic standards, many of which include socio-environmental objectives (Hufnagel et al., 2018). Place-based education (PBE), which uses the local context to teach about social ecological systems, is one way to meet these goals (Woodhouse and Knapp, 2000). Some PBE scholars focus on biophysical places (e.g., Smith, 2002), while others also consider socio-cultural attributes (e.g., Bowers, 2008). Regardless of scope, PBE can be designed to encourage civic engagement (Gruenewald, 2003). Our integrated perspective defines PBE lessons as: (1) being grounded in local biophysical and/or socio-cultural context; (2) fostering partnerships between schools and community members; (3) exploring content in interdisciplinary ways; (4) employing experiential pedagogies; and (5) promoting civic engagement (Wright et al., 2021).

Because promoting civic engagement may feel aspirational for some teachers, fostering place attachment may be an important first step (Semken and Freeman, 2008; Kudryavtsev et al., 2012). When people feel connected to their environment, they feel protective of that space (Gruenewald and Smith, 2014), call it home (Altman and Low, 1992), and develop a positive emotional connection to it that helps shape their identities (Hay, 1998; Morgan, 2010). In fact, the theory of place identity emerged from research on place attachment and explains that people's perceptions of who they are can be shaped by their childhood memories of their social and physical place (Proshansky et al., 1983). Place identity develops as children spend more time outdoors, accumulate experiences, connect positive emotions with places, and develop their sense of belonging in social ecological systems (Chawla, 1992; Dallago et al., 2009). Then, as place identity strengthens, people are more likely to advocate for and protect that place (Dresner et al., 2015), or express intentions of doing so (Buta et al., 2014; Stefaniak et al., 2017), or being civically engaged (Anton and Lawrence, 2014). Considering that place attachment develops in early adolescence, (Sobel, 1990), it makes sense to support middle school teachers in curriculum development efforts. Here, we advocate for lessons that center on visual evidence of the local environment to prompt students' place attachment.

FIGURE 1 | Camera trap photographs allow students to discover "hidden" wildlife, potentially prompting them to connect to, care for, and learn about their local place, often precursors for civic engagement. Images from camera traps were collected by middle school teachers and students in Poudre School District with support from Kevin Crooks.

VISUAL IMAGERY IN PLACE-BASED EDUCATION

Analyzing images of local environmental disturbances motivates people to be change agents (Sheppard, 2005). Photographic analysis research shows that identity, belonging, and place-attachment are tightly connected constructs (Freeman et al., 2022) and that using photographs to initiate discussions with community members, especially children, is particularly effective (Cappello, 2005; Peroff et al., 2020). Visual images convey multiple concepts at once, evoke emotive responses, and are memorable (Rodriguez and Dimitrova, 2011; Brantner et al., 2013). Furthermore, when students collect visual images, they gain ownership of the data and use them to communicate with others (Rodriguez and Dimitrova, 2011; Altinay, 2017).

Beginning in Fall 2017, we established a formal two-year partnership with middle school science teachers, university researchers, and a non-profit organization focused on wildlife conservation in the mountain west U.S. (Wright et al., 2021). Teachers explained their various goals: to integrate technology, focus on real-world examples, and allow students to analyze authentic data. We introduced them to camera traps to meet all three goals. Camera traps use infrared sensors to capture images of moving objects, including wildlife and people, and are an effective and widely used approach to non-invasively monitor and research wildlife activity and abundance (O'Connell et al., 2011). Indeed, digital technologies, like camera traps, are becoming increasingly important in real-world, data-driven conservation efforts globally (Buxton et al., 2018). During curriculum development workshops, we collectively brainstormed with teachers the types of questions biologists ask about local human-wildlife interactions and then developed lessons on limiting resources, trophic interactions, and shared natural spaces.

Teachers were excited to use wildlife camera trap images from on or near their school grounds to help their students learn about local wildlife (Wright et al., 2021). Permission was granted by the school district and city to place camera traps in natural areas on or near schools to record urban wildlife. Teachers and students periodically checked the cameras' SD cards and uploaded photographs to a shared computer drive. Professional development workshops provided teachers the time to (1) exchange and review curriculum, (2) decide how they wanted to use the photographic data, and (3) share how they were currently using these images in their lessons.

Teachers discovered that students cared deeply about issues in their own backyards and were excited to analyze photographic data, without disturbing natural areas, to determine what species were present and when they were active (**Figure 1**). Although teachers were not at first familiar with how to use camera traps and to identify photographed animals, we argue that it is well worth the effort because it allows students the chance to analyze visual images near their school grounds, uncovering a hidden world of faunal diversity that students often only learn about in textbooks. Discovering that nocturnal animals (e.g., coyotes, foxes, skunks) walked on the same paths that people used during the day elicited great enthusiasm among the students (Lin Hunter and Wright, 2019). Teachers perceived that their students were more excited and informed about their local ecological systems after analyzing camera trap images, encouraging a connection to their community and discussions about conservation (Wright et al., 2021).

DISCUSSION

Visual imagery in PBE may be an impactful precursor of developing environmental literacy. Photographs provide details that may be missed in verbal or textual descriptions of natural systems, while eliciting emotions about a place (Rodriguez and Dimitrova, 2011; Brantner et al., 2013). Young (2021) argued that when people take or capture photographs, they become "visual citizens," and when they share these images with their communities, they can promote collective action to conserve their environment. This is consistent with the goals of PBE: to increase students' understanding of the environment while encouraging them to act within their community (**Figure 1**).

Although we argue that camera trap photographs can help students discover the "hidden" biodiversity of their environment, we can only surmise that this discovery then prompts them to care about their socio-ecological world and feel motivated to learn more about species diversity and abundance, as well as trophic interactions. However, the relationship between connecting, caring, learning, and acting is well-known in environmental education (Ardoin et al., 2020). Therefore, we posit that these attributes can be fostered when individuals take time to see and understand their environments through photographs. Simply supplying teachers with cameras may not be enough. Teachers need support in learning how to set up the cameras, download the images from the memory cards, and sort through them to create a meaningful dataset for lessons. In our experience, teachers appreciated help from university wildlife biology students, scientists, and community conservation organizations (Wright et al., 2021). We found that teachers who demonstrated curricular agency and received initial support were more likely to teach using the wildlife photographs. The development of visual literacy may be a powerful component of developing environmental literacy that should be further examined if educators want to better equip global citizens to manage current and future environmental problems.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Visuospatial thinking in science education is an important form of thinking that involves the purposeful use of the human eyes to develop an internal representation. This study examined the visuospatial thinking skills of primary school students with two aims (1) identifying students' cognitive levels of these skills in domain-general learning, and (2) discovering how primary school students respond to visuospatial tasks that require interpretation of a diagrammatic representation. The study also investigated whether there are differences in how male and female students answer visuospatial thinking tasks. The participants included 93 fourth-grade students (8–9 years old), including 51 male and 42 female students, from a public primary school in Japan. The participants completed two types of paper-pencil tests. The first test required participants to complete the *Wide-range Assessment of Vision-related Essential Skills* (*WAVES*), a domain-general test that measures visual perception and eye-hand coordination skills. In the second test, students answered questions about the relationship between the movement of the sun and the behaviors of solar cells located in different places by interpreting a diagrammatic representation. Female students outperformed male students in one of the four *WAVES* index scores; otherwise, no other statistically significant differences were found. A small number of students had low visuospatial perception scores. When students were asked to explain their reasoning regarding how the solar cells worked based on their interpterion of the diagram, only a few answered correctly using perspective-taking and/or visualizing. Other students struggled to provide their reasoning, even if they had factual knowledge. Some students held an alternative conception of sunlight intensity and the sun's path in the sky. They worked through the problem from their alternative conceptions without reference to visuospatial information or taking different perspectives from the diagram. No statistically significant differences were found in the relationship between achievement in the domain-general test and the number of correct answers in the domain-specific test. The study's findings imply that students should be encouraged to practice visuospatial thinking to overcome previously held alternative conceptions. Furthermore, science education should emphasize the concept of space and teach conventional knowledge on different representation types. Further research on students' learning progress in visuospatial thinking that includes alternative conceptions such as the students' domain-specific knowledge is recommended.

KEYWORDS

external representation, internal representation, primary school science, science education, scientific diagrams, visuospatial thinking

Introduction

From a sociocultural perspective, science is seen as a practice of constructing different representation types (Latour, 1987; Roth and Tobin, 1997; Roth and McGinn, 1998). These types include *external representations*, which are constructed outside a person through language, diagrams, equations, materials, and so on, and *internal representations*, which are constructed inside a person through mental operations (Pande and Chandrasekharan, 2017). External representations have mobility, meaning they are easily transferred by their creators and users. In addition, they have immutability; that is, their properties do not change when they are transferred. They also have scalability because they can be easily re-scaled without changing their internal relationships. Moreover, they have reproducibility and can be reproduced at lower cognitive, temporal, and economic costs. Finally, external representations are characterized by combinability, as they can be easily combined with other representations (Roth and McGinn, 1998). Internal representations, in contrast, are formed through the interpretation and communication of external representations in mental processes. Thus, the two types of representation are interrelated.

This idea that multiple representation forms are used in learning is most commonly associated with science and science education. Research shows that enhancing students' representational competence through science learning is becoming increasingly important (diSessa, 2004; Gilbert, 2008; Pande and Chandrasekharan, 2017; Daniel, 2018). Representational competence in science education is defined as the students' ability to combine procedural and epistemic knowledge with content knowledge through representational practices (diSessa, 2004; Novick, 2006; Tippett, 2016; Daniel, 2018). In representational practices, students are required to move from one level of representation to another, such as transitioning from the macro-level to the microscopic level, or from some dimension of representation to another. For example, students can imagine a chemical structure, which is three-dimensional (3D), by interpreting two-dimensional (2D) drawings (Gilbert, 2008).

The cognitive process of transformation from 2D to 3D representation, or from external representation to internal representation, is a key function of visuospatial thinking. *Visuospatial thinking* or *visuospatial reasoning* is a form of thinking that involves the purposeful use of human eyes to develop an internal representation. It is characterized by both logical and creative processing of internal representations to solve problems, create new ideas, and improve skills (Mathewson, 1999; Shah and Miyake, 2005; Tversky, 2005; National Research Council, 2006; Ramadas, 2009; McCormack, 2017). Visuospatial thinking is based on a constructive amalgam of three elements: *concepts of space*, *tools of representation*, and *processes of reasoning* (National Research Council, 2006). Concepts of space include ideas related to dimensionality, continuity, proximity, and separation. Tools of representation consist of a variety of modes and media to describe, explain, and communicate the structure, operation, and function of objects and their relationships. Processes of reasoning are different thinking skills that use representation tools. Visuospatial thinking is a common cognitive process of humans, pervading everything from our everyday lives to expert practices in science, art, and other professional fields. However, each field has distinct visuospatial thinking practices (Shah and Miyake, 2005; Tversky, 2005; National Research Council, 2006).

In science education, McCormack's taxonomy of visuospatial thinking skills is well known (McCormack, 2017). This taxonomy has four components: *visual-spatial perception*, *visual-spatial memory*, *logical visual-spatial thinking*, and *creative visual-spatial thinking*. This taxonomy has a pyramid structure that is layered from visuospatial perception to creative visuospatial thinking. Visual-spatial perception includes the elementary physiological ability to observe objects and construct internal representations as mental images. Differentiating between figure and ground in complex drawings or photographs is an operation of visuospatial perception. Mathewson (1999) refers to this skill as a *vision*–defined as the ability to use one's eyes to identify, locate, and think about objects and orient oneself in the world. Visual-spatial memory comprises the ability to mentally store representations and retrieve them later, and the ability to communicate descriptions of images through drawings and language. This category includes different types of skills, such as *perspective-taking*, which is the ability to visualize objects as observed from different points of view, and *mental rotations*, which is the ability to rotate 2D or 3D objects mentally. Logical visual-spatial thinking consists of operations involving internal representations, where the operations are based on a set of rules as well as analytical and convergent thinking. Most of these operations involve logical reasoning processes. Creative visual-spatial thinking involves the production of rare, unique, or original internal representations. These can include representations produced in the realms of fantasy, invention, design, aesthetics, humor, and metaphor.

Some researchers have argued that visuospatial thinking has been overlooked by science educators (Mathewson, 1999) and that the nature of visuospatial thinking is misunderstood or has not been clarified (Newcombe and Stieff, 2012). Other researchers have reported that the development of visuospatial thinking skills impacts the ability to learn Science, Technology, Engineering, and Mathematics (STEM) subjects (Wai et al., 2009; Uttal and Cohen, 2012; Khine, 2017; Wai and Kell, 2017; Sorby et al., 2018). Wai et al. (2009) suggested that first, visuospatial thinking ability is a salient psychological characteristic among students who subsequently go on to achieve advanced educational and occupational credentials in STEM. Second, visuospatial thinking ability plays a critical role in structuring educational and occupational outcomes in the general population as well as among intellectually talented individuals. Third, measurement of visuospatial thinking should be available as a selection criterion for identifying intellectually talented students. Gagnier et al. (2022) reported that primary school teachers in the United States tended to believe that spatial thinking is more important for older students, though there were differences based on years of teaching experience. Experienced teachers were more likely to believe that spatial thinking is important at all ages, particularly in the younger grades. Moreover, students who have developmental or social problems related to visuospatial thinking may face challenges in science learning. It is well known that children with disabilities related to visuospatial perception have learning disabilities in reading, spelling, arithmetic, and other subjects (Groffman, 2006). In science learning, for example, chemistry students with lower-level visuospatial abilities are unable to perform as well as their peers with higher visuospatial abilities in solving both spatial and non-spatial chemistry problems, and they have more difficulty moving and transforming from one representation to other representations (Wu and Shah, 2004). Overall, male students tend to outperform female students on visuospatial tasks (Uttal et al., 2013; McCormack, 2017).

In a broader context, gender differences were reviewed in a variety of tests on visuospatial abilities through standardized paper-and-pencil or computerized tasks and in different fields (Halpern and Collaer, 2005). Gender differences in visuospatial abilities have been argued from three perspectives: *the evolutionary perspective*, *the biological perspective*, and *the learning and experience perspective*. From *the evolutionary perspective*, gender differences in visuospatial abilities are explained as reflections on the development of neuroarchitecture through the division of labor in hunter-gatherer societies where men traveled long distances to hunt animals and women gathered food closer to their home base. From *the biological perspective*, gender differences related to visuospatial thinking skills were explored by focusing on the "what" (ventral) and "where" (dorsal) visual pathways in the human brain, hemispheric lateralization, and exposure to gender steroid hormones. However, these differences are not fixed or immutable, but rather may be influenced by environmental and educational factors. From the learning and experience perspective, how gender differences can be developed and improved were investigated depending on the quality and quantity of training and experience in visuospatial thinking skills. Researchers have reported that visuospatial thinking skills are highly malleable; visuospatial thinking skills development and training is effective, durable, and transferable. This is one of the many promising avenues for increasing student success in STEM fields (Uttal et al., 2013; Stieff and Uttal, 2015; Cheng, 2017). Different trainings for each visuospatial thinking skill have been developed and conducted (Lane, 2005; Cheng, 2017; Williams, 2020).

There have been many studies on students' conceptual understanding of natural phenomena related to space, movement, matter, and so on (Driver et al., 1985; Barke et al., 2009; Allen, 2010). For a natural phenomenon that students can experience in daily life, students have different ideas than scientists about astronomical phenomena such as the shape of the earth, the disappearance of the sun during the night, the disappearance of stars during the day, the apparent movement of the moon, and the cycle of day and night (Vosniadou and Brewer, 1992, 1994). The nature of alternative conceptions by students is debated from the perspective of the consistency of cognitive structures (Vosniadou, 2013). On the one hand, some researchers insist that individual cognitive structures have a kind of consistency that was strengthened or accumulated through daily life. On the other hand, other researchers argue that students' understandings are not very coherent, rather they are situational or fragmented. However, both researchers agree that students should be supported to progress and acquire better conceptions that are shared with scientists (von Aufschnaiter and Rogge, 2015).

In addition to studies on students' alternative conceptions that focus on specific contents and cognitive structures, scholars have also researched students' use of cognitive skills, including visuospatial thinking skills, when learning scientific content and solving problems. Åberg-Bengtsson et al. (2017) reported how third- to sixth-grade students (aged 9–12 years) from a primary school in Sweden make sense of an illustration frequently used to explain the cause of lunar phases. In this study, a majority of students made sense of the important features of the illustration, but few students spontaneously understood the cause of the lunar phases in the intended meaning-making way. Taking different perspectives, such as the standing-on-Earth and above-the-ecliptic perspectives, which is necessary for understanding the phenomenon, was a stumbling block for the students. Another study found that preservice teachers who joined a primary education degree course created different models of day and night and the sun's path, depending on their different perspectives (Heywood et al., 2013). These studies show that operating visuospatial thinking skills, such as perspective-taking while learning science content is a challenging task not only for younger children but also for older students and preservice teachers.

Stieff (2007) examined how undergraduate students and experts processed mental rotation and a learned heuristic strategy when they solved chemistry tasks involving spatial information. While more than half of the students used the visuospatial thinking skill of mental rotation on all tasks, other students applied the analytical strategy that was taught in organic chemistry instruction. However, the experts applied *analytic strategies* to the targeted tasks as a first step before using mental rotation. The results implied that analytical strategies may become dominant as expertise grows, thereby decreasing reliance on mental rotation or other forms of visuospatial thinking skills. In other studies, Stieff (2011) reported that undergraduate students rarely used *imagistic strategies*, that is, visuospatial thinking skills on tasks that did not specifically require representation translations. Rather, students engaged in *diagrammatic strategies* that refer specifically to the application of heuristics or algorithms to domain-specific diagrams without processing complex spatial transformations. Stieff et al. (2010) pointed out that there are distinct and interactive roles for imagistic, diagrammatic, and analytic strategies for problem-solving in the science classroom. It was also shown that some high school students prefer to rely on imagistic and diagrammatic reasoning, even after instruction on how to reason analytically (Kiernan et al., 2021). These studies revealed that older students do not always apply visuospatial thinking skills to visuospatial tasks. However, whether younger students behave like older students in visuospatial tasks has not yet been clarified, except for the studies on conceptual understanding in primary astronomy (Yanagimoto and Ohtaka, 2008; Okada and Matsuura, 2014). Specifically, when younger students do not seem to process visuospatial thinking skills, there are few studies investigating whether these students engage in tasks without visual operation or have difficulties developing basic visuospatial thinking skills. Moreover, our understanding of how they recall background knowledge of natural phenomena and apply it to problem-solving in a different context is limited. Additionally, the appearance of gender differences in visuospatial abilities could vary depending on the participant's age or the task (Halpern and Collaer, 2005). To help address this, gap, this study posed the following research questions:

- What cognitive level do primary school students have in visuospatial thinking skills in domain-general learning?
- How do primary school students respond to visuospatial tasks that require the interpretation of a diagrammatic representation?
- Are there any differences between male and female students in visuospatial thinking tasks?

Materials and methods

Participants

The participants comprised 93 fourth-grade students (9–10 years old), including 51 male students (average = 10.2 years) and 42 female students (average = 10.1 years), from a public primary school in Japan. The students were taught by the same teacher. All fourth-grade students who attended the school participated in the study, except for the absentees. The *Course of Study (CoS)*, which is the national science curriculum in Japan, was developed by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) and is usually revised every 10 years. The participating fourth-grade students were taught according to the 2008 revised *CoS* (Ministry of Education, Culture, Sports, Science, and Technology, 2008), which focuses on nurturing the ability to think, decide, and express. These are emphasized at all school levels from kindergarten to upper secondary school (Matsubara, 2018), and according to the *CoS*, the sciences include physics, chemistry, biology, and earth and space science. The curriculum for fourth-grade students includes various topics, such as simple electric circuits, changes in the state of matter, the human body, seasons, and the moon and stars. The topics in this study were how the sun moves through the sky, which is taught in third grade, and how solar cells work, which is taught in fourth grade. The students had already learned this content, and no special visuospatial training was offered before this study.

Data collection and analysis

Participants completed two types of *paper-pencil tests* written in Japanese. The first test required participants to answer the *Wide-range Assessment of Vision-related Essential Skills* (*WAVES*) test, which measures visual perception and eye-hand coordination skills (Okumurara and Miura, 2014). The *WAVES* test was validated using Japanese normative data and by comparing it with the *Developmental Test of Visual Perception–Third Edition* (*DTVP-3*) (Okumura et al., 2020). The *WAVES* test comprises ten subtests and measures visuospatial thinking

TABLE 1 Skills measured by the *WAVES* subtests (Okumura et al., 2020).

Subtest	Skills measured
Line tracing	Eye-hand coordination and accuracy with relatively large movement
Form tracing	Eye-hand coordination speed and accuracy with fine-motor movement
Number comparison I	Visual-spatial awareness, visual attention, saccade, and fixation accuracy (low demand)
Number comparison II	Visual-spatial awareness, visual attention, saccade, and fixation accuracy (high demand)
Discrimination speed	Visual discrimination visual processing speed
Figure-ground speed	Figure-ground visual processing speed
Visual closure speed	Visual closure visual processing speed
Discrimination accuracy	Visual analysis, non-motor form perceptions/visual discrimination
Visual memory	Visual memory
Copying	Constructional skills, visual-motor coordination

skills (**Table 1**). *WAVES* mainly measures the visuospatial perception and visual memory components of McCormack's taxonomy of visuospatial thinking skills.

Following test instructions, the four index scores for the *WAVES* were calculated: *Eye-hand Coordination Accuracy Index* (*ECAI*), *Eye-hand Coordination General Index* (*ECGI*), *Visual Perception and Eye-hand Coordination Index* (*VPECI*), and *Visual Perception Index* (*VPI*). Developmental differences in visuospatial thinking skills among the students were then evaluated by comparing each index score to the standardized sample scores provided by the *WAVES* Guidebook (Okumurara and Miura, 2014).

The second test required students to answer questions about the relationship between the movement of the sun and the behaviors of solar cells placed in different places by interpreting a diagrammatic representation (**Figure 1**).

The students were asked to answer six questions regarding solar cells. The first two were factual knowledge questions. The first asked where the sun moves in the sky during the daytime, and the other asked how the motor works when sunlight shines on the solar cells. Students were then given three visuospatial questions. They were asked to identify the best places to move the cells to make the motor rotate faster at 9 AM, noon, and 3 PM, respectively. The building size (length, width, and height) was presented as visuospatial key information. The last question was visuospatial. This question asked what time of day the motor would move fastest at Place 6. In these last two parts, students' logical-visuospatial thinking was explored. The situation posited was 1 day in November in southern Japan, where the students participated in the test. For context, it is important to note that Japan is in the north latitude of 20–46° and an east longitude of 122–154°.

All participants completed two paper-pencil tests without instructional scaffolding, except for simple clarifications. Subsequently, structured interviews were conducted with nine students. These students were selected according to the following steps: In the first step, students were categorized into two groups: one group performed above the average for the two paper-pencil tests, and the other was not. In the second step, ten students were listed from each group. In the final step, the candidates were selected based on their science teachers' suggestions and considering gender groups. The teachers provided the personal information of students who could participate in the interview with the researcher without special support. The researchers then interviewed five male and four female students. The structured interviews, which lasted from 5 to 10 min, were intended to further probe how students engaged in the *solar cell problems*, especially focusing on the final question. The interview protocol was transcribed into text data. The scores from the *WAVES* test, answers from the solar cell problems, and verbal protocols of the interviews were analyzed. In addition, gender differences in the index scores and responses were scrutinized using the *chi-square test* and *t*-test, and *spearman rank-order correlation*. Students' responses were analyzed from *the learning and experience perspective* including students' alternative conceptions related to an astronomical phenomenon.

Results and discussion

Students' visuospatial thinking skills in domain-general learning

The visuospatial thinking skills in domain-general learning by fourth-grade students from a primary school were examined. Students' responses to each skill subtest were graded, and their index scores were calculated. Subsequently, by comparing the students' index scores to the standardized scores for *WAVES*, which show the expected scores that children can receive depending on their age, the students' cognitive levels in terms of visuospatial thinking skills were estimated. A summary of the students' four index scores is shown in **Table 2**. The distribution of students' four index scores is shown in **Figure 2**.

If a student has an index score of 100, their cognitive level in terms of visuospatial thinking skills is equal to the average level expected for students of the same age. A score above 110 indicates that the student's cognitive level is within the third quartile. A score of less than 90 means the cognitive level is within the first quartile for their age (Okumurara and Miura, 2014). In this study, the former was seen as high achievers, while the latter was seen as low achievers.

For *ECAI*, which is composed of the ratio scores for line tracing and form tracing, the mean index score for both male and female students was above 100 (male students: Mean = 108.4, SD = 13.8; female students: Mean = 114.1, SD = 7.4), and the scores for many students were higher than the

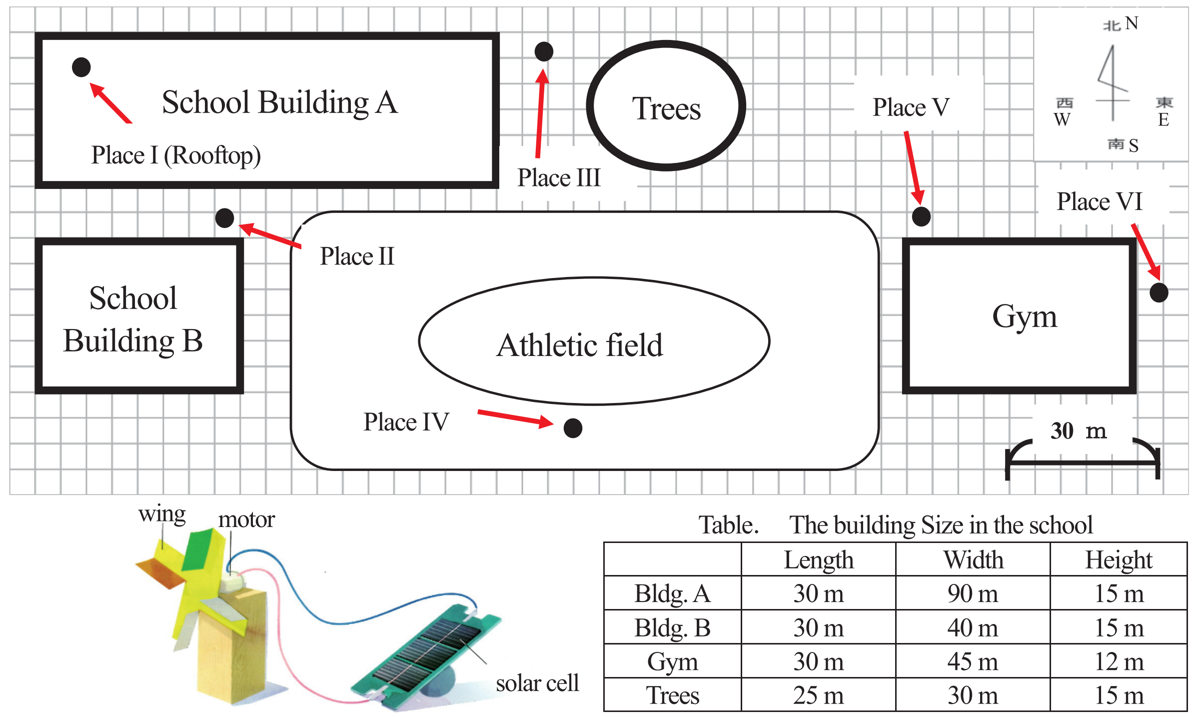

FIGURE 1
The solar cell problems.

TABLE 2 Students' *WAVES* index scores.

The index scores	Gender	Mean	Low achiever	High achiever
Eye-hand Coordination Accuracy Index (ECAI)	Male	108.4	4 (7.8%)	31 (60.8%)
	Female	114.1	0 (0.0%)	34 (79.1%)
Eye-hand Coordination General Index (ECGI)	Male	106.4	9 (17.6%)	23 (45.1%)
	Female	110.6	1 (2.3%)	27 (62.8%)
Visual Perception and Eye-hand Coordination Index (VPECI)	Male	103.3	10 (19.6%)	19 (37.3%)
	Female	108.9	1 (2.3%)	18 (41.9%)
Visual Perception Index (VPI)	Male	96.8	18 (35.3%)	13 (25.5%)
	Female	98.2	8 (18.6%)	8 (18.6%)

average level. There was a statistically significant difference in the mean *ECAI* scores for male and female students, which was found through a *t*-test ($t = -2.162$, $df = 92$, $p < 0.05$). Female students outperformed male students in terms of their ability to write and draw using their eyes and hands in coordinated ways as quickly and accurately as possible.

For the *ECGI*, composed of the sum of the scores for line tracing and form tracing, the mean index score for male and female students was also above 100 (male students: Mean = 106.4, SD = 17.1; female students: Mean = 110.6, SD = 11.4). For the *VPECI*, which is composed of the sum scores for line tracing and form tracing, ratio scores for line tracing and form tracing, number comparison (type 1) scores, discrimination speed, discrimination accuracy, visual memory, and copying, the mean index scores for male and female students were also above 100 (male students: Mean = 103.3, SD = 19.6; female students: Mean = 108.9, SD = 12.5). In addition, 40–60% of students had higher scores on these skills measures than the average.

However, for the *VPI*, the mean index scores for male and female students were under 100 (male students: Mean = 96.8, SD = 17.4; female students: Mean = 98.2, SD = 12.7). The cognitive level of visuospatial perception by the students in this study was as high as the expected ability level for the Japanese student in their age group. Overall, nine male students and one female student were considered low achievers for both the *VPECI* and *VPI* scores. Additionally, only one male student was a low achiever for all index scores. The results indicated that

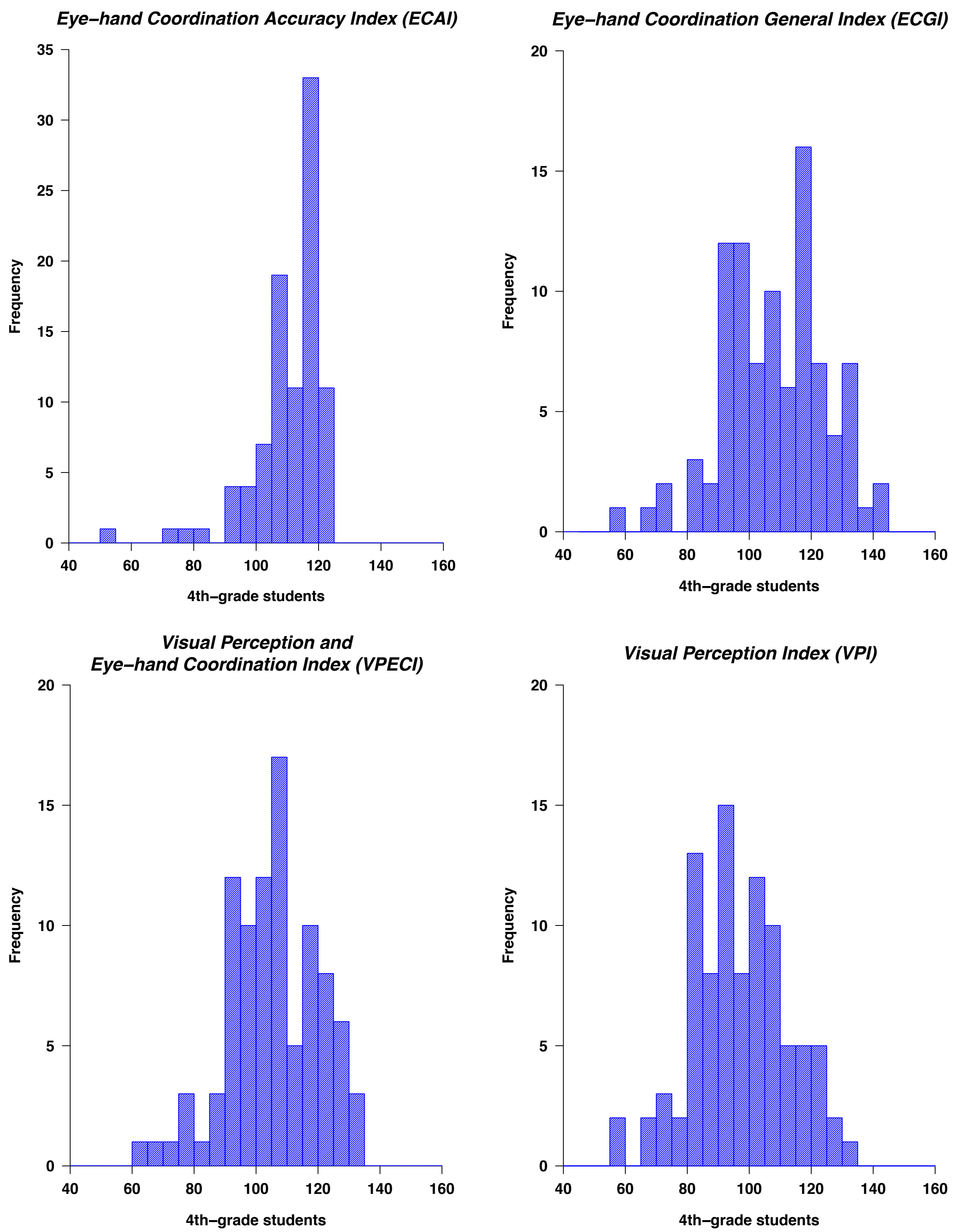

FIGURE 2
Distributions of students' four index scores.

most low-scoring students did not require immediate additional educational interventions. However, further observation of a few students might be needed to determine whether they need better visuospatial training. The *t*-test showed that no statistically significant differences between male and female students exist in the *ECGI*, *VPECI*, and *VPI* scores (*ECGI*: $t = -1.534$, $df = 92$, $p = 0.128$; *VPECI*: $t = -1.586$, $df = 92$, $p = 0.116$; *VPI*: $t = -0.515$, $df = 92$, $p = 0.608$). Although researchers have reported that male students tend to be superior to female students in visuospatial thinking skills (Uttal et al., 2013; McCormack, 2017), this kind of gender difference did not seem to apply to the students in this study.

Students' use of visuospatial thinking skills and interpretation of the diagram

In the first part of the solar cell problems, 42 (82.4%) male students and 38 (88.4%) female students answered that the sun moved from east to south to west in the sky during the daytime. Studies have found that both young students and older students find it difficult to understand the sun's path when students are required to use visuospatial thinking skills such as mental rotation and perspective-taking (Allen, 2010; Heywood et al., 2013). However, acquiring factual knowledge about the sun's path was a lower-demand task for fourth-grade students in this study. In addition, 48 (94.1%) male students and 42 (97.7%) female students correctly answered that the stronger the sunlight on the solar cell, the faster the motor rotates. The students had already learned the causal relationship between the intensity of sunlight, the current flow of the solar cells, and motor movement before this test. This is typical content for the fourth-grade science curriculum. It was seen from the responses to the two factual questions that most of the students had the factual knowledge essential to answering the later questions.

In the second part, the students answered three questions on the best places for making the motor rotate depending on the time at 9 AM, 12 noon, or 3 PM. In answering the questions, students were able to choose any options that they believed were suitable. The students' response rates to the questions are shown in **Figure 3**. From the building size information presented, we can reason that there could be places with more or less sunlight, depending on the time. In the grade four assessment rubric for students' responses on this part, students that chose suitable places at all three times, without adding unacceptable places, received the highest marks. For example, Places 1, 2, and 4, where sunlight comes from the east, were considered suitable places at nine o'clock in the morning, whereas Place 5, where sunlight was blocked by the Gym, was unsuitable. Students who chose some of the acceptable locations without choosing any unacceptable ones were marked as the second level. Third-level students chose a mix of both suitable places and unacceptable places. Finally, students who chose only unacceptable places were marked as the lowest level.

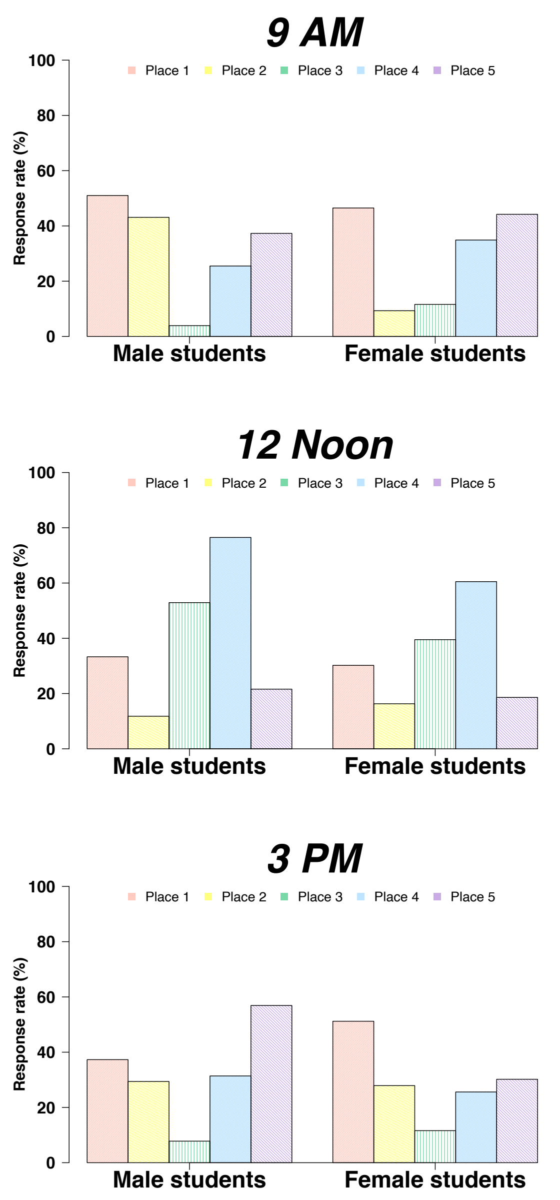

FIGURE 3
Suitable places chosen by the students.

The students' scores for the suitable place questions are shown in **Table 3**. Only a few students answered each question perfectly, but 40–65% of students found suitable places properly. It seemed easy for these fourth-grade students to determine a suitable place for the solar cell at noon because almost all of them had factual knowledge that the sun crosses the southern sky during the daytime. However, to answer the other two questions–9 AM and 3 PM–correctly, they had to guess the position of the sun and reason the path of the sunlight in the morning and afternoon. Although Place 5 was unsuitable because sunlight coming from the southeast at 9 AM would be blocked by the Gym, 19 (37.3%) male students and 19 (44.2%)

TABLE 3 Students' marks for the suitable place questions.

Marks	Male students	Female students
At 9 AM		
4: Excellent	3 (5.9%)	0 (0.0%)
3: Good	20 (39.2%)	19 (44.2%)
2: Adequate	7 (13.7%)	5 (11.6%)
1: Poor	21 (41.2%)	19 (44.2%)
At 12 noon		
4: Excellent	4 (7.8%)	0 (0.0%)
3: Good	31 (60.8%)	29 (67.4%)
2: Adequate	11 (21.6%)	11 (25.6%)
1: Poor	5 (9.8%)	3 (7.0%)
At 3 PM		
4: Excellent	2 (3.9%)	0 (0.0%)
3: Good	24 (47.1%)	22 (51.2%)
2: Adequate	17 (33.3%)	14 (32.6%)
1: Poor	8 (15.7%)	7 (16.3%)

female students thought it was a candidate. In addition, 15 (29.4%) male students and 12 (27.9%) female students answered that Place 2 was a suitable place at 3 PM. The combination of the places that students answered as suitable was also different for each time, as shown in **Figure 3**. A small number of students drew lines on the paper for cognitive help that might represent the sun's movement or sunlight. However, there were no representations, such as purposeful drawings, on the majority of papers. From these observations, it might be guessed that the students in this study had challenges in changing the position of the sun in the sky through the *mental operation* of imagining the direction of sunlight and then identifying which places were suitable. *Chi-square test* indicated that no statistically significant differences were found in the responses to the suitable place questions between male and female students (9 AM: $\chi^2 = 2.798$, $df = 3$, $p = 0.424$; 12 No: $\chi^2 = 3.914$, $df = 3$, $p = 0.271$; 3 PM: $\chi^2 = 1.776$, $df = 3$, $p = 0.620$).

In the last part, the students answered one question that asked them to identify the best time for making the motor rotate at Place 6. In answering the question, students chose one place as suitable and explained it. In the grade four assessment rubric for students' responses to this part, students were marked at the highest level when they chose just one suitable time correctly and constructed an explanation that included the relationship between the position of the sun at that time and the path of the sunlight to Place 6. In addition, to the sun being in the east at 9 AM, the students were required to mention that sunlight can reach this location without being shaded or blocked by different things. In descending order, the students who answered only the sun's position at 9 AM correctly were marked as the second level, the students who chose 9 AM but did not make a reasonable explanation were marked as the third level, and the students who could not answer anything correctly were marked as the lowest level.

TABLE 4 Students' marks for the suitable time questions.

Marks	Male students	Female students
At place 6		
4: Excellent		
Time: *correct*	5 (9.8%)	3 (7.0%)
Explanation: *complete*		
3: Good		
Time: *correct*	13 (25.5%)	9 (20.9%)
Explanation: *sufficient*		
2: Adequate		
Time: *correct*	1 (2.0%)	3 (7.0%)
Explanation: *insufficient*		
1: Poor		
Time: *incorrect*	33 (35.3%)	28 (34.9%)
Explanation: *incorrect*		

Students' responses to the suitable time question are shown in **Table 4**.

Although 18 (35.3%) male students and 12 (27.9%) female students could find a suitable time, only five (9.8%) male students and three (7.0%) female students provided both the correct time and explanation. For example, the complete explanation made by one male student was that "(The sun) is in the east direction at 9 AM and (the sunlight can) reach there without any interruption." A sufficient explanation made by one female student was that "Place 6 is in the east, the sun rises in the east." This type of explanation mentioned the direction of Place 6 and the sun rising but did not explain why the other times were not suitable. In the interview, some of the students who were marked *Excellent* or *Good* mentioned their reasoning process, including the use of visuospatial thinking skills. Student 1 (female) who was marked as *Good* mentioned that she reasoned the formation of a shadow by the different buildings and its effect on the solar cell workings. She explained that she also used the attached table, which indicated the building size, for her reasoning in later parts of the interview. In addition, she explained her visuospatial thinking as moving her body to Place 6 and looking up at the sun from this position. Her visuospatial thinking skills were *visualizing* and *perspective-taking*.

Interviewer: Then, I think that shadows will be formed because the sun moves, but were you aware of how shadows can be formed (in this question)?

Student 1: Yes.

Interviewer: How did you do it?

Student 1: Because a shadow can be made on the opposite side of the sun, there is a shadow on the athletic field and the school buildings. However, for the Gym, the sunlight was shining on it. So (I answered) Place 6.
(a few seconds later)

Interviewer: How did you do it?
Student 1: At Place 6, I move my body to the position. (And looking up at the sun) I was aware of how the sun was shining.

Of the nine students interviewed, two students mentioned that they formed a shadow for a specific time and mapped it onto the diagram by going along with the sun's movement during the daytime. The students visualized the shadows of the buildings to answer this question. They monitored their cognitive process and viewed it from a third person's perspective. Following their manifestation, they demonstrated metacognition of their visuospatial thinking. The other two students referred to their awareness of a shadow. They did not explain the details.

Some students had a typical alternative conception of sunlight intensity in which they believe the differences in temperature between the seasons are caused by differences in the distance from the sun to the earth (Allen, 2010). That is, students believe that summer is hotter than winter because the sun is closer to the earth in summer. In this study, some students demonstrated that Place 6 is a suitable place for solar cell activation because Place 6 is near the sun in the east. They seemed to explain the differences in the intensity of sunlight hitting the earth's surface based on the height of the sun in the sky. For example, student 2 (male), who was marked as *Excellent*, explained his reasoning as follows.

Student 2: Oh, here. At noon, it (the motor) rotates because (the sunlight) reaches (it) from the south, and from above, but it does not rotate so fast. For the west, it (the sunlight) comes from here (the west), but the sunlight is blocked by the Gym. For the east, it (the sun) is on this side, because the height of the sun on this side (the direction of the east) is low, the sunlight is near, then (I answered) 9 AM.

At least four students were suspected of having similar alternative conceptions following their responses to the paper-pencil tests. In addition, there were students with similar ideas in the group of students who chose 3 PM. In their visuospatial thinking, although they considered the direction of the sun in the morning, they missed that the sunlight reached Place 6 not from a vertical direction but in a diagonal direction. To better explain this, it is also necessary for them to learn concepts of space, such as surface area and angle, as one of the three elements of visuospatial thinking (National Research Council, 2006).

However, 19 (37.3%) male students and 18 (41.9%) female students answered that noon was the best time for solar cells to work. For example, the incorrect explanation made by one male student was that "Because the sun comes to the highest place at noon, the sunlight reaches easily." Of course, this is the correct explanation for a general situation. However, this does not apply to this situation in which the students must consider buildings that block sunlight as visuospatial information. For example, student 3 (male), who was marked as *Poor*, answered honestly as follows.

Interviewer: Place 6. This time, in this experiment Place 6 is very important. Did you look at this well? Didn't you look at it?
Student 3: No, I didn't look at it.
Interviewer: You didn't look at it. Didn't you find it?
Student 3: Yes, I found it.
Interviewer: You found it?
Student 3: But I didn't care about it.

In this case, he neglected the part of the question that asked him to guess the motor workings in a specific place. Regardless of whether the students intentionally ignored the part of the question referring to the location of Place 6, the students who answered noon as a suitable time did not use visuospatial information as a cue to answer it. Rather, they reasoned it based on alternative conceptions, such as "The temperature at noon is the highest in a day" and "The sun comes just above us at noon." As one student wrote, they examined how the solar cell's working changed by shedding light from different angles. However, the statement "The sun comes just above us at noon" was not true for the students in this study, who lived at north latitude 32°. They also learned about the temperature change 1 day before this study. If the students have any alternative conceptions on the topic or have learned it before, they might prefer to use their available knowledge to solve the problem first, especially in the case of novel problems or cognitively loaded tasks. The diagram given was drawn from a vertical viewpoint, the students did not question whether they should change this, so they had the same point of view. That is, they continued to maintain one perspective without taking different perspectives into account. The current problem was not just a matter of visuospatial thinking skills but also a matter of whether or not students had the appropriate background knowledge for this context. As reported, the students' alternative conceptions seemed to interrupt their scientific and visuospatial thinking if they had no instructional scaffolding. Students' cognitive processes in the context that included a physical experiment in an outdoor environment are in line with the nature of understanding of observational astronomy by the different students as explored by Vosniadou and Brewer (1992, 1994); Kyriakopoulou and Vosniadou (2014, 2020). Behind students' cognitive behaviors in this study is the fact that they use an alternative conception induced from ordinary and perceptional experiences, therefore, they may not distinguish the scientific representation from perceptional-based representations. Although learning an epistemological perspective that can contribute to cognitive flexibility to consider different possible representations of the same situation or phenomenon is

TABLE 5 Students' achievement level and the number of correct answers on the two tests.

Gender	*WAVES* achievement level	Number of correct answers on the *solar cell problems*				
		0	1	2	3	4
Male students	Total	5 (9.8%)	13 (25.5%)	14 (30.2%)	16 (32.6%)	3 (3.9%)
	High	1 (2.0%)	3 (5.9%)	5 (9.8%)	2 (3.9%)	2 (3.9%)
	Average	2 (3.9%)	7 (13.7%)	6 (11.8%)	13 (25.5%)	1 (2.0%)
	Low	2 (3.9%)	3 (5.9%)	3 (5.9%)	1 (2.0%)	0 (0.0%)
Female students	Total	2 (4.7%)	14 (32.6%)	13 (30.2%)	14 (32.6%)	0 (0.0%)
	High	0 (0.0%)	1 (2.3%)	2 (4.7%)	5 (11.6%)	0 (0.0%)
	Average	2 (4.7%)	12 (27.9%)	11 (25.6%)	9 (20.9%)	0 (0.0%)
	Low	0 (0.0%)	1 (2.3%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

recommended (Kyriakopoulou and Vosniadou, 2014), we assume the fourth-grade students in this study had no chance to use or learn this concept until this study. The *chi-square test* indicated there were no statistically significant differences in the responses to the suitable time question between male and female students (χ^2 = 1.611, *df* = 3, *p* = 0.657). Alternative conceptions that some students had were rooted in shared ordinary lives and perceptional experiences, then there was no evidence that either male or female students had a better understanding of these conceptions or related experiences. The students interpreted the diagram based on alternative conceptions of astronomical phenomena. This could be another plausible reason to support that no gender differences were found, additionally, the students were younger than participants in studies where gender differences were reported. Generally speaking, a phenomenological understanding emphasizes learning through direct observation of actual phenomena in the science curriculum in lower grades. It could be inferred that the fourth-grade students in this study lacked opportunities to develop visuospatial thinking skills in their science lessons.

Students' visuospatial thinking skills in domain-general and domain-specific learning

Overall, by examining students' visuospatial thinking skills, such as visuospatial perception and visual memory, in domain-general thinking and domain-specific logical visuospatial thinking almost no statistically significant differences between male and female students were found in their responses to the two paper-pencil tests, as mentioned above. The students' achievement levels on the *WAVES* test, which were evaluated based on their *VPECI* and *VPI* scores, and the number of correct answers to the solar cell problems (marked as *excellent* or *good*) are shown in **Table 5**. For older students, it was reported that male students tend to outperform female students (Uttal et al., 2013; McCormack, 2017). However, this trend did not apply to the primary school students in this study. Both male and female students had the same level of factual knowledge, and they reasoned in similar ways to answer the questions.

The results implied that differences in students' responses to questions and their use of visuospatial thinking were not influenced by gender. Instead, their responses were influenced by alternative conceptions held before this study or by the framing of the questions as visuospatial problems. In addition, no statistically significant differences were found in the measures between achievement and the number of correct answers (*chi-square test*: χ^2 = 8.983, *df* = 8, *p* = 0.344). Then, the correlation between these measures was weak (ρ = 0.221, *p* = 0.032). In this study, there seemed to be no significant relationship between visuospatial perception, measured as domain-general thinking, and logical visuospatial thinking skills, measured as domain-specific thinking. Even if visuospatial thinking skills are malleable and transferable across the domains, students' visuospatial thinking skills could depend on their domain-specific knowledge, which is a body of contextual knowledge in science.

Conclusion

Many different representations are used in science and science education. The cognitive process of transformation from a 2D to 3D representation, or from external representation to internal representation, is a key function of visuospatial thinking. Visuospatial thinking is characterized by both logical and creative processing of internal representations to solve problems, create new ideas, and improve skills. Visuospatial thinking is constructed from concepts of space, representation tools, and thinking skills. It is suggested that the taxonomy of visual thinking skills in science education has a pyramid structure that is layered with visuospatial perception, visuospatial memory, logical visuospatial thinking, and creative visuospatial thinking. This study examined whether there were primary school students with difficulties developing visuospatial thinking skills in domain-general learning. The study also explored how primary school students respond to visuospatial tasks that require interpretation of a diagrammatic representation and gender differences in visuospatial thinking task answers.

The student's cognitive level of visuospatial thinking skills was examined through the *WAVES* test, and four index scores were calculated: *ECAI*, *ECGI*, *VPECI*, and *VPI*. Female students outperformed male students in terms of their ability to write and draw using their eyes and hands in coordinated ways, as shown in the *ECAI* scores. However, no statistically significant differences were found in the *ECGI*, *VPECI*, and *VPI* scores of male and female students. The results show that the cognitive level of visuospatial perception by the students in this study was not as expected based on the recommendation from *WAVES*. Overall, there was a limited number of students identified as low achievers on both *VPECI* and *VPI* scores.

The students' use of visuospatial thinking skills in interpreting the diagram was examined by answering another assignment about the relationship between the movement of the sun and the behaviors of solar cells placed in different places (solar cell problems). From students' responses to the questions, most had the factual knowledge that the sun travels from east to south to west in the sky during the daytime, and the stronger the sunlight on the solar cell, the faster the motor rotates. When students were asked about the motor workings in different places at the same time, it was easy for them to reason a suitable place for the solar cells at noon, using factual knowledge of the sun's path. However, some students struggled to reason where the cells should be placed at other times of day, which requires *mental rotation* and *visualization*. When students were asked about the motor workings in different places at the same time, a limited number of students answered correctly, with the use of *perspective-taking* and/or *visualization*. Some students had an alternative conception of the sunlight intensity and the sun's path in the sky. They reasoned the problem from their alternative conceptions without using visuospatial information or taking different perspectives from the original perspective given in the diagram. No statistically significant differences were found in the relationship between achievement in the domain-general test and the number of correct answers in the domain-specific test between male and female students.

The implications for science teaching from this study are to encourage students to engage in visuospatial thinking practices, such as perspective-taking. In addition, teachers should emphasize that the concepts of space, such as dimension, and conventional knowledge of different representations, such as a map, are drawn from one perspective. This study was limited in that it examined primary school students' visuospatial perception through a domain-general test and domain-specific logical visuospatial thinking through the interpretation of a diagram. The standardized test used in this study did not fully cover visuospatial thinking skills in the domain-general. A more targeted instrument for examining specific visuospatial thinking skills such as mental rotation would be needed to know students' cognitive level of visuospatial thinking skills. The study did not investigate students' developmental differences in visuospatial thinking in domain-general and domain-specific or the relationship between them. From the theoretical framework of visuospatial thinking, which is constructed from concepts of space, tools of representation, and thinking skills, further research on students' learning progress, including alternative conceptions like domain-specific knowledge, is recommended.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Both were involved in the study design collaboratively. KK was involved in collecting and analyzing data. SU led the analysis and set an overarching argument for the study and was involved in writing the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Visual images of the biological microcosmos: Viewers' perception of realism, preference, and desire to explore

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Visual images are crucial for communicating science in educational contexts and amongst practitioners. Reading images contributes to meaning-making in society at large, and images are fundamental communicative tools in public spaces such as science centers. Here, visitors are exposed to a range of static, dynamic, and digital visual representations accessible through various multimodal and interactive possibilities. Images conveying scientific phenomena differ to what extent they represent real objects, and include photographs, schematic illustrations, and measurement-based models. Depicting realism in biological objects, structures and processes through images differs with respect to, *inter alia*, shading, color, and surface texture. Although research has shown that aspects of these properties can both potentially benefit and impair interpretation, little is known about their impact on viewers' visual preference and inclination for further exploration. Therefore the aim of this study is to investigate what effect visual properties have on visitors' perception of biological images integrated in an interactive science center exhibit. Visitors responded to a questionnaire designed to assess the impact of three indicators of realism (shading, color, and surface texture) and biological content (e.g., cells and viruses) on participants' preferences, perceptions of whether biological images depicted real objects, and their desire to further explore images. Inspired by discrete choice experiments, image pairs were systematically varied to allow participants to make direct choices between images with different properties. Binary logistic regression analysis revealed that the three indicators of realism were all significant predictors of participants' assessments that images depict real objects. Shadows emerged as a significant predictor of preference for further exploration together with the presence of cells in the image. Correlation analysis indicated that images that were more often selected as depicting real objects were also more often selected for further exploration. We interpret the results in terms of construal level theory in that a biological image perceived as a realistic portrayal would induce a desire for further exploration. The findings have implications for considering the role of realism and preference in the design of images for communicating science in public spaces.

KEYWORDS

biological images, realism, visual preferences and exploration, construal level theory, science centers

Introduction

Development in human knowledge about the world has accompanied an increasing diversity of visual representations and images used to communicate and represent science. A domain of knowledge in which this rings particularly true is the biological sciences, where a multitude of visual imagery is used to communicate levels of biological organization, from unobservable submicroscopic entities through to the tangible macroscopic scale.

An influential aspect of interpreting a biological image is realism, a term that refers to the accurate mapping between the visual representation and reality. Recently, the use of realistic images for conveying scientific content has gained even more traction with the advent of visualization technology such as virtual reality (e.g., Skulmowski et al., 2021), and the exposure of the public to biological visuals in museums and science centers (e.g., Höst et al., 2018). This trend is also vividly apparent in current society, with citizens negotiating and perceiving the wave of biological visual communication in the wake of COVID-19, where biological imagery is a core component in shaping the narrative of the pandemic (e.g., Callender et al., 2020). In contrast with realism, visual abstraction through extracting aspects of a representation also influences perception and understanding. Examples of the influence of abstract properties have been shown in current studies where abstract and perceptually bland visuals of biological change are associated with superior learning in adults, while very young children benefit most from perceptually rich representations (Menendez et al., 2022, 2020). Here, as has been recently shown by Skulmowski (2022), if the aim of an image is for viewers to focus on underlying relationships, abstract images may sometimes be superior to realistic representations.

While debating the virtues of realism versus abstraction in visually communicating science, caution must be taken in making assumptions about the perceptual strengths and limitations of image properties for representing biological phenomena. On this note, according to Smallman and St. John (2005), the assumption that people prefer realistic images is born out of erroneous generalizations such as the fallacy that the human eye is an error-free mental camera, a naïve notion that reinforces the assumed "preference" and automatic positive benefits of realism over other forms. Furthermore, viewers' representational preferences in interpreting biological visual representations also depends on their previous experience, their perception of the narrative, as well as competence in processing what is often complex imagery (e.g., Pozzer and Roth, 2003; Griffard, 2013). Although the literature suggests that selection and presentation of visual information should be driven from findings in vision science (Smallman and St. John, 2005), little is known about the communicative influence of fine-grained comparisons between the characteristics of visual realism in scientific images. Moreover, there is limited knowledge about what viewer characteristics affect interpretation of biological images, and what might benefit or hinder interpretation (e.g., Skulmowski, 2022). In contributing to this emerging perspective, this study investigates how properties of biological images relate to viewers' visual preferences, their perceptions of realism, and their desire to explore encountered visual images further.

Theoretical background

Communicating biology through visual images

Visual images are fundamental in the communication of science and are deployed as a representational language among science practitioners, in educational contexts, as well as society at large. In the sciences, visual representations often depict phenomena through various levels and formats that shuttle between the macroscopic, submicroscopic, and symbolic (Johnstone, 1991). In biology, visual images provide an avenue for engaging with and building knowledge about biological structures and processes that are often beyond direct human visual perception. Meaning-making of visual images takes place constantly; when pupils and students view static representations adorned in biology textbooks, right through to public engagement with visualizations in museums and science centers.

The literature contains multiple approaches and taxonomies for distinguishing between how different types of visual representations communicate scientific knowledge (e.g., Gilbert, 2005; Offerdahl et al., 2017). For example, inspired by the classification of visual representations composed by Lohse et al. (1994), Schönborn and Bögeholz (2013) proposed that five primary types of visual representations are used to communicate biology, namely Graphs, Network charts, Structure diagrams, Process diagrams and Photo-realistic pictures. Graphs plot numerical data and encode quantitative information, inherent in representations such as a line graph of population growth. Network charts depict relationships among biological components often through the spatial arrangement of symbols, such as a diagram of a neural network. The visual communication of physical biological objects, such as a sketch of the human heart in cross-section, are termed Structure diagrams, while Process diagrams such as an illustration of gene splicing, are used to convey temporal processes associated with biological objects. Lastly, Photo-realistic pictures realistically depict biological entities, and take the form of, for example, a micrograph of a cell membrane bilayer, or photograph of a terrestrial habitat.

Biology employs and relies on an abundance of diverse visual forms to depict biological meaning, visual forms that in turn can evoke emotion as well as induce or stifle a viewer's curiosity. For instance, work by Lenski and Großschedl (2022, this issue) has shown that biological images with attributes such as appealing colors can positively influence viewers' emotions, deepen their image processing and lead to improved learning. At the same time, Eilam (2013) has previously pointed out that while an image might inspire curiosity and provide aesthetic pleasure, it is also important to be aware of what visual elements might diminish these positive dimensions.

Realism in biological images, aspects of visual properties and preference

An eloquent review by Alesandrini (1984) conveyed that all types of pictorial representations, whether they are realistic, analogical, or abstract, must be explored in terms of their characteristics as communication and learning tools. In response to this call made 40 years ago, continuing to study and classify how different representational forms can be used most effectively for perception is of high interest. When it comes to identifying visual properties that influence perception, Wanger et al. (1992) mention shading and surface texture as two important visual cues for perceiving spatial relations in images. In biology images, visual properties such as shading communicate depth and three dimensions (Griffard, 2013), whilst color and texture properties are related to perceiving a biological structure as authentic (Eilam, 2013). In addition, Rademacher et al. (2001) have presented experimental results indicating that the softness of shadows and the smoothness of surfaces are important parameters for the perception of visual realism. Wang and Doube (2011) have proposed that realism in photographic images based on gradient variance (surface roughness), color variance, and shadow softness have a major influence on perception.

In terms of communicating biology through visual representations, Pozzer and Roth (2003) have posited that biological representations can be classified along a continuum according to the level of contextual detail that they contain. Such a continuum ranges from more detail (less abstraction) to less detail (more abstraction), where a photograph of a flower would lie toward the more detail and less abstraction end while a symbolic equation would lie toward the less detail and more abstraction end. In relation to this work in a biochemistry context, Schönborn and Anderson (2009) deployed what they referred to as a real to abstract continuum to designate visual representations of antibody-antigen interaction. For example, an electron micrograph (× 1,000,000) of antibody-antigen complexes would lie at the realistic end, a stylized space-filling model that pictorially depicts molecular surface interaction between antigen and antibody would lie near the center, while an abstract symbolic portrayal of antibody-antigen interaction represented by a graphical plot of absorbance versus concentration, would lie at the abstract end.

For a quarter of a century, Francis Dwyer studied students' interpretation of static representations across a visual realism continuum, where the structure of the human heart was often the visually communicated subject of interest. In multiple studies, Dwyer (1967, 1969) found that in comparison with other representations, realistic pictures of the heart were superior for meeting learning objectives. Dwyer's explanation for these results was that the greater pragmatic detail provided by realistic representations offers students a more natural way to encode the visual information. In a later study that also adopted a representational continuum, Joseph and Dwyer (1984) explored students' interpretation of a merged representation consisting of an abstract line drawing of one half of the heart with a realistic photograph of the other. The study found that higher levels of prior knowledge supported students' learning with the realistic half of the representation, while the abstract half supported students with lower prior knowledge more. In addition, previous work (Dwyer, 1975) also showed that students with lower prior knowledge spent more time on processing realistic representations of the heart. As early as the 1960's, Dwyer's work already revealed that the perceived and actual benefits of representations for pedagogical outcomes depend on multiple criteria. For instance, the greater the number of representations students have been exposed to, the more superior their procedural skills for decoding visual information. Overall, Dwyer's extensive contributions to the literature have shown that it is important to systematically identify what representational markings and components are most beneficial for learning. One clear finding was that students favored colored representations of the heart over single color alternatives, where Dwyer (1970, 1972) identified several relationships between colored displays and increased motivation in students to learn.

Recent work by Skulmowski (2022) using skull and bone renderings as subject materials shows that learning tasks that require students to focus on surface and shape dimensions when transferring knowledge from one context to another, are not necessarily improved when the images are realistic. In his study, transfer tasks included students being required to transfer their interpretation of anatomical skull images (e.g., a dog skull) to other skull images (e.g., a pig skull). The work also found that shape distinctness in images did not influence learning with schematic or realistic representations. Nevertheless, interpreting less distinct shapes was associated with higher levels of cognitive load, levels that were reduced when realistic features and shape distinctness were fused. Another recent study by Skulmowski et al. (2021) provided a model for comparing the levels of realism inherent in scientific visualizations. The authors probed the contrast in the literature that while multiple studies have found realism to be useful for learners, other studies show abstract representations to be superior. As part of the development of a cognitive model of learning with realistic visualizations, these same researchers define realism as a combination of geometry, shading and rendering. Merging these dimensions provides different levels of perceptual load for the viewer. Their work advocates that although it might be naïve to merely assume that realism is always superior, the characteristics of what realistic images contribute to perception and learning needs more refinement. During the same period, Skulmowski and Rey (2021) investigated the effect of visual appearance of bacteria on individuals' assessment of pathogen properties. Among the findings, they show that realistic images were rated as more credible than schematic images. In addition, they observed that disfluency in the bacterial images (i.e., depicting bacteria as irregularly shaped with appendages and hair-like strands, as opposed to perfectly round and smooth) also led to images being rated as more credible.

Level of construal in scientific visual representations

In a preceding study (Höst et al., 2018), we proposed that the tendency of science center visitors to interact with certain types of images could be partly explained by construal level theory (e.g., Trope and Liberman, 2010). According to construal level theory, people engage differently with objects depending on the psychological distance between the object and the individual. Short psychological distances are associated with low level construal (i.e., focusing on details) while long distances would give rise to high level construal (i.e., focusing on the big picture). The concept of psychological distance encompasses multiple different types of distances, such as temporal, spatial, hypotheticality (whether something appears likely to occur, or to exist), and familiarity (Fiedler, 2007). Thus, depending on the properties of objects, different kinds of psychological distances arise, which in turn, give rise to different types of construal. For example, use of color versus grayscale in images may be associated with different temporal psychological distances, where distant times are associated with less color (e.g., because old photos are often grayscale) (Lee et al., 2014). Our emanating idea from this work was that the properties of biological images give rise to different construal levels, and that low level construal is associated with more interactive behaviors, and vice versa. The rationale is that a low-level construal would emphasize the details of an image, and therefore, would motivate a user to look closer by a desire to further interact with it through actions made possible with modern technology such as zooming and reorienting the image.

Aim of the study

The objective of the research is to explore how visual properties (i.e., shading, surface texture, and color) and content of biological representations relate to viewers' preferences, perceptions of realism and desire to explore further.

Materials and methods

Study design and visualization context

A survey study was conducted in which an electronic questionnaire was deployed in a science center context. Inspired by discrete choice experiments (Mangham et al., 2009), the questionnaire instrument exposed respondents to pairs of images and asked them to select one based on specified criteria. Volunteering visitors responded anonymously to the survey using a tablet placed in conjunction with a related interactive visualization exhibit called *Microcosmos*. The data were analyzed quantitatively in two steps. First, overall patterns in the responses were identified, and second, a predictive statistical model was tested to see if properties of the image could explain the observed patterns.

The Microcosmos exhibit is a digital touch table interface housed at the digital science center Visualization Center C in Sweden. The table provides public visitors with an opportunity to view and explore visual representations and images of biological structures and processes. One objective of the table is to provide visitors with access to (sub)microscopic biological images that are divorced from everyday visual perception. The embedded visual content of Microcosmos includes biological images and representations that visually communicate proteins, viruses, cells, molecules, genes, life processes, and disease. The visual content is represented at multiple levels of biological organization, and through various visual properties such as color, brightness, and contrast. The images cover abstract, stylistic, and realistic examples of biological representation and depict many of the biological representation conventions and formats typically used to convey biological phenomena. Visitors can select and explore the different representations through finger-based gestures.

Questionnaire design

A questionnaire was developed to probe visitors' perceptions and reactions to the images embedded in the Microcosmos table exhibit. Assessment of images consisted of participants responding to three questions, each of which required the participant to select one image from an image pair. The first question ("Which of the following two images do you prefer most?") was designed to elicit information about an overall preference. The second question ("Which of the following two images looks most like a real object to you?") was designed to probe participants' assessment of the relative realism of the images in terms of the extent to which the images give the impression of depicting something that physically exists. Thus, the formulation was not intended to induce respondents to evaluate the factual correctness of the images from a scientific point of view. The third question ("Which of the following two images would you like to continue exploring the most?") was designed to elicit a behavioral intention with respect to interactive exploration. Following each of the three forced-choice responses, the respondents were also asked to motivate their answers. **Figure 1** displays a screenshot of the survey screen interface.

Images from the Microcosmos exhibit were chosen for inclusion in the electronic survey based on their visual properties. Four main blocks of four images each were constructed. These consisted, respectively, of (A) images where shading, colors and surface texture created a clear sense of depth in the images; (B) images where colors and shading gave some experience of three-dimensional shapes, albeit clearly of a "flatter" nature than the previous group of images; (C) images where a "watercolor" style had been used and where a range of bright colors, but few depth cues, emphasized molecular and intracellular components (e.g., Goodsell, 2005); and (D) images that contained only a few colors and where no depth cues had been used. In addition, (E) one flat image in grayscale was included. Thus, a total of 17 images were included in five sets of images, which were used as blocks in the randomization of image pairs (see **Figure 2**). All possible 112 combinations of images between blocks were included in the randomization, while all combinations of images within blocks were excluded.

The questionnaire also included background questions, asking for each respondent's age and gender. Age was provided by selecting one of nine age ranges (consisting of "5 years or younger", "6 to 12 years", "13–20 years", "21–30 years", "31–40 years", and "71 years or older").

Data collection

The questionnaire was implemented as an anonymous electronic survey which science center visitors accessed via a tablet mounted next to the Microcosmos exhibit. Informed consent was provided by a text on the start screen that informed participants about the research, and that by responding to the questions, they gave their permission for us to use their responses in the research project. Due to the anonymous, unsupervised, and participant-initiated data collection procedure, it was not possible to collect informed consent from caretakers of any minors that may have responded to the questionnaire. Therefore, we only included data from persons whose stated age was above 20 years in the research. Once initiating the questionnaire, participants could choose to continue or simply discontinue their participation.

Data were collected during a period of 8 weeks. During this time the survey was activated 275 times, yielding a total of 94 complete responses in which respondents aged more than 20 had answered each of the three image selection questions. Each displayed image pair was generated from a randomized list of pairs. The electronic survey form reset automatically after each complete survey response or reset after 2 min of inactivation. The survey software was written with the CakePHP framework and the obtained response data was stored in a local MySQL database on campus.

Data analysis

In a first step, a ranking of the images was constructed for each variable (i.e., image preference, perceived realism, and desire to explore) based on the responses. For each image, the fraction of responses where a user selected that image was calculated across all cases where that image was one of the offered options. Thus, each image was associated with three values in the range 0–1, one for each of the three variables (see **Table 1**). A value of 1 indicated that an image was always selected, irrespective of what other image it was combined with, while a value of 0 would show that the image was never selected. To compare how the scores and the resulting ranking of images related to each other and to findings from usage statistics from the Microcosmos exhibit, Spearman's rank correlation was calculated between the scores for image preference, perceived realism, desire to explore, and relative ranking of the individual images based on data from a previous study (Höst et al., 2018).

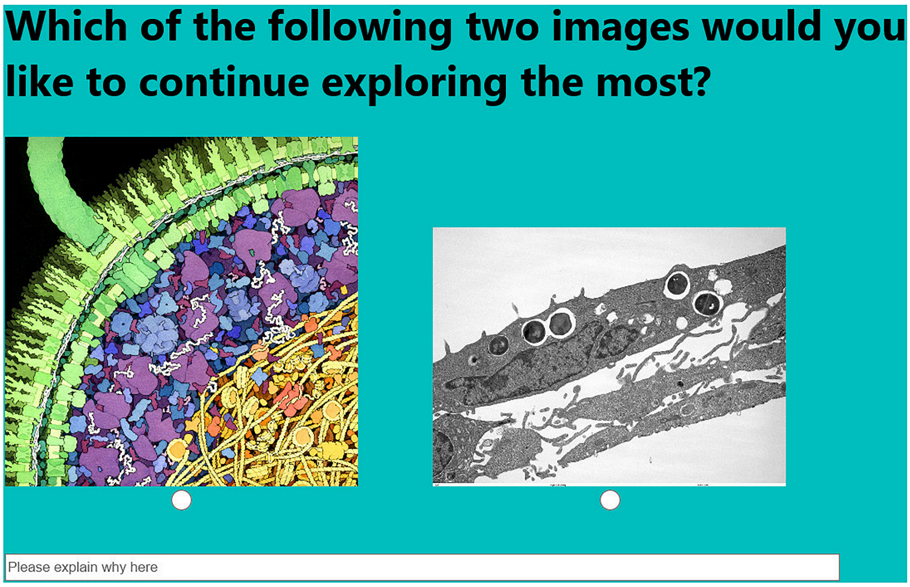

FIGURE 1
Screenshot of the data collection interface, with one example of a pair of images taken from the Microcosmos exhibit (Höst et al., 2018). In this example, participants are asked to indicate which image they would like to explore further, as an indication of their interaction intention.

TABLE 1 Fraction of times each image was selected out of the total number of times it was shown.

Image	Prefer	Realism	Explore
A1	0.36	0.63	0.62
A2	0.43	0.82	0.63
A3	**0.17**	0.75	0.60
A4	0.67	**0.85**	**0.75**
B1	0.50	0.43	0.44
B2	**0.89**	0.75	0.73
B3	0.50	0.22	**0.27**
B4	0.50	0.43	0.56
C1	0.45	0.53	0.64
C2	0.67	**0.00**	0.50
C3	0.25	0.29	0.47
C4	0.36	0.62	0.38
D1	0.62	0.25	0.33
D2	0.58	0.50	0.38
D3	0.70	0.29	0.33
D4	0.36	0.30	0.33
E1	0.38	0.46	0.47

Highest and lowest values are indicated in bold.

Image descriptors were defined to represent realism and content using a coding scheme. Each image was assigned a value for three different aspects of what the literature suggests may contribute to the perceived realism of an image (e.g., Rademacher et al., 2001). The shadows variable describes how light interacts with the objects in the image, while the surface roughness variable describes the degree to which the surface appears to contain microstructures and other discontinuities, and color variance describes the variability of the colors in an image. Codes were assigned in the form of values according to the following code definitions, which were developed iteratively.

Shadows

None (value 0) – There is no apparent effect from the positions and shapes of objects in the image on how the light appears to interact with the objects. There are no shadows or other depth cues in relation to the spatial positions of objects. *Darkening/unfocused depth cue or directional light* (value 1) – There are indications of depth in the image, even though they may be inconsistently applied throughout the image space. For example, this can be achieved by making objects that lie "deeper" in the image darker or unfocused. There could also be indications that light comes from some direction, which can be shown by one side of an object being darker (orientated away from the light source) than another side (orientated toward the light source). *Casting shadows* (value 2) – Objects clearly and consistently cast shadows on themselves and on each other. Shading may also indicate complex surface structures of an object through progressively darker shading in deeper cavities (e.g., "ambient occlusion" rendering).

Surface roughness

None/regions of same color (value 0) – The surface does not have any indication of structure, other than perhaps surface areas that differ in color from one another. *Gradients* (value 1) – Surface structure is consistently indicated by smooth gradients in color or shade. *Textured surface* (value 2) – The surface has fine-grained variability that gives the impression of microstructures that contributes to a more or less "rough" appearance.

Color variance

Monochrome/single color (value 0) – The image only depicts objects using one color. This can be a true monochrome depiction with only a single color against a uniform background, or it could be different shades of a single color. *Simple colors (multicolor with few shades)* (value 1) – Few colors are used and they appear in only a limited number of different shades. *Complex colors (multicolor with many shades)* (value 2) – Multiple colors are used and appear in multiple shades.

In addition, the content of each image was coded using the following dichotomous variables (using 0 = no, 1 = yes): Virus (image includes one or more viruses); Cell (image includes one or more cells), Molecule (image includes one or more molecules), Imaging data (image is directly based on output from imaging measurements such as electron microscopy). The images employed and the corresponding codes are provided as **Supplementary Material** to this article.

In a second step, binary logistic regression (Tabachnick and Fidell, 2014; Field, 2018) was used to investigate the importance of the image properties for respondents' decisions. A new dependent variable was constructed, where each participant decision was coded as 1 if the chosen image had a higher-ranking score (see **Table 1**) than the image that was not chosen, otherwise it was coded as 0. Predictor variables that represented the realism and content aspects of the images were calculated by discerning the difference in variable value for each descriptor between the selected image and the unselected image in each displayed pair (Mangham et al., 2009). The predictor variables were entered in two steps. Firstly, models were assessed where only the three realism predictors were used, and secondly, the four content predictor variables were entered so that the model included all predictors. Model fits were compared to assess which of the models best explained the data.

All statistical analyses were performed using Jamovi 2.0 (The jamovi project, 2021). An alpha level of 0.05 was used throughout.

Results

A total of 94 anonymous participants completed the questionnaire (46 of which stated female gender, 37 male and 11 other/preferred not to answer). A large fraction of the possible 112 image pairs were included in the study; the data collection yielded data for 85 unique pairs (76% completeness) for the preference question, 87 unique pairs (78% completeness) for perceived realism, and 92 unique pairs (82% completeness) for desire to explore, respectively.

Overall patterns of preference, perceived realism and desire to explore

Table 1 shows, for each image and assessment question, how frequently that image was selected when it was displayed to participants. These fractions range between 0.17 and 0.89 for preference, 0.00–0.85 for realism, and 0.27–0.75 for desire to explore. Correlation coefficients were calculated for the three types of values in **Table 1** and the relative ranking of the same images observed in another study (Höst et al., 2018). As shown in **Table 2**, a statistically significant correlation was found between the scores for perceived realism and desire to explore. No other significant correlations were observed.

Influence of visual properties and biological content on image choices

Two sequential binary logistic regression analyses were performed for each discrete choice criterion (i.e., image preference, perceived realism, and desire to explore). In the first, predictor variables related to visual realism (i.e., shadows, surface roughness, and color variation) were entered. In the second, predictor variables related to the content (i.e., presence of viruses, cells, molecules, and imaging data) were inputted. The two models were compared to ascertain whether the content-related variables added predictive power to the model.

For preference, the model with only variables related to realism indicated that the shadow predictor variable was a significant and negative influence in the decision while the surface roughness predictor variable had a significant and positive influence (**Table 3**). These influences were retained in the full model, which also included the predictor variables related to content. In addition, the cell and molecule predictor variables also became significant, with positive influence on the decision. The full model was found to provide a better fit for the data ($\chi^2 = 14.4$, df = 4, $p = 0.006$) and is therefore interpreted. The model with all predictors was statistically significant and classified 81.9% of the cases correctly. There was a significant relationship between selecting an image with a higher preference score and the predictors in the model ($\chi^2 = 36.1$, df = 7, $p < 0.001$). Nagelkerke's R^2 was 0.456.

In summary, relatively higher values for shadow decrease the probability that an image with a higher-ranking score will be selected, while increased values for surface roughness, cell and molecule increased the probability. This indicates that among the realism predictor variables, the presence of shadows and surface roughness, but not variation in color, are important determinants of participants' preferences. Likewise, the presence of cells and molecules, but not viruses or measurement data, are important determinants of what image participants prefer.

In the case of perceived realism, the model with only predictor variables related to realism indicated that the three

TABLE 2 Spearman's rho correlation coefficients between image scores for preference, realism, desire to explore and relative ranking in previous data (Höst et al., 2018).

	Preference	Realism	Desire to explore	Relative ranking in Höst et al. (2018)
Preference	–			
Realism	−0.17 (p = 0.526)	–		
Desire to explore	0.03 (p = 0.899)	0.74 (p < 0.001)	–	
Relative ranking in Höst et al. (2018)	−0.272 (p = 0.290)	−0.05 (p = 0.859)	0.02 (p = 0.940)	–

Correlation coefficients are given with *p*-values for statistical significance in parenthesis.

TABLE 3 Binary logistic regression analysis of participants' image preferences.

							95% Confidence interval	
	Predictor	Estimate	SE	Z	p	Odds ratio	Lower	Upper
	Intercept	0.90	0.27	3.39	< 0.001	2.47	1.46	4.20
Model 1	Shadows	−0.84	0.27	−3.13	0.002	0.43	0.26	0.73
	Surface roughness	0.58	0.22	2.64	0.008	1.79	1.16	2.75
	Color	0.10	0.31	0.32	0.749	1.11	0.61	2.05
	Intercept	0.81	0.30	2.73	0.006	2.24	1.26	4.01
	Shadows	−1.03	0.35	−2.94	0.003	0.36	0.18	0.71
	Surface roughness	1.09	0.43	2.51	0.012	2.98	1.27	6.96
Model 2	Color	0.34	0.43	0.79	0.430	1.40	0.61	3.21
	Virus	−1.12	0.62	−1.82	0.070	0.33	0.10	1.10
	Cell	1.03	0.48	2.13	0.033	2.81	1.09	7.25
	Molecule	1.86	0.92	2.02	0.043	6.42	1.06	38.96
	Measurement data	0.82	0.73	1.13	0.266	2.28	0.55	9.47

predictors significantly and positively influenced the decision (Table 4). This influence was retained for shadows and color variation, but not for surface roughness, when the predictor variables related to content were entered. None of the content-related predictor variables had any significant influence on the decision. The full model was not found to give a better fit for the data (χ^2 = 4.33, df = 4, p = 0.363), and therefore the model with only variables related to realism were interpreted. The model with the three realism predictors was statistically significant and classified 92.7% of the cases correctly. There was a significant relationship between selecting an image with a higher preference score and the predictors in the model (χ^2 = 54.6, df = 3, p < 0.001). Nagelkerke's R^2 was 0.656.

In summary, relatively higher values for shadows, surface roughness and color variation increased the probability of an image with a higher-ranking score being selected, in turn indicating that all three dimensions were of importance in participants' assessments of which image looks more like a real object.

For desire to explore, all three predictors related to realism significantly and positively influenced the decision (Table 5) in the first model. However, when the content-related predictor variables were entered, only the shadows variable remained significant. In addition, the cell predictor variable showed a significant and positive influence on the decisions. The full model was found to give a better fit for the data (χ^2 = 16.2, df = 4, p = 0.003) and was therefore interpreted. The model with all predictors was statistically significant and classified 84.0% of the cases correctly. There was a significant relationship between selecting an image with a higher preference score and the predictors in the model (χ^2 = 60.5, df = 7, p < 0.001). Nagelkerke's R^2 was 0.664.

In summary, relatively higher values for shadows, but not surface roughness or color difference, increased the probability of participants selecting an image. The presence of cells was also important for participants' desire to explore an image.

Discussion

The underlying hypothesis that guided this research was the idea that perceived realism in a biological image would make participants more interested in exploring that image. The hypothesis is supported by the revealed positive correlation between image scores for perceived realism and desire to explore. In turn, this indicates that if an image tended to be

TABLE 4 Binary logistic regression analysis of participants' assessment of whether images look like real objects.

	Predictor	Estimate	SE	Z	p	Odds ratio	95% Confidence interval	
							Lower	Upper
	Intercept	1.36	0.41	3.3	<0.001	3.91	1.75	8.75
Model 1	Shadows	0.71	0.35	2.1	0.039	2.03	1.04	4.00
	Surface roughness	0.76	0.29	2.65	0.008	2.13	1.22	3.73
	Color	1.96	0.59	3.31	<0.001	7.10	2.22	22.67
	Intercept	1.41	0.45	3.12	0.002	4.08	1.69	9.89
	Shadows	1.22	0.54	2.27	0.023	3.37	1.18	9.63
	Surface roughness	0.41	0.43	0.96	0.338	1.51	0.65	3.52
Model 2	Color	1.95	0.69	2.84	0.004	7.01	1.83	26.86
	Virus	0.60	0.76	0.80	0.424	1.83	0.42	8.03
	Cell	−0.55	0.86	−0.64	0.522	0.58	0.11	3.11
	Molecule	−1.36	1.25	−1.09	0.275	0.26	0.02	2.94
	Measurement data	0.24	1.10	0.22	0.827	1.27	0.15	10.85

TABLE 5 Binary logistic regression analysis of participants' desire to explore images.

	Predictor	Estimate	SE	Z	p	Odds ratio	95% Confidence interval	
							Lower	Upper
	Intercept	0.65	0.30	2.18	0.029	1.91	1.07	3.43
Model 1	Shadows	0.86	0.30	2.91	0.004	2.37	1.33	4.24
	Surface roughness	0.48	0.23	2.13	0.033	1.62	1.04	2.51
	Color	1.15	0.38	3.03	0.002	3.16	1.50	6.66
	Intercept	0.62	0.35	1.80	0.072	1.86	0.95	3.66
	Shadows	1.12	0.37	3.01	0.003	3.06	1.48	6.35
	Surface roughness	−0.38	0.47	−0.80	0.424	0.69	0.27	1.73
Model 2	Color	0.79	0.48	1.63	0.102	2.20	0.85	5.69
	Virus	0.78	0.60	1.30	0.192	2.18	0.68	7.03
	Cell	2.06	0.70	2.94	0.003	7.88	1.99	31.13
	Molecule	−1.09	1.16	−0.94	0.345	0.34	0.03	3.24
	Measurement data	−0.54	0.90	−0.60	0.548	0.58	0.10	3.41

selected as being most like a real object, it would also tend to be selected as the one which is most inviting for further exploration. In terms of image properties, the presence of shadows predicted both perceived realism and desire to explore an image further (**Table 6**). This indicates a potential link between what makes persons perceive an image as depicting a real image and what makes it attractive for further exploration. Certainly, given two images, more use of shadows in one of them is the only factor of the three related to visual realism that would increase the probability of that image being chosen for further exploration. Furthermore, the presence of cells in one but not the other image would increase the probability of that image being chosen for further exploration. Thus, the depicted content of an image is clearly important for a person's interest in exploring that image, while the depicted content is not critical for perceiving something as a real object.

Given two images, more use of shadows, surface roughness and color variation in one of the images would increase the probability of that image being chosen as being most like a real object. In this regard, the findings corroborate suggestions from the literature that shadows, surface roughness and color variation are important for perceiving an image as a depiction of a real object (e.g., Rademacher et al., 2001; Wang and Doube, 2011). In this line, recent work indicates that it should not merely be assumed that realistic images are superior for retention of information or for applying knowledge from one context to another. The benefit of realistic representations is dependent on the nature of the foreseen interpretation task, with a particular advantage when the intention is for the viewer to remember or learn surface details (e.g., Skulmowski, 2022). Moreover, Sayim and Cavanagh (2011) have shown that a viewers' recognition on an image such as

TABLE 6 Summary of findings from binary logistic regression analysis.

	Preference	Perceived realism	Desire to explore
Shadows	–	+	+
Surface roughness	+	+	0
Color variation	0	+	0
Virus	0	0	0
Cell	+	0	+
Molecule	+	0	0
Measurement data	0	0	0

For each predictor variable, positive (+), negative (−), and neutral (0) influence are indicated for the assessment of the relative preference, perceived realism, and desire to explore, respectively.

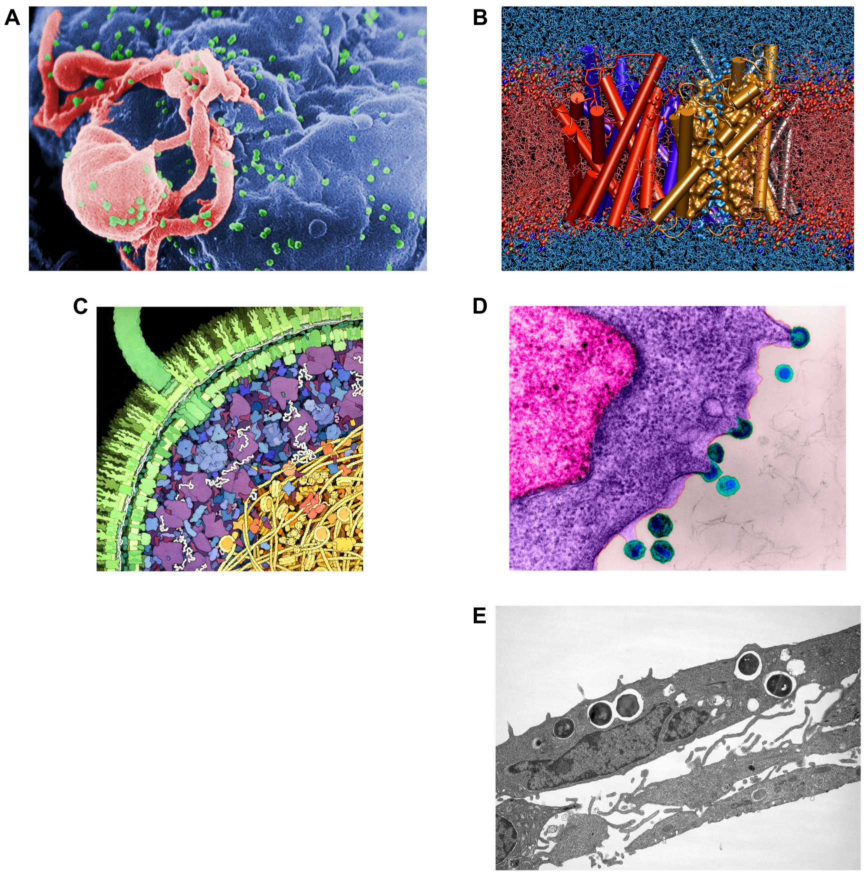

FIGURE 2
Example images from each of the five blocks **(A–E)** of images that were included in discrete choice-inspired comparisons. Block **(A)** The example image depicts HIV viruses budding from a lymphocyte cell. Credit: Photo Credit: C. Goldsmith, Content Providers: CDC/C. Goldsmith, P. Feorino, E. L. Palmer, W. R. McManus. Block **(B)** The example image shows the water transport protein aquaporin together with a plasma membrane and water molecules. Credit: Emad Tajkhorshid, NIH Center for Macromolecular Modeling and Bioinformatics, University of Illinois at Urbana-Champaign. Block **(C)** The example image illustrates a part of an *Escherichia coli* cell in cross-section. Credit: David S. Goodsell, the Scripps Research Institute. Block **(D)** HIV viruses released from human lymph tissue. Credit: Dennis Kunkel microscopy/Science Photo Library/IBL. Block **(E)** The example image shows *Staphylococcus aureus* infection in lung cells. Credit: Todd Jarry, Ambrose Cheung, Louisa Howard.

abstract sketch or line drawing is closely related to memory. If an abstract line drawing is interpreted as familiar, memory inputs the missing details pertaining to depth and surface texture, also often resulting in a three-dimensional interpretation.

In a preceding study, we analyzed science center visitors' use of the Microcosmos exhibit (Höst et al., 2018). The findings concluded that visitors tended to engage more with images that portrayed viruses, were colorful and represented imaging output. None of these variables were revealed in the present study as significant influences on participants' choice in relation to further exploration. In addition, no correlations were found between relative ranking in the previous study and the values for desire to explore in this study. It is likely that the differences in the respective "choice situations" may explain this discrepancy. In this study, inspired by discrete choice experiments, image pairs were systematically varied to allow participants to make direct choices between widely differing images. In contrast, the Microcosmos exhibit was organized by content topic, so that visitors would decide to interact with a particular image in the context of other thematically related images (e.g., virus images, depending on what theme was selected).

When it comes to results regarding participants' image preferences, these appear to be influenced in a complex way by multiple characteristics. Clearly, the pattern of influence of the predictors is not the same as for perceived realism or desire to explore (**Table 6**). Given the relatively low model fit for this data, it seems that the individual esthetic judgments involved in the decisions of which image participants preferred cannot be adequately captured by the relatively simple image characterization used in this study. In this regard, Skulmowski (2022) has recently shown that the benefits of realism appear highly dependent on the situation and calls for continuing research into identifying what fine-grained realistic features support or hinder perception.

In the present study, data were collected without supervision in an authentic environment. While this reduced our control of the process, it may contribute to ecological validity that would be lacking in a more clinical laboratory setting. Nevertheless, supervised data collection wherein science center visitors are approached to respond to the survey could serve to increase the number of participants and provide better insight into who responded. The authentic context also limited the selection of images used in the study, given that it was premised on examining participants' perceptions of the images that were present in the adjacent Microcosmos exhibit.

The hypothesis that images depicting entities that look like real objects would be preferred for further exploration was based on construal level theory (Trope and Liberman, 2003). The perceived realism was intended to capture the hypotheticality dimension of psychological distance (Trope and Liberman, 2010), which asserts that real objects are associated with a shorter psychological distance than imagined objects. The logic is that the lower-level construal resulting from an object perceived to be real would focus participants more on the details and concrete aspects of the image, which would invite them to explore the image in more detail by, for example, observing it for a longer period or focusing on specific parts.

While the findings can support the above interpretation, there are of course other avenues through which properties of the images could influence a person's tendency to approach the content at different construal levels. For example, differences in prior information about the portrayed object may be associated with different psychological distances (informational distance) (Fiedler, 2007). In a science communication context, this would make the scientific prior knowledge about the content of the biological images important (e.g., Eilam, 2013) and could perhaps explain the finding in this study that the presence of cells, which may to some extent be a known biological object to most adults, are associated with a desire to continue to explore. In addition, biological content knowledge would also be associated with a more developed visual literacy regarding scientific communication, which could have important consequences for how the images are processed. Duan and Bombara (2022) found that visual literacy moderates the effect of climate change images that differ in the level of abstraction. For less visually literate participants, abstract images were associated with perceiving a longer psychological distance, and vice versa, while this effect was absent for more visually literate participants. Hence, scientific pre-knowledge, including familiarity with disciplinary representational conventions, is an interesting parameter to include in future studies that can build on what is already known in the visual literacy literature (Schönborn and Anderson, 2010).

The findings of this study may have implications for practitioners in public science center exhibits. Given the importance of self-guided interactive exploration in modern science communication venues, inviting visitors to start exploring exhibits is very important. In this regard, the results could indicate that depictions that look like real objects may be associated with a stronger attractive power. In addition, the findings relate to the pedagogical discussion of whether science learning is best served by introducing realistic images early or if it is more beneficial to start with schematic visuals in the classroom (e.g., Menendez et al., 2022). The observed tendency to prefer exploring realistic images could indicate that such images may be a plausible starting point from a motivational perspective. However, research that analyzes the connection between scientific image properties, construal level, and learning-related behaviors is only in its infancy. Future research could explore a wider range of authentic images as well as systematic variation of realism indicators in a synthetic dataset (e.g., Skulmowski et al., 2021). In combination with further unpacking how biological visual images might shape viewers' visual narratives (e.g., Callender et al., 2020), future work could also investigate the interplay between visualizations and construal level in other science education fields, for example astronomy. Such studies could also widen the methodological repertoire to include eye-tracking techniques for example (Gong and Chu, 2022).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

GH, KS, and LT conceptualized the study design and the data collection procedure. GH conducted the primary analysis and drafted the first version of the manuscript. KS performed the synthesis of the current state of the art. GH and KS revised and finalized the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Greek Upper Primary Grade Students' Images About Science and Scientists: An Alternative Descriptive Piece of the Puzzle

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This study examined the perceptions of upper primary grade level students about science, scientists, and their work. Participants were 284 fifth- and sixth-grade students (aged 10–12) from six urban areas of Attica (Greece). An open-ended questionnaire was employed for data selection. Students' responses were analyzed both qualitatively (through thematic analysis) and quantitatively. The findings suggest that the participants in this study hold distinct perceptions of what science is, who a scientist is, and how science is done. Although most students referred to science and scientists in a positive light, our findings suggested that they held traditional and narrow perceptions of such issues (e.g., a scientist is a brilliant, talented person who works in natural sciences, science is a contributor to human welfare, or science is a product). Our data also suggested that the students could not make a clear distinction between science and technology, concepts that were used interchangeably in our study. Educational implications that may help breaking these naïve perceptions were discussed.

Keywords: perceptions about science, perceptions about scientists, science, primary school, students, stereotypes, Greece

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INTRODUCTION

Investigating Students' perceptions of science and scientists is an extremely fruitful field of research, and has long been of constant interest to scientists, researchers, and scholars. Knowing how students perceive science and scientists is considered important as these perceptions affect future academic and career choices (Garriott et al., 2017; Christidou et al., 2021). Many stakeholders have already expressed their concerns about the low participation rates of students studying science at the secondary/university level (Scholes and Stahl, 2020). Recent studies have also shown that the demographics of people working in STEM fields doesn't reflect inclusiveness and equality of access (Scott, 2018; Segarra et al., 2020; Shepherd et al., 2020; Cech and Waidzunas, 2021; Fry et al., 2021) and that there is a *"shortage of scientific personnel"* internationally (Meyer et al., 2019; Walls, 2022). With most countries recognizing the economic and social benefits of having scientifically engaged citizens, efforts to increase the number of individuals involved in science are a central issue in many state's central education policy (Shin et al., 2015; Chen, 2019).

In this context, students' perceptions about science and scientists are considered as a useful diagnostic tool that shows how they learn and think about science (Zimmerman and Bell, 2014), and a first step in capturing the views they have about *"who becomes a scientist," "who works in science," "what science is,"* etc. (Thomson et al., 2019). As research shows, boys and girls make decisions about science careers long before they graduate from college, so understanding early their views about science and their opinions of scientists is critical (Farland-Smith and Ledger, 2018). Furthermore, it is supported that if children do not form positive views about science and scientists throughout their primary school years, they are not likely to do so in secondary school and beyond (Smail, 1993; Grossman and Farland-Smith, 2021).

This paper examines these issues for primary school students enrolled in Greek schools. Based on our review, existing research in Greece is relatively limited and focuses on Students' drawings of scientists and their work, by using various versions of Draw-A-Scientist Test (DAST) (Chambers, 1983) tool (Christidou et al., 2012, 2021; Emvalotis and Koutsianou, 2018). Our approach, unlike the previous ones, adopted an open-ended questionnaire to gather data and a more qualitative data analysis framework for examining Students' responses. We believe that our results will expand the findings obtained in previous studies, providing a more comprehensive characterization of Students' views.

LITERATURE REVIEW

Students' Perceptions About Science

Although many studies have investigated perceptions about science of high school students (Songer and Linn, 1991; Griffiths and Barry, 1993; Griffiths and Barman, 1995; Tsai, 1998; Shi, 2021), college/university students (Liu and Tsai, 2008; Vhurumuku, 2010; Sangsa-ard et al., 2014; Akgun and Kaya, 2020), and science teachers (Abell and Smith, 1994; Leblebicioglu et al., 2021) in both Western and non-Western countries, only a limited number of studies have focused on primary school Students' perceptions about science (e.g., BouJaoude and El Khalick, 1995; Stein and McRobbie, 1997; Kang et al., 2005). In what follows, we present these studies in more detail.

One of the most widely cited studies investigating how students view science is the one conducted by Driver et al. (1996) with primary and high school students (ages 9, 12, and 16) in England. The researchers interviewed same-age pairs of students about their conceptions regarding the purposes of science. They also investigated the extent to which students understand science as a social enterprise. The authors analyzed the data and found that the young students tended to see science as an approach *"providing solutions to technical problems"* (p. 138). It was also shown that students rarely see science as a social enterprise, as they believe that scientists are working in isolation, and that they solve their scientific controversies based (mostly/only) on empirical evidence. Finally, the findings outlined that students perceive science as a process related to the natural sciences.

A similar study conducted by BouJaoude and El Khalick (1995) explored how Lebanese students (N = 80, ages 11–13) define the concept of science. The researchers also investigated Students' perceptions of its usage and its purpose. The students asked to fill out a questionnaire with open-ended questions and to participate in semi-structured interviews, which were based on the following question scheme: *"What is the definition of science?," "What comes to your mind when you hear the word science?," and "What is the purpose of science?."* The findings (from their thematic analysis) showed that the responses of students could be grouped around six core themes (in descending order of percentages): science is *"a course that provides information about humans, animals, plants, earth, sky and stars," "a subject that is divided into other subjects such as physics, chemistry and biology," "a method for doing things," "a subject to teach new things," "a subject that enlightens and gives the truth about nature,"* and *"a subject we study in the classroom."* Regarding the Students' perceptions of the purpose of science, the themes that emerged from the Students' responses (presented in descending order of frequency) were the following: the purpose of science is related to *"academic preparation," "preparation for future careers," "achieving higher social status," "helping people in solving everyday problems," "discovering new things,"* and *"helping people to appreciate and understand nature."* As shown, most of the students defined science as an academic subject and found science useful in terms of preparation for a higher social status. Finally, students stated that science is applied mostly in an academic setting rather than in everyday situations.

In another study, Stein and McRobbie (1997) explored the perceptions of fourth- (N = 20), seventh- (N = 30), ninth- (N = 33), and eleventh- graders (N = 68) attending Australian schools. Students were engaged in half-hour free-writing meetings, discussing the question *"What is science?"* The analysis of the data was done qualitatively through the phenomenological approach. The results of the analysis revealed six categories that described six different perceptions of the concept of science by students (presented from the most unsophisticated to the most sophisticated): science *"as something that is done or learned in school," "as a consumable product," "as a study of the world," "as a process," "as a dynamic knowledge,"* and *"as something that is influenced by the social context."* The results showed that the fourth-graders (9–10 years old) contributed mostly to the first and fourth categories, which reflect conceptions about science that are limited to school science experiences such as specific courses or laboratory activities. Regarding seventh-graders (12–13 years old), the results showed that their answers were limited to the first four categories, with no references to categories five and six, which were perceived as more informed.

Harwell (2000) assessed female ninth-graders' (N = 217) perceptions about science by asking them *"What is science?"* She used Rubba and Harkness (1993, 1996) framework to qualitatively analyze Students' responses under three categories: "*realistic*" (if the response expressed an appropriate view), *"has merit"* (if the statement expressed some acceptable aspects), and *"naïve"* (if the response expressed a view which was inappropriate). The majority of the answers (94%) were categorized as *"naïve"* (including responses that referred to science as a study of subjects or fields; carrying out experiments;

inventing or designing things; finding and using knowledge to make a world a better place). Other girls' responses (5%) were categorized as *"meritorious"* (including answers that referred to science as a body of knowledge that explains the world around us; exploring the unknown; discovering new things: organization of people who have ideas and techniques for discovering new knowledge). Only 14 participants (7%) referred to science through a *"realistic"* viewpoint (including references to science as a systematic, investigative process and the resulting knowledge). The perceptions of the girls in this study indicated a *"naïve"* grasp of science which reflects the tendency of students to view the purpose of science as giving answers to technical problems rather than giving explanations about the world around us (Driver et al., 1996).

Similarly, Elder (2002) explored the perceptions of American primary school students ($N = 211$, ages 10–11) about the concept of science by asking the following open-ended question: *"What do you think science is?"* Thematic analysis was used to analyze the answers of students. The responses were grouped under three categories: "*poor,*" *"fair,"* and "*good.*" The first category (*poor*) incorporated answers stating that science is an end product or that science is a subject to be learned. In the *"poor"* theme, the author categorized unrelated ideas or vague descriptions as well. Second, the category of "*good*" answers included the responses that showed an advanced understanding of the purpose of science (e.g., science is explaining phenomena or science is a learning process). Finally, in the category of *"fair"* answers were placed the responses that were neither developed nor undeveloped. Based on the data, the author found that the three quarters of the students hold a *"poor"* or *"fair"* understanding of the purpose of science.

In a similar study, Kang et al. (2005) explored the perceptions of Korean students ($N = 534$, age 12) about science. The students were asked to choose which (of the four) option best completes the following sentence: *"Scientists are those who are working on science. To put scientist work in brief, it is...."* The results showed that the majority of sixth-graders considered science to be a process by which scientists *"invent things to make the world a better place to live in"* (naïve perception). The researchers supported that this trend may arise because students may confuse science with technology (the achievements of which facilitate our everyday life). The second most common Students' choice was the *"science is about making new discoveries and adding them to the knowledge of nature."* Finally, the choice *"with science we are investigating natural phenomena and we are explaining the reasons for those phenomena"* (reflecting the developed perception) was preferred by only a minority of students. Overall, the research results showed that few students had developed perceptions of the concept of science, while the majority of them had poor perceptions that (as researchers suggested) may arise from a confusion between science and technology.

In summary, our review revealed that very often students perceive science as something valuable to society, since it solves problems and produces goods that are consumed by humans. It could be said that such perceptions are reflecting a utilitarian/instrumentalist view of science (Park and Lee, 2009) and indicating a way of thinking that conflates science and technology to the point where there is little or no separation between them (Constantinou et al., 2010). The literature review also showed that Students' conceptions about science are often limited to school science experiences. It is also indicated that students very often contextualize science as a school-related phenomenon. As relevant studies suggest, the above findings represent naïve (unsophisticated) perceptions about science (Ryan and Aikenhead, 1992; Holbrook and Rannikmae, 2007).

Students' Perceptions About Scientists and Their Work

Empirical studies conducted in this research field have a long tradition. One of the seminal studies that investigated Students' perceptions of scientists and their work was published by Mead and Métraux (1957) 60 years ago. In their research, 35,000 students attending high schools in the United States were asked to describe their views about science and scientists by completing open-ended sentences. The analysis of Students' responses showed that participants used positive (brilliant, dedicated, essential, etc.) and negative (antisocial, lonely, isolated, etc.) descriptions about scientists. Although the results were enlightening, their qualitative tool was criticized due to (a) the demanding analysis of the data it required and (b) the difficulty that students encountered when verbalizing their descriptions (Schibeci and Sorensen, 1983; Finson et al., 1995).

To overcome these constraints, Chambers (1983), based on Mead and Métraux's (1957) findings, suggested the "Draw-A-Scientist-Test" (DAST) (Chambers, 1983), which is a simple, open-ended projective test that asks people to draw a scientist on a blank sheet (Samaras et al., 2012; Haeusler and Donovan, 2020). Few years later, in order to investigate more systematically the stereotypical characteristics portrayed in children's drawings of scientists, Finson et al. (1995) developed the "Draw-A-Scientist-Checklist" (DAST-C). This checklist provided researchers with a set of stereotypical indicators (Lab Coat, Eyeglasses, Moustache, Laboratory Equipment, etc.) that allowed easy data collection and analysis of Student's drawings. DAST and DAST-C have been used in a plethora of studies worldwide (e.g., Chionas and Emvalotis, 2021; Christidou et al., 2021; Barakat, 2022; Jones and Hite, 2022) and are considered as two of the most well-known, validated tools in the field. It is true that compared to other tools they have significant strengths as: (a) they rely on non-verbal/non-written forms of communication (drawings), which makes them ideal for use with very young participants, (b) they provide the opportunity for easy comparison of different languages, and (c) they require a straightforward data collection process that does not need special experience (Finson et al., 1995; Reinisch et al., 2017; Lamminpää et al., 2020). As a consequence, DAST and DAST-C (and their modified versions, e.g., Farland Smith, 2012; Christidou et al., 2021) have dominated research focusing on the exploration Students' perceptions of scientists.

Systematic reviews regarding DAST studies (e.g., Finson, 2002; Ferguson and Lezotte, 2020) confirm that students, for more than 30 years, are holding common narrow images of scientists, regardless of their background (Students' age, nationality, culture, gender) (Emvalotis and Koutsianou, 2018; Meyer et al., 2019; Bozzato et al., 2021; Karacam et al., 2021; Leavy and Hourigan, 2021). As research findings highlight, students (very often) draw scientists as bald, middle–aged men with facial hair using test tubes, wearing laboratory coats, carrying out dangerous experiments, working indoors, etc. (Newton and Newton, 1998; Koren and Bar, 2009; Christidou et al., 2012; Emvalotis and Koutsianou, 2018). These results are considered extremely valuable, as they reflect the predominant way children perceive scientists (Chionas and Emvalotis, 2021).

Specifically, in Greece, although the published DAST studies are limited, their results are quite consistent, since almost all of the DAST-C indicators (with slight differences in percentages) are present to some extent, in Greek primary Students' drawings. For example, Samaras et al. (2012) found that primary school students view scientists in a rather stereotypical way, as they mainly depicted them as males who wore glasses and lab coats, and worked in a laboratory setting, which is relevant to natural sciences. Christidou et al. (2012) found that although students used less stereotypical indicators on average than in Samaras et al. (2012), a strong gender stereotype emerged once more, i.e., the majority of students (despite their gender) drew mostly male scientists. What was also interesting in that study was that many students depicted scientists working in the field rather than in a laboratory setting, a result that contradicted Samaras et al.'s (2012) study. More recently, Christidou et al. (2016) found that lower primary school students in Greece used less stereotypical indicators regarding scientists' outfit compared to gender and workplace indicators. The results indicated that most students drew young male scientists wearing casual clothes, without glasses, working in isolation in a laboratory. Emvalotis and Koutsianou (2018) found that Greek students mostly drew male scientists working in a chemistry laboratory, whereas almost half of the students drew scientists wearing lab coats. As the authors highlighted, Greek students in recent years have the tendency to represent scientists wearing casual clothes, with no mustache, beard, or glasses. On the other hand, the Greek participants still hold the narrow image of the chemist who performs experiments and works in isolation. Christidou et al. (2021) assessed Greek primary school Students' images of scientists from a different perspective. They focused on a systematic investigation of scientists' emotions as depicted by children in their drawings. The results showed that scientists were mainly depicted with pleasant, smiling expressions and positive emotions such as pride and happiness, which means that children tend to attribute positive characteristics to scientists' personalities. On the other hand, some participants associated scientists with negative emotions such as anger, anxiety, fear, and sadness, which suggests that students may understand the multidimensional nature of the scientific endeavor. Finally, few children depicted an emotionless scientist.

Although the draw-a-picture approach is a useful technique for investigating perceptions about science and scientists (Padwick et al., 2016), it has some notable drawbacks. For example, researchers doubt whether students portray a particular type of scientist intentionally or they do so because they do not have the drawing skills to portray them differently (Sumrall, 1995; Haeusler and Donovan, 2020). Moreover, it is supported that children may depict sketches that they believe will be easily recognizable by researchers, making them not that authentic (Finson and Pederson, 2011). Furthermore, DAST findings are considered limited, as they do not represent the whole range of student perceptions of scientists (Barman, 2009). As Christidou et al. (2021) highlighted: "*identifying the elements in children's drawings that indicate stereotypic images, sheds light only on part of their thinking and overall mindset*" (p. 3). Students may hold multiple and more complex perceptions of scientists than those depicted in their drawings (Avraamidou, 2013; Nowell et al., 2017). Finally, this method is not sensitive to the identification of personality traits and skills of the scientist, as it focuses mainly on different indicators, as cited above.

Taking these limitations into account, researchers turned to alternative approaches such as interviews (Padwick et al., 2016), questionnaires (Song and Kim, 1999; Özgelen, 2017; Kenneth Jones and Hite, 2020), word association tests (Ateş et al., 2021), biographies analyses (Dagher and Ford, 2005), diamond nine based sorting activities (Padwick et al., 2016) or mixed DAST methods (Farland-Smith and Ledger, 2018). Since such methodological options have a more open approach than the predefined indicators used in DAST-C, their results are quite interesting and fruitful.

For example, Song and Kim (1999) investigated Korean Students' perceptions (N = 1,137, ages 11, 13, 15) about scientists, through a 12 five-point semantic differential scale which represented 12 characteristics of scientists (e.g., *careless—accurate, stupid—intelligent, lazy—industrious,* etc.). The results revealed that Korean students highly ranked scientists in the positive characteristics of the scale, such as intelligence, imagination, and accuracy (i.e., *imaginative, smart, accurate, responsible, and active* were scored positively), while they scored negatively ethical and affective aspects of scientists, as they ranked them high in selfishness and irreligiousness (i.e., *humanist, caregiver, open-minded, fascinating, and religious* were scored slightly negatively). As it was shown, Korean students saw scientists favorably in terms of cognition but negatively in terms of personality, spirituality, and creativity. It is worth noting that when students were asked to compare themselves to scientists, they ranked themselves lower in cognitive qualities but higher in effect and ethics, indicating that they feel largely different from them. Finally, when students were asked to write down the name of their favorite scientist, most of them listed male scientists who were Physicists (e.g., *Einstein, Bell,* etc.), reflecting that students tended to perceive scientists as males working in the natural sciences (Carli et al., 2016).

Walls (2012) examined African American Students' perceptions (N = 23, age 8) of scientists and science through an *"Identify-A-Scientist"* task alongside with interviews. The collected data were used to answer the following questions: *"What do scientists look like?" "What qualities do scientists possess?"* and *"What scientists do?"* The thematic analysis of Students' responses showed that the most frequent emergent themes regarding the appearance of scientists were (in descending order): *eyeglasses, professional attire, gender, lab* *coat, age/maturity*. The aforementioned findings showed that the participants' views about scientist appearance could be considered highly stereotypical, given that they were in line with the results of several related studies where similar narrow images about scientists were found (Chambers, 1983; Fung, 2002; Türkmen, 2008; Chionas and Emvalotis, 2021). Results also showed that the three most common traits that the students attributed to scientists were *intelligence, studiousness,* and *happiness*. Although these findings were promising, because they were highlighting a positive view on scientists' personality, it is not sure that they do not reflect (as well) the *"brainy and busy"* stereotypic image of scientists (Özgelen, 2017). Finally, regarding the question *"What scientists do?"* findings revealed that these students related the scientific endeavor with the act of *problem solving, inventing, discovering, experimenting,* and *teaching*. It is interesting to note that although the majority of these practices are taking place in a lab, which is the stereotypical working place of scientists (Ruiz-Mallén et al., 2018), responses of students categorized under the *"teaching"* theme revealed that these students also perceived that scientists can do their works in alternative settings/locations as well (schools, offices, and museums).

Padwick et al. (2016) collected data from students of seven primary schools located in the North of England (N = 350, ages 7–11). Researchers used the Diamond 9 technique (Clark, 2012) to investigate Students' perceptions about scientists. Diamond 9 is an activity in which people rank concepts, phrases, or images in the shape of a diamond and, in that sense, it allows the exploration of individuals' positions on a particular topic (Rockett and Percival, 2002). Regarding the procedure, students were given nine cards presenting nine different character aspects: *clever, cool, creative, kind, friendly, fun, hard-working, sensible, and strange*. At first, students should rank the words into a diamond shape, with *"least like me"* characteristics at the bottom and *"most like me"* traits at the top of the diamond. Afterward, participants should repeat the process, but their second diamond should refer to scientists' characteristics *("least like a scientist"* at the bottom and *"most like a scientist"* at the top). The results revealed that students tend to perceive scientists as *hard-working, clever,* and *creative*, while they do not view scientists as *strange, cool,* and *fun*. Interpreting the results, it could be noted that students have, to some extent, narrow perceptions of scientists such as that they are clever or that they are not funny and are not cool. On the other hand, Students' view scientists as not strange people, which is a result that is counter to the common view of scientists.

Kenneth Jones and Hite (2020) examined Korean Students' (N = 159, ages 5–19) perceptions of scientists by analyzing Students' open-ended answers to the question *"Write down three words that best describe a scientist."* Researchers used Morgenroth et al. (2015) *Motivational Theory of Role Modeling (MTRM)* as a theoretical framework for their study. Students' responses were thematically analyzed under the three core constructs of *MTRM*: *"goal embodiment"* (what scientists do), *"attainability"* (how scientists do it), and *"desirability"* (actions and qualities of scientists). Along with recognizing items that fit into one of the themes, the researchers developed a codebook determining whether Students' responses referred to a positive or negative indicators of each construct. For example, traits like *awesome* and *brave* were coded as positive aspects of the desirability theme while *boring* and *nerd* were treated as negative signs of desirability construct. Or, for example, science activities such as *experimenting, observing* etc. were categorized as positive *"goal embodiment"* aspects whereas *guns, poison, bomb making* were seen as negative aspects of that theme. Results showed high positive frequencies of the goal embodiment construct, and low positive frequencies for the attainability and desirability constructs which means that although, in general, students viewed scientists positively, working in science was not something attainable or desirable.

Another recent analysis conducted by Scholes and Stahl (2020) explored Australian fourth-graders' (N = 45, ages 9–10) perceptions of scientists, science and career in science. In that research, students were interviewed about several themes such as if they wanted to be scientists, what kind of work scientists do and how scientists might look like. The data were analyzed with thematic analysis under the following themes and sub-categories: (a) the *"stereotypical perceptions of scientist"* theme, which divided into *"non-gendered"* and *"paraphernalia"* categories, and (b) the *"non-aspiration to become a scientist"* theme, which separated into *"difficulties and pressure"* and *"science work as physically dangerous."* Results indicated that students used non-gendered language when talking about science and scientists (e.g., *"they"*), which suggests that there may be some reduction in the *"usually a man"* stereotype that students traditionally have about scientists. On the other hand, Students' perceptions of scientists remained grounded in the messy, clever, lab-worker image of a scientist who must work under pressure with specialized and dangerous equipment. According to the authors, these perceptions may reflect a slice of the underlying Students' ideas regarding the masculine characteristics that a scientist should have such as strength, bravery etc.

More recently, Hite and White (2022) investigated Hispanic fourth- and fifth-graders' perceptions of science and scientists before and after environmental after-school club participation. Researchers adopted both quantitative and qualitative techniques to address their research questions. In the qualitative part of their research students were asked to list three words that came to their mind when they thought about a scientist. To analyze the data, a four-theme framework was used. Specifically, Students' responses categorized under the *"positive"* (e.g., brave, dedicated, studious, creative, smart, intelligent, good), *"eccentric"* (crazy, hair, Einstein, serious, busy, specific), *"neutral"* (experiment, test, safety equipment, chemistry, observe, equipment), and *"sinister"* (potions, danger, monsters, aliens, explosives, poisons) themes. As results showed, almost half of the words students used referred positively to scientists. Regarding the categories *"eccentric"* and *"neutral,"* they gathered about a quarter of the Students' answers each. The fewest answers were grouped around the category *"sinister."*

In summary, our review revealed that very often students perceive scientists in a positive manner, but they traditionally provide negative descriptions as well. Although scientists are perceived as having positive characteristics in general (e.g., regarding their personality traits, skills, abilities), this does not necessarily mean that students view them in a non-stereotypical way. As cited above, many times students believe that scientists have some exceptional abilities and skills or that they are especially gifted individuals. On the other hand, students usually view scientists as crazy, anti-social and eccentric individuals. Overall, scientists are considered by students as people who think and act in a way that is different from *"normal"* people (Tintori and Palomba, 2017).

RESEARCH AIM AND QUESTIONS

The present study attempted to investigate Greek primary school Students' perceptions about science and scientists by applying a more qualitative analysis framework than previous studies. Specifically, in this study an open-ended written questionnaire was administered to fifth- and sixth- grade students and a novel thematic analysis framework was used.

The research questions, which the present study sought to answer, were:

(1) What are the perceptions of Greek fifth- and sixth-graders regarding science?

(2) What are the perceptions of Greek fifth- and sixth-graders regarding scientists and their work?

(3) Do common trends emerge amongst Students' perceptions of science and scientists and the images they have about these issues?

MATERIALS AND METHODS

Participants

The study was conducted using a convenience sample formed by 284 primary school students (137 girls and 147 boys, ages 10–12) from six primary schools located in southern parts of Attica in Greece. One hundred thirteen students were attending fifth grade (65 girls and 68 boys) and 151 students (72 girls and 79 boys) were attending sixth grade, during the 2018–2019 school year. The socioeconomic status of the students was medium. Consent was obtained from the school director and the Students' families.

Procedures

Student participants were administered a written assessment which included an open-ended questionnaire (see "Instruments" section). The instrument was administered by each classroom teacher, and the completion process lasted about half an hour with the presence of the teacher in the classroom. Efforts were made to ensure that teachers did not provide any information to the participants. Participation in this study was entirely voluntary, and each student was assigned a unique identifying number to ensure its anonymity.

Instruments

A questionnaire containing five open questions was developed for this research. These questions have been part of other research schemes in the past (e.g., Harwell, 2000; Lederman and Khishfe, 2002; Walls, 2012). Specifically, participants were asked to briefly describe what they thought science is (*"Could you briefly describe what you think science is?"*). *"Could you briefly describe a great scientific discovery you know about?"* was the second question administered to students. The third and fourth items asked participants to fill a short list providing three adjectives that they would use to describe a scientist, and three adjectives that they would NOT use *("What three adjectives would you use to describe a scientist?," "What three adjectives would NOT you use to describe a scientist?"*). The last question asked students to write about a great scientist they knew (*"Could you please name a great scientist you know?"*).

Data Analysis

The open questions generated qualitative data from children's own responses. Textual data were analyzed using the thematic analysis approach (Braun and Clarke, 2022). Our approach was inductive, as we developed codes and themes from the data content without trying to fit into existing coding schemes (Ho et al., 2017). However, our academic and personal interests meant that analysis has been somewhat deductive (Nowell et al., 2017). At first, in the analysis preparation phase, survey responses were typed into a Microsoft Excel document and organized by question. At this stage, the data were reproduced *"as written"* and were not *"corrected"* in any way (e.g., spelling and grammatical errors have not been changed). The first author carried out a thematic analysis using Braun and Clarke's guidelines (Braun and Clarke, 2021, 2022). He initially read and re-read the data to note *"interesting features."* Then, he moved to more detailed and systematic engagement with the data to spot key features on them (Terry et al., 2017). Afterward, he re-arranged the data to identify broader patterns of meaning or *"potential* (initial) *themes."* These themes were then reviewed, refined, and named. It is worth noting that, at a few points throughout the analysis, the codes were rearranged to better reflect the themes identified in the data. Finally, the second author reviewed the themes and the associated quotes. After discussion meetings, it was decided that Students' responses did accurately capture the essence of each theme, so the process came to an end. The following metrics were used to ensure that authors were not bias dominating the results (**Table 1**).

TABLE 1 | Quality measures that applied in the study.

Quality measures	Actions employed	Description
Credibility	Investigator triangulation (Korstjens and Moser, 2018)	The two authors coded, analyzed, and interpreted the data.
Dependability and Confirmability	Audit trail (Scharp and Sanders, 2019)	We described transparently the research steps taken from the begging of our study to the development and reporting of the findings.

RESULTS

Question 1: "Could You Briefly Describe What You Think Science Is?"

Participants' perceptions about the concept of science were elicited through the question "*Could you briefly describe what you think science is?*" The analysis of Students' textual data revealed four main themes: *"Science as a contributor to human welfare,"* *"Science as objects/products,"* *"Science as set of practices,"* and *"Science as a school subject."* A description of each theme and indicative examples are provided below.

Science as a Contributor to Human Welfare

Under this theme, we grouped those responses related to Students' perceptions reflecting the important role of science in our lives (N = 116, percentage 40%). Many students recognized science as being useful in everyday life, as contributing to problem—solving, and as advancing our society. The following quotations show that students perceive science as an asset for mankind:

> *"Science is very important for mankind, because it helps people to achieve different types of goals."* (P_{31})

> *"Science leads to an improvement of the quality of life for mankind."* (P_{36})

> *"Science makes the world better and has contributed greatly to our knowledge for the physical world. Without it there would be no progress."* (P_{39}).

> *"Science is knowledge which is important for the progress of mankind."* (P_{48})

> *"It is very important for mankind because it has offered a lot to us."* (P_{156})

A number of respondents expressed the view that science appears to be necessary in our present-day society and that science has a positive impact on it. For example:

> *"Science is very important for our society."* (P_{61})

> *"When research is done that will help our society."* (P_{116})

> *"Science is when one discovers something good for society."* (P_{130})

> *"Science is important. It helps our society move forward."* (P_{213})

Others commented that science might be helpful to any person in the solving of today's problems. In that sense, some students reported that the importance of science lies in its usefulness in solving problems generally. The following responses offer such exemplars:

> *"Science solves our everyday problems."* (P_{209})

> *"Science solves the strange problems that confuse ordinary people."* (P_{84})

> *"Science is something we use every day, and which solves problems in our world."* (P_{228})

> *"Science helps people solve problems, such as environmental problems."* (P_{229})

> *"Science is the solution to our life's problems. It answers our questions."* (P_{241})

Science as Objects/Products

Science as objects was the second most often mentioned description of science (N = 86, percentage 30%). The Students' responses under this theme contained references to scientific discoveries, scientific products, and technological achievements. Some students reported general descriptions of objects, for example:

> *"Science is the discoveries, and they require a lot of work."* (P_{140})

> *"Science is the various discoveries that scientists make."* (P_{128})

> *"Science is when a person discovers a new invention."* (P_{188})

On the other hand, some students referred specifically to technological achievements and everyday equipment with which they usually interact. In that case, Students' description of the concept of science reflected an explicit acknowledgment of a relationship with technology. For example:

> *"Science is important because without it there would not be Internet, Wi-Fi, mobile phones and computers."* (P_{42})

> *"Science is creativity with which various discoveries are made... such as technology, phones, cars, light and many other things that are useful or even useless to us."* (P_{144})

> *"Science helps people in various ways... like car and television."* (P_{167})

Science as a Set of Practices

On this particular theme, students referred to science as a set of different practices (N = 64, percentage 20%). Several respondents expressed the view that science is based on experimentation:

> *"Science is experiments."* ($P_{7,148}$)

> *"Science is experiments that determine our future."* (P_{15})

> *"Science is experiments and discoveries that help people or do not help them."* (P_{43})

Other students referred to scientific practices that precede or follow the experimentation phase but are important parts of the so-called *"scientific method,"* as taught in the science class. For instance:

> *"Science is a method. Somebody does experiments, observes, and then concludes."* (P_{164})

> *"Science is experiments which support a scientific theory."* (P_{184})

> *"Science is various theories that when we merge them we draw conclusions that help us to understand some things better."* (P_{202})

> *"Science is a series of inquiry steps and observations, until scientists reach conclusions."* (P_{246})

Science as a School Subject

In this category, we included Students' responses naming various scientific research fields, such as physics, chemistry, biology, mathematics, psychology and linguistics, medicine, and astronomy (N = 35, percentage 12%).

"Science is physics and mathematics. If you connect them, you can solve everything." (P_{41})

"Science is a combination of biology, physics, chemistry, and mathematics." (P_{42})

"Science is studied by scientists such as doctors, chemists, and astronomers." (P_{115})

"Science is chemistry, mathematics, history, biology, psychology, and linguistics." (P_{257})

Also, in this category were included the descriptions of the students who gave specific examples of school subjects or academic courses, such as physics, chemistry, mathematics, biology, etc., or made general type formalities. Some responses in this category are presented below.

"Science is the subjects taught in universities." (P_{163})

"Science is some courses taught in schools." (P_{194})

"Science is not a specific subject. Science is many subjects for example linguistics, mathematics, biology, physics, and more." (P_{250})

"Science is all lessons together." (P_{252})

Finally, in this category, we have included responses referring indirectly to specific scientific disciplines. Some indicative examples are the following.

"Science is the study of the environment and natural phenomena." (P_{53})

"Science concerns the professions that find solutions to some diseases and deal with the human body." (P_{284})

Question 2: "Could You Briefly Describe a Great Scientific Discovery You Know About?"

In regard to Question 2, Students' responses to thematic analysis revealed two general themes. These themes were subsequently named: (1) *"Great Discoveries"* and (2) *"Great Inventions."* Under the first theme, we grouped responses that described various discoveries. The term *"discovery"* in our study referred to *"the act of becoming aware of something previously existing but unknown"* (Noé, 2002, p.31). On the other hand, we conceptualized the term *"invention"* as a creative process occurring within a technological milieu and drives to a novel solution that improves the quality of our life (Corazza and von Thienen, 2021). So, *"Great Inventions"* theme covered responses that highlighted such solutions.

Great Discoveries

The theme *"Great Discoveries"* consisted of responses that described discoveries from various scientific fields. We have further thematically analyzed that theme to differentiate between *(1a) "Space Science Discoveries," (1b) "Earth Science Discoveries,"* and *(1c) "Physics Discoveries."* **Table 2** provides basic information about the aforementioned subthemes alongside some of the indicative examples from within these subthemes.

Great Inventions

Under the *"Great Inventions"* theme, we identified four subthemes, including *(2a) "Health Science Inventions," (2b) "Information and Communication Science Inventions," (2c) "Domestic Life Inventions,"* and *(2d) "Transportation Inventions."* Indicative examples associated with these subthemes are presented in **Table 3**.

Question 3: "What Three Adjectives Would You Use to Describe a Scientist?"

Results regarding the third question showed that students talked about scientists by using various descriptions. Because students mentioned a total of 150 different characteristics, the richness of perceptions associated with scientists was considered significantly high. Our analysis showed that students' responses could be grouped under the following core themes: (1) *"Personality,"* (2) *"Skills,"* (3) *"Work,"* and (4) *"Appearance."* We further thematically analyzed the *"Personality"* theme to differentiate between *"Personality—Cognitive"* (clever, smart, genius, etc.) and *"Personality—Social"* (boring, annoying, etc.). Twenty-two responses did not seem to fit within these main themes, so we created the *"Other"* theme to include these codes. In **Table 4**, theme descriptions and indicative examples of codes included in each theme are presented.

Our descriptive analysis of data showed that *smart* or synonyms such as *clever*, *intelligent,* etc. were the most reported characteristics (∼33%). *Creative* (∼7%) was the second most frequent reported code. A similar percentage of students reported that scientists are considered as *patient, careful*, *hard-working, inventive,* or *serious* persons (3–4%). The next Word Cloud (**Figure 1**) is plotted to present the most frequently referred characteristics (above 1%).

Regarding the type of characteristics that students used to describe scientists, we found that "*Personality*" was the most reported category/theme (428 out of 770). Looking in more detail across the *"Personality"* theme, we found that 36.9% of words referred to cognitive traits (*"Personality—Cognitive*" theme) and 18.7% referred to social characteristics (*"Personality—Social"* theme). Three hundred two of the 770 responses (39.2%) focused on scientists' skills. As a result, "*Skills*" was the second most frequently reported theme. Finally, descriptive analysis showed that less than 3% of Students' responses were aligned with "*Work*" and *"Appearance"* codes. The above findings are presented in the following diagram (**Figure 2**).

Question 4: "What Three Adjectives Would You NOT Use to Describe a Scientist?"

Thematic analysis of the questionnaire data identified 178 words represented in children's responses to the question *"What three adjectives would you NOT use to describe a scientist?."* These words were classified by the researchers under the same four themes and subthemes as shown in **Table 4**. **Table 5** shows indicative examples for each theme.

TABLE 2 | Great discoveries' subthemes, their descriptions, and indicative examples.

Subtheme	Description	Indicative examples
Space science discoveries	Responses that describe discoveries related to space science.	*"Liquid water exists on Mars."* (P_{122}) *"Pluto that turned red on February 5, 2010."* (P_{144})
Earth science discoveries	Answers that contain discoveries related to the scientific field of geography.	*"The Earth is round."* (P_{69}) *"The discovery that the Earth is not flat but round"* (P_{259}) *"The discovery of America by Columbus."* (P_{262}) *"Ozone depletion."* (P_{262})
Physics discoveries	Responses referred to physics discoveries.	*"Newton who was in his room and passed the light through a prism and the reflection in the white cloth created the rainbow."* (P_{169}) *"The phenomenon of reflection and diffusion of light. When a ray of light meets a smooth and glossy surface it is reflected, while when it meets a rough surface, it diffuses."* (P_{273}) *"Electromagnetism discovered by Oersted and Faraday."* (P_{33}) *"Molecules are made up of smaller particles. Atoms are made up of the nucleus and the electrons that move around the nucleus."* (P_{252}) *"That Newton discovered gravity."* (P_{19})

TABLE 3 | Great inventions' subthemes, their descriptions, and indicative examples.

Subtheme name	Subtheme description	Indicative examples
Health science inventions	Responses that mention inventions related to health sciences (medicine, dentistry, pharmacy).	*"Drugs used to treat cancer."* (P_{117}) *"Drugs that stop migraine headaches."* (P_{32}) *"Medicines that can cure diseases."* (P_{226}) *"Thermometers"* (P_{4}) *"Penicillin."* (P_{91})
Information and communication science inventions	Responses that state inventions for information reception, recording, and communications.	*"The personal computer."* (P_{262}) *"The telephone."* (P_{262}) *"The radio."* (P_{262}) *"The television."* (P_{262})
Domestic life inventions	Responses describing inventions that help people to meet the basic needs of a domestic life.	*"The washing machines."* (P_{262}) *"The fridge."* (P_{262}) *"The light bulb."* (P_{259})
Transportation inventions	Responses referring to inventions, which allow transportation.	*"The car."* (P_{262}) *"The airplane."* (P_{262}) *"The wheel."* (P_{262})

TABLE 4 | Framework for analysis of children's responses to *"What three adjectives would you use to describe a scientist?"*

Theme name	Theme description	Indicative examples
Personality	Words that described cognitive and social characteristics of scientists.	Cognitive: Smart, Intelligent, Genius, Brainy, Clever, Wise Social: Enthusiastic, Polite, Conversational, Fascinating, Open, Boring, Different, Strange, Crazy, Alone, Conservative, Deranged
Skills	Answers referring to competences and abilities attributed to scientists.	Creative, Patient, Careful, Hardworking, Concentrated, Devoted, Responsible, Focused, Productive, Cautious, Well Educated, Studious, Bookish
Work	Words related to specific fields of study.	Astrophysicist, Doctor, Teacher, Physicist
Appearance	Items related to physical appearance of scientists.	Thin, Handsome, Slim, White-haired, Dirty, Beard, Thick, Tall, Well dressed, Short, Untidy
Other	Any word that does not fit into one of the preceding categories.	Rich, Awake, Perfect, Fantastic, Justified

Our analysis showed that scientists were mainly described as people that are not *stupid* (∼15%). In a lesser percentage (∼7%) students said that scientists are not *lazy* or are not *irresponsible*. Between 2 and 5%, we found various words that students believe that don't reflect scientists' characteristics such as *boring, careless, social, crazy, fool,* and *illiterate*. With the following Word Cloud (**Figure 3**), we have visualized the most frequently discussed characteristics (above 1%).

Regarding the type of characteristics that students said that do not describe scientists, "*Personality*" theme was, once more, the most reported category/theme (53.9%). More specifically, 21.6% of words referred to cognitive traits (*"Personality—Cognitive*" theme) and 32.3% referred to social characteristics (*"Personality—Social*" theme). Thirty seven percent of students used characteristics categorized under the *"Skills*" theme. Thirty-four students used «*"Appearance*" codes (5%) in their

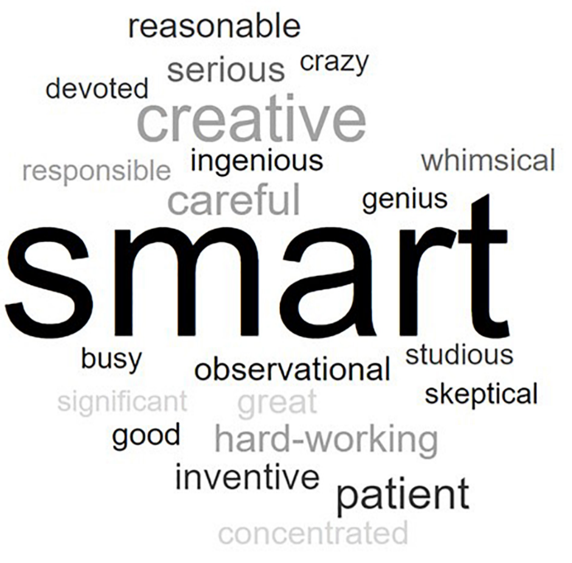

FIGURE 1 | Word Cloud presenting the most frequent descriptions of scientists.

descriptions. Twenty-six responses included to the *"Other"* theme. The following pie chart (**Figure 4**) shows the frequencies of the aforementioned core categories.

Question 5: "Could You Please Name a Great Scientist You Know?"

In Question 5, students were asked to name a great scientist they knew. The collected answers to this question were 225 (79.22%). Students who didn't respond were 59 (20.78%). In total, 28 different names of scientists were identified. **Table 6** presents the frequency distributions of the names of scientists whose percentage exceeded 1%.

DISCUSSION

This study sought to understand how Greek primary school students perceive science, scientists, and their work. Fifth- and sixth-graders were asked to complete a written questionnaire containing five open-ended questions. The collected data were analyzed through the thematic analysis method.

The findings revealed that the vast majority of the students perceived science primarily as a means for improving and evolving their lives (*"science as a contributor to human welfare"*), a result which is in line with those from similar studies (Driver et al., 1996; Stein and McRobbie, 1997; Aikenhead, 2005; Padwick et al., 2016). Recent research also showed that scientists are perceived by students to be servants of humanity and altruistic people who are dedicated to serving the welfare of society (Koren and Bar, 2009; Bartoszeck and Bartoszeck, 2017). We believe that these results could be related to the media influence on Students' views about science and scientists (Lee and Scheufele, 2006; Silver and Rushton, 2008) for at least two reasons. First, nowadays scientific topics are more frequently presented in the media than in the past (Gelmez Burakgazi and Yildirim, 2014). Since they increasingly put technological innovations under the auspices of the scientific sphere, they (indirectly) promote perceptions of sciences' usefulness for humanity. Second, such ideas are very close to scientist's depictions that are presented in the traditional media. As scholars highlight, this "heroic scientist" archetype is very often reproduced (Nisbet and Dudo, 2013;

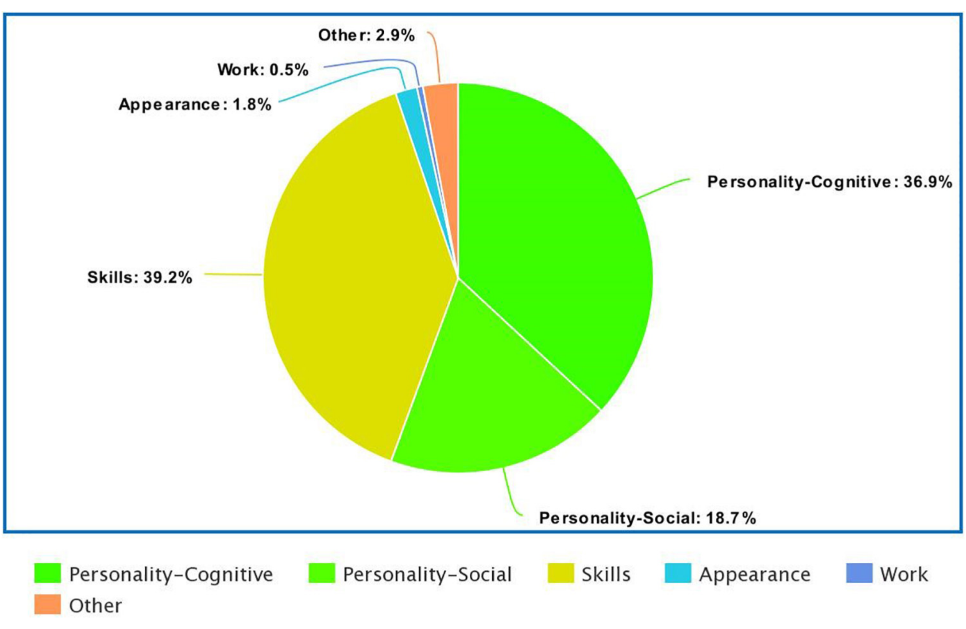

FIGURE 2 | Types of descriptions of scientists (organized by themes).

TABLE 5 | Framework for analysis of children's responses to *"What three adjectives would you NOT use to describe a scientist?"*

Theme name	Indicative examples
Personality	Cognitive: Stupid, Moron, Idiot, Brainless, Fool, Empty-headed Social: Forgettable, Boring, Social, Funny, Immature, Insignificant, Unimportant
Skills	Lazy, Careless, Impatient, Superficial, Irresponsible, Illiterate, Uneducated, Work-shy, Remiss, Scatterbrained
Work	Trucker, Secretary
Appearance	Thick, Tall, Athletic, Ugly, Handsome. Body builder, Short, Thin, Black-haired, Bald, Strong
Other	Rich, Poor, Tired, Naughty

FIGURE 3 | Word Cloud presenting the most frequent words that do NOT describe scientists.

Fujiwara et al., 2022), and in that sense, it is possible to have influenced Students' views.

Our study also found that many students, as expected, described science in the light of its achievements or through references to its products, which is in line with the results of recent studies (Newton and Newton, 1998; Elder, 2002). This result seems to be in agreement with educational reports which claim that science *"as a product"* or *"body of knowledge"* is an extremely familiar dimension of science for students (Bell, 2009). Unfortunately, this trend may reflect (as well) the traditional confusion that exists among students between the concepts of science and technology (Ryan and Aikenhead, 1992; Kang et al., 2005), as they often believe that it is the science that provides our society with gadgets and other practical solutions (Clough, 2000). It is worth noting that the above trend is in line with the results of many studies that asked students to depict a scientist while working, since very often technological products are present in Students' drawings (Samaras et al., 2012; Leblebicioglu et al., 2021), while "symbols of technology" are regarded as one of the basic DAST-C stereotypical indicators assessed in relevant studies. Concluding, we should note that the above perceptions are considered as naïve by researchers and are expressed by a large proportion of students of this age worldwide (Elder, 2002; Kang et al., 2005).

The students also linked the concept of science with various disciplines that were mainly referred to natural Sciences (biology, chemistry, physics), a finding that has emerged in the past from other researchers and corresponds to a stereotypical and unsophisticated perception of science (BouJaoude and El Khalick, 1995; Armağan, 2017). This outcome also indicates that the Greek Students' written responses presented considerable similarities with children's pictorial representations of the scientists both in Greece (Samaras et al., 2012; Christidou et al., 2016; Emvalotis and Koutsianou, 2018) and worldwide (Blagdanic et al., 2019; Bozzato et al., 2021), i.e., very often students draw scientists as professionals working in the fields of physics, chemistry, and biology and are surrounded by flasks, test tubes, bottles etc. Previous studies have also captured that the activities related to social sciences and humanities are very hard to be presented in drawing (Blagdanic et al., 2019). Our results extend to these findings, since the written answers of Greek students were rarely related to these fields (Christidou et al., 2012; Samaras et al., 2012) which shows that, traditionally, students believe that science is related (mostly) to the study of the natural world (Emvalotis and Koutsianou, 2018).

Finally, a small part of the Students' responses included descriptions related to the processes of science, descriptions that are considered sophisticated (Elder, 2002; Kang et al., 2005). This means that students find it difficult to describe in a few words the meaning of science through its processes, which was not the case when drawings were used as a tool to collect data about children's perceptions of scientists and their work in other studies. For example, recently Lamminpää et al. (2020) found that 95 of the 104 evaluated children's drawings included portrayals of some kind of scientific process (experimenting, discussing results, etc.), a result that is contrary to our finding. It is also interesting that although Students' responses in that category were few, these were focused upon the delineation of activities that themselves have encountered through school science and as a result the emphasis of their responses was given on inquiry processes. This finding contradicts the notion that many students may perceive a mismatch between what it means to do science in the classroom and what science in real life entails (Zhai et al., 2014) as they directly referred to well-known science classroom processes to conceptualize the scientific endeavor. The results from the question of scientific discoveries showed that the students presented discoveries mainly in the field of natural sciences (Space Science, Earth Science, Physics). The above areas, as shown by previous research (Chambers, 1983; Song and Kim, 1999; Rodari, 2007; Narayan et al., 2009; Emvalotis and Koutsianou, 2018), seem to reflect areas that students stereotypically perceive as key areas of specialization of scientists. At the same time, a large part of the students, as mentioned above, did not seem to distinguish science from technology, since technological innovations were presented in the place of discoveries. This finding is similar to

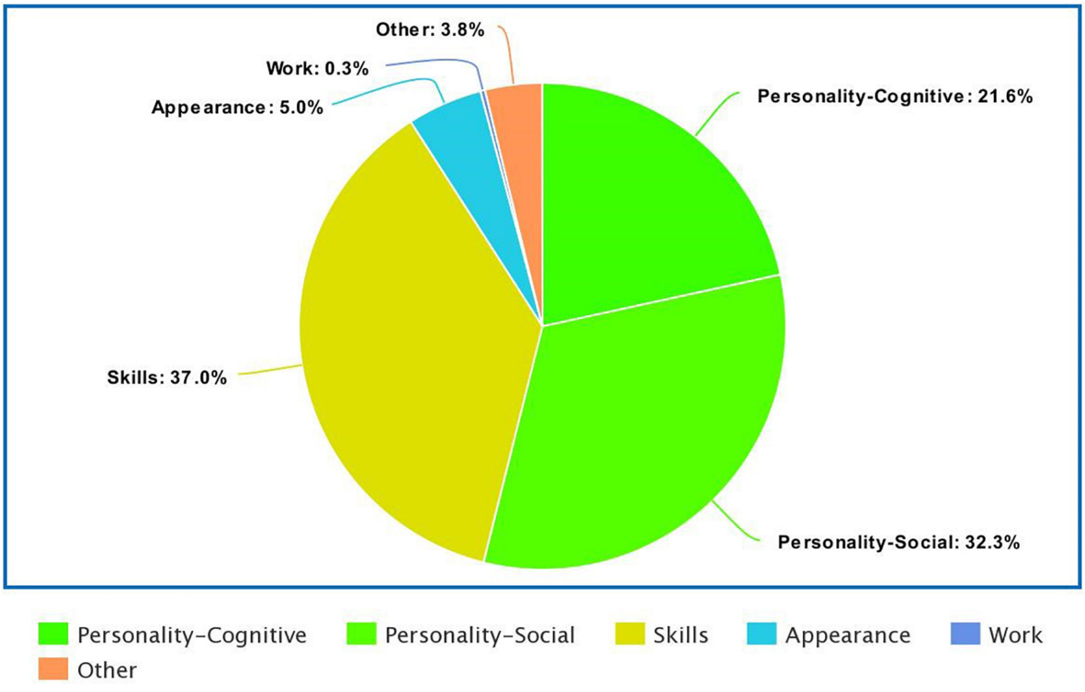

FIGURE 4 | Types of words used that do NOT describe scientists (organized by themes).

those of Ryan and Aikenhead (1992), Rennie and Jarvis (1995), and Constantinou et al. (2010) who found that students fail to distinguish between science and technology concepts which in many cases were used interchangeably.

Our study also revealed that positive scientists' characteristics were relatively common in Students' responses, and negative traits were rare. Though not entirely surprising in light of other recent studies (Archer et al., 2013; Shimwell et al., 2021), we found that the scarcity of negative characteristics in our sample to be notable. Furthermore, the positive descriptions students used to describe scientists fell into various categories: personal characteristics, social characteristics, skills, and appearance, which means that students may generally view scientists positively. While this may seem encouraging at first, it may also conceal stereotypes about Students' understanding of scientists. For example, our findings showed that most participants seeing scientists as purely *"clever"* and *"intelligent"* (or not stupid). These traits might reflect a stereotypical view about scientists' mental abilities as they indicate that scientists have some kind of *"special brain"* (Lei et al., 2019). In this context, students also mentioned that scientists are *"hardworking," "dedicated,"* and *"patient"* people (or that they are not lazy and impatient individuals) which are some other common positive stereotypes that students have for scientists (Schinske et al., 2015).

It is also interesting that contrary to the findings of earlier studies (Karacam, 2016; Woods-Townsend et al., 2016) we did not find that students view scientists as *"boring"* people, but in contrast they characterized them as interesting personalities. It is also worth noting that the trend of viewing scientists as *"mad"* or *"crazy"* people (Tuckey, 1992; Ruiz-Mallén and Escalas, 2012) was weak in our study, which is consistent with what has been found in recent studies (Emvalotis and Koutsianou, 2018). This finding may be explained by the idea that an increasing number of films and books portray scientists as people who, in addition to science, have fun, relax, have favorite activities, and have a family (Haynes, 2016). Nonetheless, despite the fact that images of scientists have improved over time, many representations continue to overemphasize specific attributes that may mislead individuals' perceptions of science and scientists. Misleading images of scientists, whether good or negative, confuse the

TABLE 6 | Most common great scientists' names.

Scientists' names	Frequency	Percentage (%)
Einstein	117	52
Hawking	39	17.30
Edison	9	4.00
Bell	8	3.55
Volta	7	3.11
Lakhdar	6	2.66
Newton	6	2.66
Celsius	4	1.77
Curie	4	1.77
Oersted	4	1.77
Franklin	3	1.33
Tesla	3	1.33

Responses below 1%: Da Vinci, Verne, Colombus, Fahrenheit, Faraday, Ford, Frankenstein, Fraunhofer, Galileo, van Gogh, Gray, Gutenberg, Voltaire, Aristotle, Archimedes, Charalampakis.

students not only about the work scientists conduct, but also about their character traits (Fujiwara et al., 2022). For example, in our research, students described scientists as non-social people, which confirms the *"lonely scientist"* stereotype that is very common in media (Nisbet and Dudo, 2013).

Our results also showed that the students described the scientists mainly through their personality traits and not that much through their skills, their appearance, or their specialty. The present results are significant in at least two major respects. First, the students used only few adjectives about the appearance of the scientists, which did not reveal any tendency, but instead seemed to describe them in a variety of ways (Christidou et al., 2016; Emvalotis and Koutsianou, 2018). This is a key difference between the data in this study and the DAST studies. Also, it seems that our data did not provide descriptions that reflected stereotypes, such as a scientist being a person with a laboratory coat and gray hair which are some of the stereotypical images that students use when depicting scientists. On the one hand, this may be due to the fact that the children were asked to provide a descriptive text rather than a drawing, so they did not have to choose the clothes or physical features for the scientist. On the other hand, this finding, while preliminary, may indicate that more and more students are seeing scientists in a way that goes beyond the traditional (male, middle-aged, bald, etc.) (Samaras et al., 2012; Emvalotis and Koutsianou, 2018). Second, students cited scientists' skills in a lesser extent than their personality characteristics. In our view, the most compelling explanation for the present finding is that children may think that scientists have some innate personality qualities (Dewitt et al., 2012; Archer et al., 2013) that seem to be conceived as more important than the non-innate skills (Schinske et al., 2016). These results are not very encouraging because, if this is the case, then students who do not consider themselves belonging to this *"special group"* of people may not get engaged in science in the future (Archer et al., 2010, 2013).

Regarding the famous scientist, the majority of students reported male scientists, a finding that is consistent with the results of several studies where drawings were used as research data (Türkmen, 2008; Christidou et al., 2012; Emvalotis and Koutsianou, 2018). In that sense, we could argue that no matter the data collection method, i.e., drawings or verbal/written responses, the male stereotype of a scientist dominates the minds of the students. As many studies confirm, the public visual image of science worldwide is largely male (Mitchell and McKinnon, 2019), a tendency that also has been found in the recent study of Christidou et al. (2019), where one thousand publicly available photos of scientific researchers located in Greek archives have been analyzed. The names of scientists that students cited were also interesting, because the vast majority of them limited almost exclusively to scientists that exist in the Greek science textbooks of the fifth and sixth grade (Einstein, Edison, Bell, Volta, Newton, Celsius, Curie, Oersted, Franklin, Tesla), a finding that can be explained in the context of the influence that the contents of the school curriculum have on Students' perceptions of science and scientists (She, 1995; Türkmen, 2008; Yacoubian et al., 2017). Similar studies with teachers revealed similar trends regarding their favorite scientist, so it is possible that students' perceptions may have been influenced by their teacher's views as well (Yalcin, 2012; Gheith and Aljaberi, 2019; El Takach and Yacoubian, 2020). Albert Einstein seems to be still the most popular scientist for students, a result that is in line with other recent studies (Song and Kim, 1999; El Takach and Yacoubian, 2020; Ivgin et al., 2021). This finding was more or less expected because students very often view scientists as middle-aged people with wacky hair and mustaches, which means that Einstein-like appearances of the scientist are very popular to them (Ozel, 2012; Blagdanic et al., 2019). Also of interest was the high frequency of references to Stephen Hawking, who, in contrast to the results of similar studies appeared to be the second most frequently cited scientist among the Greek students. This finding contradicts the results of other studies that found almost complete absence of contemporary scientists in the citations of students (El Takach and Yacoubian, 2020; Ivgin et al., 2021). This inconsistency may be due to the fact that the media referred frequently to Stephen Hawking's death, which coincided with the time of our investigation. As it is mentioned earlier, media influence Students' perceptions of science and scientists (Buldu, 2006; Zhai et al., 2014), so it is possible that the students were controlled. Finally, our results showed that the participants tend to imagine prototypical examples of scientists working in the natural sciences, which supports similar stereotypical evidence from previous studies (Ozel, 2012; Samaras et al., 2012; Carli et al., 2016; Blagdanic et al., 2019).

Educational Implications

Our findings contribute to the existing literature in several ways. Knowing what fifth- and sixth-graders' perceptions of science and scientists are, we created a starting point for how Students' practice and be supported by their teachers. The results highlighted that interventions to challenge Students' perceptions about science and scientists are needed, mainly targeting to the narrow image of the *"smart"* charismatic scientist, who works exclusively in the field of natural sciences. In this context, teachers are advised to carry out a variety of in and out school activities that will help breaking these narrow views (e.g., visits to the workplace of scientists, meetings with scientists in the classroom etc.). It is supported that such interactions allow students to view scientists as ordinary people, who are working in a wide range of scientific areas (Woods-Townsend et al., 2016; Shimwell et al., 2021). Regarding the naïve ideas that students have about science, and the difficulty to distinguish between science and technology, it is strongly suggested that teachers (and prospective teachers) should become more informed on such issues and also more capable to design appropriate learning environments that will allow students to develop more sophisticated views about science and technology (Constantinou et al., 2010). Our results can also be used by National Governmental Institutions (such as Ministry of Education, Institute of Educational Policy, etc.) in various ways. Given that the newly introduced law for the upgrading of Greek schools allows free choice of school materials from approved school textbooks (Eurydice, 2022), we suggest that textbook authors must carefully plan what they are going to include in new textbooks in order to prevent reinforcing misleading information and stereotypes. It is also suggested that various national stakeholders, such as Photodentro, which is the Greek National Educational Content Aggregator for Primary and Secondary education (Karagiannidis et al., 2022) should include appropriate visual, print, and digital media educational material, with which a more realistic view will be attributed to science and scientists.

Limitations and Future Research Directions

The study reported here has a number of limitations. First, regarding the students participated in our work, we selected participants conveniently. As a result, the findings of the present study should be interpreted with caution as they might not be appropriately generalizable beyond the selected participants. Further research is required to determine whether they can apply more broadly to other groups of participants. This study was also limited by the absence of more data. As we limited students to briefly answer our questions, or to provide a single word to describe scientists, we were not allowed to gain a better understanding of what they really had in mind. To overcome this issue, future studies may wish to use focus groups or one on one interviews in order to encourage students to think deeply and include more details to their responses. A further limitation concerns the instrument was used to assess the perceptions held by the students. As it is relatively new in its use, compared to DAST-C (Chambers, 1983) or V-NOS (Lederman et al., 2002), it should be thoroughly tested for its effectiveness by future researchers. Finally, the present study does not uncover the mechanisms by which varying Students' perceptions about science and scientists were shaped. It is proposed that future research should focus on the influence of various factors (Students' socio-economic background, parents' academic level, teachers' views etc.) may have in Students' perceptions of science and scientists.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Research Ethics Committee—Department of Primary Education, School of Education Sciences, University of Ioannina. Written informed consent to participate in this study was provided by the participants or their legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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The role of representational competencies for students' learning from an educational video game for astronomy

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Educational video games can engage students in authentic STEM practices, which often involve visual representations. In particular, because most interactions within video games are mediated through visual representations, video games provide opportunities for students to experience disciplinary practices with visual representations. Prior research on learning with visual representations in non-game contexts suggests that visual representations may confuse students if they lack prerequisite representational-competencies. However, it is unclear how this research applies to game environments. To address this gap, we investigated the role of representational-competencies for students' learning from video games. We first conducted a single-case study of a high-performing undergraduate student playing an astronomy game as an assignment in an astronomy course. We found that this student had difficulties making sense of the visual representations in the game. We interpret these difficulties as indicating a lack of representational-competencies. Further, these difficulties seemed to lead to the student's inability to relate the game experiences to the content covered in his astronomy course. A second study investigated whether interventions that have proven successful in structured learning environments to support representational-competencies would enhance students' learning from visual representations in the video game. We randomly assigned 45 students enrolled in an undergraduate course to two conditions. Students either received representational-competency support while playing the astronomy game or they did not receive this support. Results showed no effects of representational-competency supports. This suggests that instructional designs that are effective for representational-competency supports in structured learning environments may not be effective for educational video games. We discuss implications for future research, for designers of educational games, and for educators.

KEYWORDS

representational competencies, sense-making, perceptual fluency, educational video games, unstructured learning environments, astronomy

Introduction

Educational video games are powerful tools that can engage students in authentic practices of STEM disciplines (Clark et al., 2009). Disciplinary practices often include the use of visual representations (visuals for short) to solve problems and communicate with others (Airey and Linder, 2009). Prior research shows that visual representations can confuse students unless they have prerequisite representational-competencies (Kozma and Russell, 2005; Ainsworth, 2006; Rau, 2017a). These competencies include the ability to make sense of how visual representations show relevant information and to fluently perceive disciplinary information in them (Rau, 2017a). Further, research on representational competencies shows that students' learning outcomes can be enhanced if they receive instructional support for these representational competencies while interacting with visuals (Bodemer et al., 2005; Rau and Wu, 2018).

However, prior research on representational competencies focused on structured learning environments. We consider structured learning environments as those where instruction follows a specific plan, usually directed by a teacher or instructional designer (Stanescu et al., 2016). By contrast, in unstructured learning environments, learning activities are constructed by students, within the constraints of the given context (Stanescu et al., 2016). We consider video games as unstructured learning environments because students can decide on the path they take through the game (Honey and Hilton, 2011).

Structured environments are designed to purposefully engage students with visual representations in ways that encourage reflection, whereas video games aim to intuitively engage students with visual representations without requiring reflection (Virk et al., 2015). Further, in structured environments, the dominant medium for information delivery is usually text or speech, and visual representations are used to augment this information. By contrast, video games are highly visual at their core (Virk et al., 2015). Therefore, it is unclear whether prior research on structured learning environments generalizes to educational video games. Indeed, as detailed below, we found few studies that investigated the role of representational competencies for students' learning with visual representations in video games.

To address this gap, we conducted two studies. First, we conducted a single-case study that served to ascertain whether representational competencies are an issue in learning within educational video games in the first place. To this end, we selected a high-performing student playing an astronomy video game for an undergraduate astronomy course. We expected that this student would successfully learn from visual representations within the game. We found that the student had difficulties with the visual representations that seemed to impede his learning from the game. This motivated a second study, which experimentally that tested whether representational-competency supports designed based on prior research on structured learning environments would enhance learning from the game. We found that the representational-competency supports were ineffective. Our findings yield novel insights into how representational competencies affect learning in unstructured educational contexts and have implications for the design of educational video games.

Theoretical background

In the following, we briefly review prior research on visual representations in educational video games and in structured learning environments to highlight the gap we seek to address.

Visual representations in educational video games

Defining educational video games is not straightforward, in part, because platforms differ in terms of their game-like features (de Freitas and Oliver, 2006). For the purpose of our studies, we define games as interactive experiences that model disciplinary phenomena of interest, allow students to take actions that impact aspects of the phenomena, and incorporate goals and ongoing feedback for measuring progress (Clark et al., 2009). Further, we focus on video games that are played via computers, gaming platforms (e.g., Xbox), or other digital devices (e.g., smart phones) (Gee, 2003). We also focus on educational video games that are specifically designed to achieve learning goals, as opposed to recreational games designed purely for entertainment (Belanich et al., 2009). Finally, we focus on educational video games that are systematically designed based on educational research. We discuss the specific game we chose for our studies in section visual representations in educational video games.

By definition, video games are highly visual, and one of their strengths is that they can engage students in disciplinary practices that involve interactions with visual representations (Clark et al., 2009; Holbert and Wilensky, 2019). Many STEM disciplinary practices centrally involve the ability to use visual representations to solve problems and communicate with others both verbally and non-verbally (Airey and Linder, 2009; Rau, 2017a). Indeed, scientists in multiple disciplines use visual representations to make abstract concepts visible, predict and explain scientific phenomena, and communicate ideas within their community of practice (Kozma and Russell, 2005; Gilbert, 2008). For example, line emission spectra (see Figure 1) are used to determine the presence of compounds in celestial bodies in astronomy or to determine the identity of gases in chemistry. Hence, an important goal of educational video games is to immerse students in disciplinary practices with visual representations (Habgood and Ainsworth, 2011; Virk et al., 2015; Virk and Clark, 2019). The present studies focus on those visual representations within games that serve as disciplinary tools (e.g., line emission spectra), as opposed to visual representations that purely serve to engage students with the game environment (e.g., a spaceship) or to navigate the game (e.g., a map of the environment).

While little prior research specifically focused on the role of disciplinary visual representations in educational video games,

FIGURE 1
Example line emission spectrum of a gas. Each element emits a unique line emission spectrum, which allows astronomers and chemists to use line emission spectra to determine the presence of compounds.

our review of the literature identified several ways in which visual representations may enhance students' learning within games. First, we found that educational video games include visual representations that allow students to see and interact with abstract concepts within the discipline [e.g., speed of light; Kortemeyer et al., 2013]. Second, visual representations can support students' conceptual understanding of disciplinary phenomena (e.g., DNA encoding; Corredor et al., 2014). Third, because the visual representations mimic tools used within the discipline, they serve to enculturate students into disciplinary practices (e.g., modeling physical phenomena based on data; Sengupta et al., 2015).

However, our review also identified several obstacles that may reduce the effectiveness of visual representations within educational video games. First, some games (e.g., Annetta et al., 2013) place high demands on students to learn gameplay conventions and navigation, which may impede their ability to invest cognitive effort into making sense of disciplinary visual representations. Second, encountering a multitude of visual representations within games can make it difficult for students to focus on those visual representations that depict relevant disciplinary content, which can reduce their ability to make sense of the visual representations (Lim et al., 2006). Finally, in some games, visual representations are incorporated into passive components of the game (e.g., students may view but not interact with an animation), which may reduce students' focus on these visual representations, thereby interfering with their ability to make sense of the visual representations (Anderson and Barnett, 2013).

In sum, visual representations within games offer opportunities for students to engage with disciplinary content. However, students may have difficulties in making sense of these visual representations.

Visual representations in structured learning environments

Our review of research on visual representations in educational video games parallels findings from prior research on visual representations in structured learning environments. That is, this research shows that visual representations can enhance students' learning because they visualize abstract concepts, allow for modeling of domain-relevant processes, and enable students to participate in disciplinary practices (Gilbert, 2008; Rau, 2017a).

This line of prior research also identified several obstacles that could impede students' learning with visual representations, which parallel difficulties observed in the context of video games. Specifically, making sense of visual representations is cognitively demanding, especially when students are asked to make connections among multiple visual representations (Ainsworth et al., 2002; Rau, 2017a). Further, students tend to have difficulties distinguishing relevant visual features from irrelevant ones (Goldstone and Son, 2005). Finally, students tend not to make sense of visual representations unless they have to actively manipulate them (Bodemer et al., 2004).

In contrast to research on educational video games, research on learning with visual representations has investigated how to help students overcome these difficulties by supporting their representational competencies: knowledge about how visual representations show disciplinary information (Rau, 2017a). In particular, this research suggests they need support for two broad types of representational competencies—sense-making competencies and perceptual fluency (Ainsworth, 2006; Kellman and Massey, 2013; Rau, 2017a).

Sense-making competencies describe the ability to explain how visual features of a representation depict discipline-specific concepts and to explain connections between multiple visual representations based on conceptual mappings (Seufert, 2003; Ainsworth, 2006). For example, when learning about the Doppler shift, students must make sense of the visual representations in Figure 2. Specifically, this involves understanding that when a planet orbits a star (shown by the animated celestial object), the gravity of the planet causes the star's light emissions to shift red or blue (shown by the electromagnetic spectrum) based on the movement toward or away from a point in space at a specific speed (shown by the graph) (Franknoi et al., 2017). Students acquire these sense-making competencies through sense-making processes (Ainsworth, 2006; Rau, 2017a), which involve effortful, verbal explaining of conceptual information (Chi et al., 1989; Koedinger et al., 2012).

This line of research developed design principles for instructional interventions that support sense-making processes (see Seufert, 2003; Bodemer et al., 2004; Koedinger et al., 2012; Rau, 2017a,b). Sense-making interventions should prompt students to explain to themselves or to someone else how visual representations show disciplinary concepts. These prompts should encourage students to actively establish mappings between the visual representations and the concepts they show. Sense-making interventions can deliver prompts in a variety of ways, for

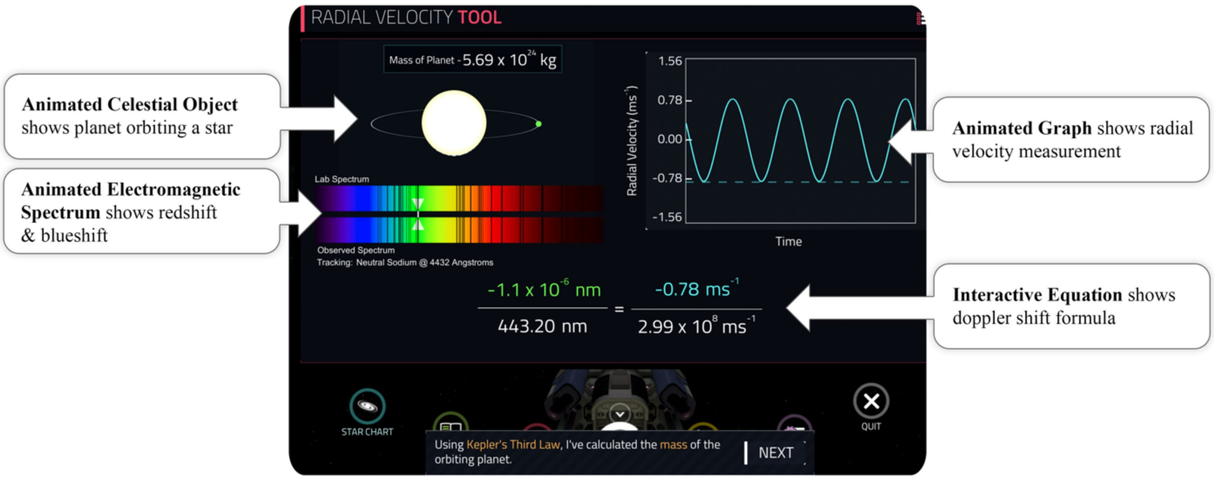

FIGURE 2
Example sense-making task: Students must connect the visual representations related to the Doppler shift: planet orbiting a star (top left), electromagnetic spectrum (bottom left), radial velocity graph (top right), and the corresponding equation (bottom center) to understand the concept of using doppler shift to identify planets orbiting a star. This task is presented in the Radial Velocity Tool of the game, discussed below.

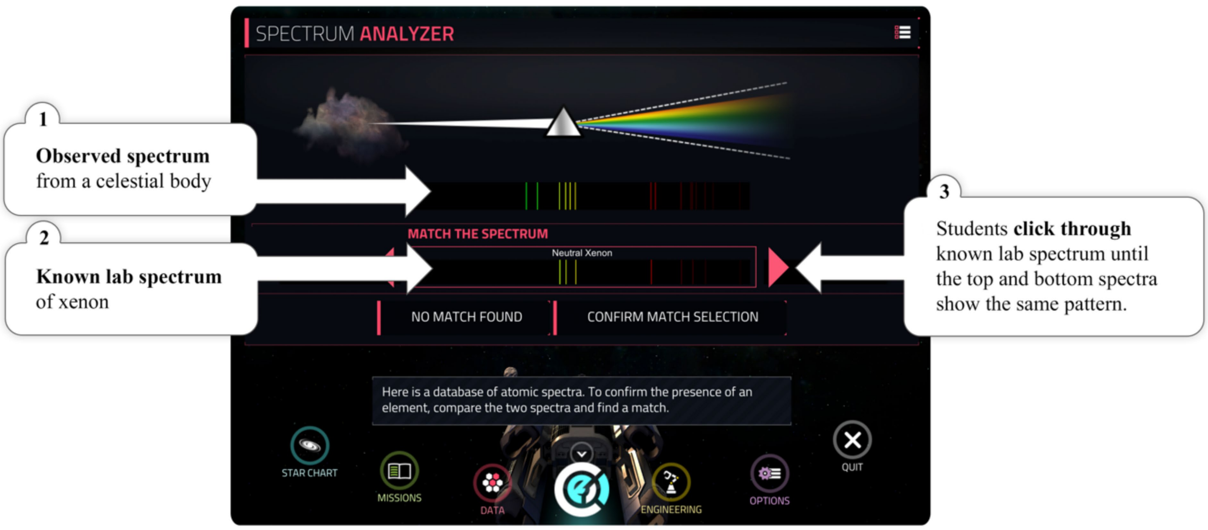

FIGURE 3
Example line emission spectra task: Students are asked to judge whether the observed spectrum (top) matches a lab spectrum (bottom). In this case, the student should see that the two spectra match. This task was presented in the Spectrum Analyzer Tool of the game, discussed below.

examples as self-explanation prompts (Rau, 2017b), prompts to draw (Fiorella and Mayer, 2016), or prompts to explain the visual representations to someone else (Rau et al., 2017).

Perceptual fluency describes the ability to quickly and effortlessly extract meaningful information from visual representations and to fluently translate among different representational systems (Kellman and Massey, 2013; Rau, 2017a). For instance, when working with line emission spectra, the ability to quickly see whether an observed spectrum matches a lab spectrum allows students to determine which elements are present in a given compound, as illustrated in Figure 3. Students acquire perceptual fluency through inductive pattern-recognition processes that are nonverbal (Goldstone, 1997; Gibson, 2000; Fahle and Poggio, 2002). These processes are non-verbal because they do not require verbal explanation (Kellman and Garrigan, 2009; Kellman and Massey, 2013). They are considered to be inductive because they do not require explicit instruction (Koedinger et al., 2012) but rely on recognizing patterns that appear across many examples (Gibson, 1969, 2000).

This line of research has developed instructional design principles for interventions that support perceptual-induction processes (see Kellman et al., 2008, 2010; Rau, 2017a). Perceptual-fluency interventions expose students to a large variety of visual representations and ask students to quickly judge or classify the visual representations based on the information they show. The visual representations should be sequenced in ways that contrast relevant visual features while varying irrelevant visual features. Throughout, students should be prompted to solve the tasks quickly without explaining their answers because explanations can interfere with perceptual processing (Schooler et al., 1997). Similarly, feedback should be provided on the accuracy of student answers but without explanations, so as not to disrupt perceptual processing. Perceptual-fluency interventions can prompt perceptual processing in a variety of ways, for example, by asking students to categorize systematically varied examples (Rau, 2017b) or to rapidly construct disciplinary visual representations (Eastwood, 2013).

Prior research shows that combining these two types of instructional support for sense-making and perceptual-fluency competencies enhances students' learning of disciplinary knowledge from structured learning environments (Rau et al., 2017; Rau and Wu, 2018). Further, perceptual-fluency interventions are usually offered after students have acquired sense-making competencies (Kellman et al., 2008, 2010), and this sequence was found to be more effective in experimental studies (Rau, 2018).

Study 1: Single-case study

Our brief literature review suggests that the difficulties students encounter with visual representations in educational video games are similar to those they encounter in structured learning environments. While this suggests that a lack of representational competencies could be a stumbling block in the context of educational video games, research on video games has not focused on representational competencies specifically. To close this gap, we conducted a single-case study to explore:

> Research question 1 (RQ1): How does an undergraduate student use visual representations in an educational video game?

The single-case study methodology allowed us to take a holistic approach to gain deep understanding of one student's entire learning experience over multiple weeks within an undergraduate course. The goal of the single-case study was to ascertain whether representational competencies might pose an issue in learning within educational video games. We considered this goal as a prerequisite for investigating whether support for representational competencies may enhance students' learning from an educational video game (see Study 2).

Methods

Video game context: At play in the cosmos

We chose a game for our study that has the explicit goal to familiarize students with multiple visual representations of astronomical phenomena: At Play in the Cosmos (Squire, 2021). The game is a single-player adventure designed to engage students in applying introductory astronomy concepts. Specifically, the game design targeted students with non-STEM majors with no prior astronomy experience to align with those students who typically took introductory astronomy courses at the undergraduate level (Gear Learning, 2017). In the game, students take on the role of an intergalactic explorer and contractor for a corporation that mines resources in space. They captain their own spaceship and are aided by the on-board Cosmic Operations Research Interface who acts as their guide during 22 scripted missions. In each mission, students travel through space using an interactive star chart (see Figure 4) to complete challenges. In doing so, they use real astronomical data to observe and measure real astrophysical objects such as galaxies and nebulas. The first three missions of the game serve as a tutorial which introduces students to basic gameplay mechanics, the user interface including a subset of seven tools available in the game, and introductory physics concepts. After the first three missions, students can play the remaining missions in any order, however, the game presents an unfolding narrative to rescue the galaxy from the Corporation if played in linear order. In addition to the scripted missions, the game includes a sandbox mode where students can freely explore galaxies and instructors can design activities using the objects and tools within the game.

One major goal of the game is for students to learn how and why astronomers use visual representations as tools for understanding the universe and its evolution (e.g., line emission spectra, see Figure 1). Hence, students engage with visual representations as part of the tools they use to gather information and resources (Squire, 2021). In using the visual representations, students learn about concepts related to measuring celestial objects (e.g., Doppler shift, see Figure 2). While most of the interactions within the game focus on the visual representations, it also aims at helping students connect visual representations to equations that describe the same concepts (see Figure 2).

The game offers several visual representations that serve as tools for problem solving within the game because they parallel the scientific process that astronomers use in the field. The electromagnetic spectrum (Figure 1) is an important tool in multiple disciplines, such as astronomy and chemistry. Electromagnetic spectra represent the electromagnetic radiation emitted or absorbed by objects, such as visible light and ultraviolet radiation (Franknoi et al., 2017). Electromagnetic spectra play an important role in many subject areas. For example, astronomy students use electromagnetic spectra when learning to identify critical properties of celestial bodies (Bardar et al., 2005); and chemistry students use electromagnetic spectra when learning about Planck's quantum theory (Moore and Stanitski, 2015). Within the game, multiple tools expose students to electromagnetic spectra including: the Radial Velocity Tool (Figure 2) and the Spectrum Analyzer Tool (Figure 3). Students use the Radial Velocity Tool to determine the presence of planets orbiting stars. For instance, students use the tool to identify a habitable planet

FIGURE 4
Interactive Star Chart. Students use the in-game Star Chart to navigate to various locations in the galaxy and access tools to observe and measure data from celestial objects. The game designers purposely created the star chart as “slices” of the galaxy to enable students to understand the scale of the universe while designing within the constraints of the gaming engine.

within the Milky Way galaxy. Students use the Spectrum Analyzer to match observed spectra to laboratory spectra to determine the properties of celestial objects. For instance, students travel to Supernova 1987A to determine if sodium gas is present in its ejecta (Bary, 2017).

The game was designed as a collaboration between the University of Wisconsin-Madison and W.W. Norton & Company. The design team included multiple astronomy subject matter experts, educators, artists, and game designers (Squire, 2021). The design team used an iterative development process that included multiple rounds of playtesting with students. They also conducted a formal beta-test pilot study across five universities with 440 students) (Dalsen, 2017) and an alpha-test pilot study with professors at two universities with 184 students (Squire, 2021). Both pilot studies showed positive perceptions of the game and its contribution to learning astronomy concepts.

Study context and participant

We conducted the single-case study as part of an eight-week online introductory astronomy course at our institution. The course was titled “The Evolving Universe: Stars, Galaxies, and Cosmology” and covered the importance of light in astronomy for understanding the past, present, and future of the universe. The instructor chose At Play in the Cosmos to provide students with an immersive experience into the topics covered in the course. In particular, the game was intended to provide experience in how astronomers use tools to work with the light emitted by celestial objects to identify their composition and structure. It was also intended to provide students with a sense of what the various celestial objects look like and how simple mathematical equations serve to calculate critical information about these celestial objects.

Students in this course used the game for six homework assignments. Students played through the scripted missions in the game in the first four weeks of class. Then, they used the sandbox mode to complete activities designed by the instructor in the next two weeks of the course. The instructor of the course considered the game an add-on to the course that was relatively independent of other course materials. Specifically, the instructor did not ask students to reflect on their experiences in the game and did not provide information on how the game aligned with astronomy practices.

For our study, we selected one student, Simon (pseudonym). The instructor considered him a high performing student based on his performance on weekly short papers, weekly quizzes, and a long-term project within the class. The instructor noted that Simon’s written assignments were very thorough and demonstrated conceptual understanding of the astronomy content addressed in the class. Further, he had extensive gaming experience. Simon started playing games when he was 3 years old and played on multiple platforms including GameCube, GameBoy, DS, Xbox, and PC. He also had prior experience with educational video games especially in Math where he played Cool Math (2018). Simon was majoring in political science and Chinese. He enrolled in the course to fulfill a physical science prerequisite for his majors. Although he had no previous formal experience with astronomy, he followed NASA and SpaceX on social media and watched space related content on YouTube. Simon was an appropriate selection because he fit the target audience for the game given that he had no previous formal experience with astronomy and given that he was a non-STEM major (Gear Learning, 2017). Further, based on his performance on the assignments within the course, we expected him to be successful in learning with the visual representations in the game. On the flipside, we reasoned that if Simon has difficulties learning with visual representations in the game, we could expect lower-performing students to experience difficulties as well.

Data collection and analysis

We conducted seven semi-structure interviews. The goal of the interviews were to understand Simon's successes and challenges while playing the game as well as how he used the visual representations related to the electromagnetic spectrum to gain conceptual understanding of the spectra and how they are used within astronomy. The interview questions were designed to encourage Simon to reflect on his experiences in the game and to explain how he interacted with the visual representations within the game to better understand astronomy concepts. Further, the interview questions aimed to elicit explanations of concepts related to the electromagnetic spectrum outside the context of the specific experiences Simon had in the game.

The first interview was conducted one week before he started playing the game to gain some general insights into his prior experiences with astronomy, visual representations, and video games. The remaining six interviews occurred after each game assignment in Weeks 1–4, 6, and 8. Each of the six interviews followed the same semi-structured procedure. Specifically, to start the interview, we asked Simon some general questions about when he completed the game in the preceding week, whether he played it in one or multiple sessions, and about successes and difficulties in playing the game. We then asked about the specific visualization tools he encountered in his game play, what role the visual tool played in learning within the game, how he learned to interact with the visual tool, and in what scenarios an astronomer might use the visual tool. We asked follow-up questions depending on how the student responded to the questions, asking him to say more about the question or to elaborate on specific parts of the answer. Example questions from the interview protocols are included in section data collection and analysis (Supplementary Appendix S1).

All interviews were transcribed. We analyzed the data using grounded theory (Glaser and Strauss, 1967). That is, we qualitatively reviewed the interview data to identify key themes that characterized Simon's experiences with the visual representations in the game tools. To establish inter-subjectivity, we then formalized the recurring themes into a coding scheme. Shaffer (2017) argues that social moderation is the best strategy for very small data sets. Because our transcripts comprised only 541 lines of data, we followed this recommendation. Thus, two independent coders applied the coding scheme to the data and used social moderation until there was agreement on each code (Herrenkohl and Cornelius, 2013).

Results

Our grounded analysis revealed two major themes. First, Simon engaged with the visual representations at a superficial level. For example, when asked about the Spectrum Analyzer Tool (see Figure 3) in Week 2, he focused on the operations used to manipulate the visual representation rather than the conceptual interpretation of the visual representation: "if there was a gas cloud, you could shine the spectrum analyzer and shine beams and see if anything was reflected or see what colors come out," and when prompted to elaborate: "you can determine the composition, you know, the composition of anything, I guess like a cloud or something like that," and "I mean, you just look and look what matches." In addition to Simon's focus on operations, these excerpts illustrate that he did not actually understand the visual representation's role as an astronomy tools (because the Spectrum Analyzer Tool captures light; it does not shine light). Similarly, in Week 3, when asked about the Radial Velocity Tool (see Figure 2), he said: "I could figure out […] if there was a planet in front of a star or not by measuring it over time." When asked to elaborate, he said: "it shows radial velocity going up and down." When proved further if he was confused about any aspects of the visual representation, he stated: "I mean, yeah, there's a lot of stuff on the screen." These examples illustrate that Simon described the operations used to manipulate them (e.g., "you could shine the spectrum analyzer"), described superficial visual features (e.g., the graph "going up and down") and engaged in pattern recognition (e.g., "you just look and look what matches). He did not engage with the visual representations at a conceptual level; that is, he did not reflect on the meaning of these features nor any connections to other visual representations that were present at the same time. Across the interviews, this superficial processing of the visual representations and a resulting lack of sense-making seemed to be a recurring theme.

Second, Simon had difficulties understanding the disciplinary practices with visual representations that were portrayed in the game, which was the learning goal of the game. When asked about how the game portrayed what astronomers do, he said, "I mean, sure, it was more sci-fi type like, obviously you're not in space doing all that stuff." He also said: "I don't really know if it's realistic or not because I don't know how scientists go about doing all that stuff." When probed further about specific ideas that may be more realistic, he said: "It all felt the same. I guess where we were just doing calculations of the star during the first part was more realistic than the back half of the game where it just went completely sci-fi." When probed further to relate what he said to the visual representations in the game, he said, "the [electromagnetic spectra] probably don't differ, but maybe how they get them probably differs from the way the spaceship uses them." Simon never went beyond focusing on the spaceship in explaining which aspects of the game reflect realistic astronomy practices from game.

When asked about the concept underlying the in-game tool, however, he stated: "well, that's more important to me because the electromagnetic spectrum allows [astronomers] to see different things in space like using a higher wavelength of light, they can see deeper into the milky way galaxy, so it allows them to see different things and observe different things that would be of importance to whatever they would want to do for research." This statement indicated that Simon was able to articulate the importance of the concept underlying the game, that the electromagnetic spectrum can be used to analyze light, but he did not connect this concept to the tools used in the game nor their real-world equivalents. Across the interviews, we observed a recurring emphasis on surface-level differences between the game and real-world astronomy and a lack of a deep understanding of which of the portrayed astronomy practices around visual representations were realistic.

Discussion

Overall, our single-case study revealed that Simon engaged with the visual representations at a relatively superficial level. We did not find evidence that he attempted to make sense of how the visual representations showed astronomy concepts or that he reflected on which aspects of the visual representations reflected realistic disciplinary practices. Simon's lack of sense-making of the game visual representations aligns with findings from prior research on educational video games and on structured learning environments that students often have difficulties in making sense of visual representations spontaneously (e.g., Ainsworth et al., 2002; Anderson and Barnett, 2013). We also found that Simon had difficulties understanding how the visual representations within the game correspond to disciplinary tools within astronomy. Because this was the learning goal of the game, this finding suggests that Simon did not benefit from the game as intended by the instructor or the game designers (Squire, 2021).

A plausible explanation for these findings is that the design of the game aligns more with the design of perceptual-fluency supports than with the design of sense-making supports. Specifically, recall that prior research suggests that effective sense-making supports prompt students to explain relations between visual representations and the concepts they show (e.g., Seufert, 2003; Bodemer et al., 2004; Koedinger et al., 2012). While students interact with the visual representations in the game, they do not receive prompts to explain how the visual representations show astronomy concepts or how various visual representations relate to one another. Likewise, when students made mistakes, the game did not offer reflective feedback. In contrast, the design of the game seems more aligned with the instructional design principles for perceptual-fluency supports, which target non-verbal, inductive learning processes of pattern recognition (e.g., Kellman et al., 2008, 2010; Rau, 2017a). Specifically, the game asks students to identify visual patterns and provides only correctness feedback. In line with this interpretation, Simon's interview responses indicate that he engaged in some level of perceptual processing of the visual representations based on pattern recognition.

Further, it seems plausible that Simon's issues in understanding the role of the game visual representations as disciplinary visual representations results from his lack of sense-making of the visual representations. If Simon did not make sense of how the visual representations in the game depict astronomy concepts, he may not have been able to understand why these visual representations are tools for disciplinary practices in astronomy. In other words, if Simon did not understand the conceptual ideas underlying the visual representations in the game, he may not have been able to connect those ideas to the broader disciplinary context outside of the game. This issue may be particularly relevant in the context of video games that provide a fictional narrative as a context of the game, which could obscure the authenticity of the visual representations in the game. While the game seemed to support some level of perceptual fluency by virtue of engaging Simon in pattern recognition, prior research suggests that this may be suboptimal: perceptual-fluency support has been shown to be ineffective if students did not previously receive sense-making support because it can give students a false sense of familiarity with visual representations they do not conceptually understand (e.g., Rau, 2018).

In sum, the single-case study indicates that a high-performing student had difficulties making sense of visual representations within the game, which seemed to reduce his understanding of the visual representations as disciplinary tools.

Study 2: Class experiment

The single-case study suggests that a lack of sense-making support within the game could pose an issue to students' benefit from the game. This leads to the question whether providing instructional support for representational competencies (i.e., sense-making competencies and perceptual fluency) would improve students' benefit from the game. Specifically, we ask:

> RQ2: Does the game lead to pretest-to-posttest learning gains of sense-making competencies (RQ2a), of perceptual fluency (RQ2b), and astronomy content knowledge (RQ2c)?
>
> RQ3: Does support for representational competencies enhance undergraduate students' benefit from the game with respect to their learning of sense-making competencies (RQ3a), of perceptual fluency (RQ3b), and astronomy content knowledge (RQ3c)?

Further, we explored:

> RQ4: How do undergraduate students experience the visual representations within the game?

We addressed these questions with an experiment that compared how representational-competency supports affect learning within the game.

Methods

Participants

We recruited 45 undergraduates from an introductory chemistry course at our institution—a large midwestern university. The course

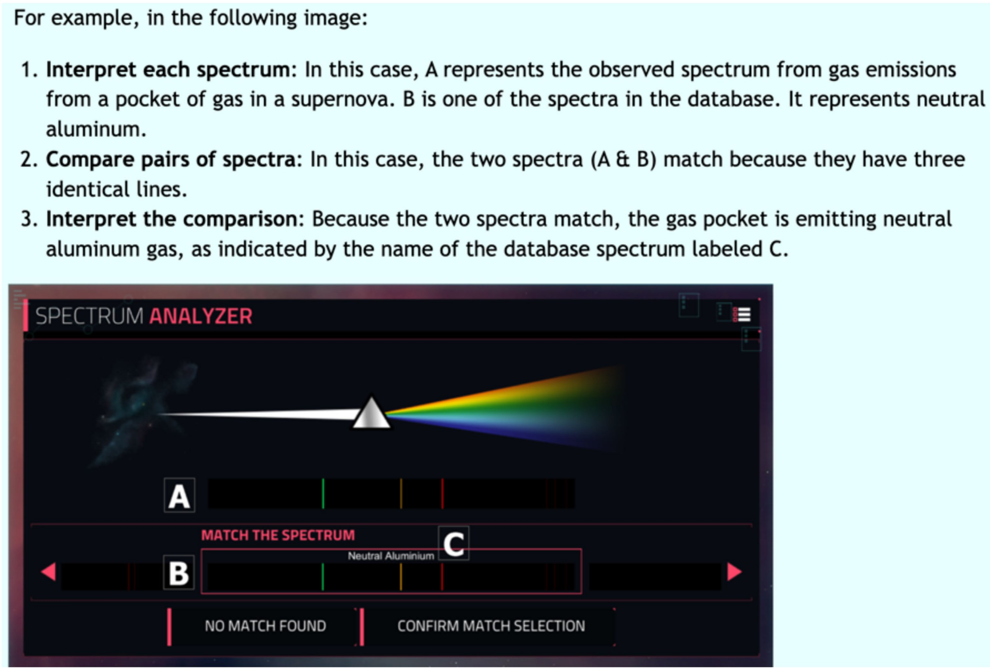

FIGURE 5
Example sense-making support: Students received a prompt that asked students to interpret each spectrum, compare pairs of spectra, and interpret the comparison, with a concrete example (in this case, with the Spectrum Analyzer within Mission 1).

had no formal prerequisites but was advertised to students in beginning or intermediate level chemistry courses. Of the 45 students, three students had prior astronomy courses, ten had prior astronomy lessons in another science course, 16 had prior informal experiences with astronomy such as planetarium visits or social media, 15 students had no experience at all, and one student did not complete the survey. 40 of the students had at least one STEM major, one student had a non-STEM major, three students were undecided, and one student did not complete the survey. 29 students rarely or never played video games, twelve students played sometimes, and three students played very often. Thus, although the student majors did not align with the target population of the game (the game was designed primarily for non-STEM majors as explained above), the students' prior gaming experiences aligned with the target population of game. Further, the instructor was willing to implement multiple conditions within the course, so we could test our research questions.

A portion of the same game from the case study was used for two required homework assignments. Students played ten missions of approximately 70 minutes of gameplay. The instructor used the game as an illustration of how electromagnetic spectra, which students encountered earlier in the semester, are used in related disciplines.

Experimental design

Students were randomly assigned to one of two conditions. The *control condition* received no support for representational competencies while playing the game. Because prior research on representational competencies shows that the combination of support for sense-making competencies and perceptual fluency improve disciplinary learning outcomes, the *support condition* received support for sense-making competencies and support for perceptual fluency at separate times while playing the game. Support was designed based on prior research on structured learning environments described above.

Specifically, sense-making support was given in the form of prompts, displayed on the computer screen prior to playing a set of five missions of the game (see Figure 5). Students were able to revisit this screen at any time, but whether and how often they did was not recorded. The prompts outlined how to engage with the visual representations in a three-step process. First, students were asked to interpret each visual representation separately. Second, they were asked to compare pairs of visual representations. Third, they were asked to explain the comparison in reference to astronomy concepts. For example, as shown in Figure 5, when students were about to work with the Spectrum Analyzer Tool, the prompt would first ask students to interpret what each electromagnetic spectrum showed, second to compare similarities and differences of two electromagnetic spectra, and third to explain what the comparison indicates about the presence of a substance in a star.

Perceptual-fluency support was also delivered via prompts, displayed on the screen prior to playing a set of five missions of the game (Figure 6). Students were able to revisit this screen at any time, but whether and how often they did was not recorded. The prompts instructed students to train their ability to use the visual representations quickly to make decisions within the game. To this

Research shows that experts are incredibly efficient and fluent at translating among visuals. The continuous practice and immediate feedback you get in At Play in the Cosmos will help you achieve that level of fluency. This week, as you work with the Spectrum Analyzer, we ask you to focus on efficiency and fluency. Here is some advice for how to become fluent with this tool:

1. **Do not overthink it:** Do NOT think about why the spectra match.
2. **Focus on speed and intuitions:** Move quickly through the options and pick the one that intuitively "just looks" right.
3. **Accept mistakes:** Don't be afraid to make mistakes because even if you pick the wrong one, you can **try again**.

This approach may seem strange at first. You are probably used to being asked to reflect and explain; but that is NOT what we are asking you to do when you work with the spectrum analyzer activities this week. Instead, really try to quickly and intuitively decide which spectrum is the matching one. Even if this seems strange at first, it will really help you train your intuitions about the spectrum analyzer, and it will help you achieve the level of fluency that makes experts efficient at using this tool. Once you can use these visuals more intuitively and automatically, you'll have more head room to think deeply about the astronomy concepts.

FIGURE 6
Example perceptual-fluency support: Students received a prompt that asked students to not overthink it, focus on speed and intuitions, and accept mistakes, with a concrete example (in this case, with the Spectrum Analyzer).

end, students were asked not to overthink their interactions with the visual representations, to focus on speed, rely on their intuitions about the match, and to accept mistakes.

In line with prior research (Rau, 2018), sense-making support was given during the first homework assignment with the game, and perceptual-fluency support during the second homework assignment with the game.

Measures

To address RQs 2a and 3a, we assessed students' *sense-making competencies*. We created three isomorphic tests (i.e., with questions that were structurally identical but asked about different example celestial objects or compounds). The sense-making test included four questions with three parts each, yielding twelve items each worth one point for a total of twelve possible points. Each question provided two electromagnetic spectra and asked students whether they matched, why or why not they matched, what they could infer from the match, and how they went about determining the match. Open-response items were graded based on a codebook that described the sense-making competencies assessed by each item and captured multiple ways of describing how the given visual representation depicts astronomy concepts. Inter-rater reliability was established by two independent raters on 20% percent of the data and revealed a kappa over .700 on each code. Prior to statistical analysis, we investigated the internal reliability of the scale using Cronbach's Alpha with results indicating questionable internal reliability of $a = 0.671$. Step-wise item analysis indicated that removing two questions would increase the internal reliability resulting in a ten-point scale with acceptable internal reliability of $a = 0.702$. We computed the average of the correct items for each student for each test time. The test was administered as a pretest, an intermediate posttest given after students had finished the first homework assignment with the game, and a posttest given after students had finished the second homework assignment with the game. The order of the test versions was counterbalanced across participants (e.g., some students received test version A as the pretest, B as the intermediate test, and C as the posttest, whereas the sequence for other students was A-C-B, etc.).

To address RQs 2b and 3b, we assessed students' *perceptual fluency* with three isomorphic test versions that were counterbalanced across the three test times. The perceptual-fluency test included three items that showed an electromagnetic spectrum and asked students to select the best match out of four other electromagnetic spectra. Each correct question was worth one point for a total of three possible points. Cronbach's Alpha indicated poor internal reliability of $a = 0.270$, however, due to the short scale, no items were eliminated. We computed the average of correct items for each student for each test time.

To address RQs 2c and 3c, we assessed students' *content knowledge* with three isomorphic test versions that were counterbalanced across the three test times. The content test included two multiple-choice items and eight open-ended items, which asked students to solve problems with the visual representations they encountered in the game. One item was worth two points while the rest of the items were worth one point for a total of nine points. Open-response items were graded based on a codebook that described the conceptual knowledge assessed by each item and captured multiple ways of describing the targeted concept. Inter-rater reliability was established by two independent raters on 20% percent of the data and revealed substantial agreement with kappa over .700 on each code. Cronbach's Alpha indicated a poor internal reliability of $a = 0.295$. Step-wise individual item analysis indicated that the internal reliability would increase with the removal of the two multiple-choice items resulting in poor internal reliability of $a = 0.384$. The final resulting scale was six-items with a possible total of seven points. We computed the average of the correct items for a content outcome score for each student for each test time.

To address RQ4, we made use of weekly *reflection papers* that students had to write for the course. In the course, students had to submit several reflection papers over the course of the semester, and they were typically allowed to choose which topics to reflect on. However, for the purpose of this study, we asked students specifically to reflect on what they did or did not understand about the visual representations in the game and what role the visual representations played in their learning from the game. Since the study span multiple homework assignments, students had multiple opportunities to write reflection papers, and several students chose to reflect on the video game multiple times. Consequently, the number of reflection papers for each student ranged from one to three papers. We included all reflection papers that regarded the game in our analyses. We started our analysis with the broad idea of confusion and completed an iterative open-coding process until clear themes emerged related to students' (1) general impressions of the game, (2) indications of difficulties with visual representations, and (3) game critiques. We defined difficulties as expressions of confusion, uncertainty or difficulty understanding, or a lack of learning related to a concept or visual representations within the game. We defined game critiques as explanations about reasons why the game did not support their learning or led to confusion or struggle. Together, our analysis of these aspects was intended to capture students' internal struggles related to the content and visual representations and their external attribution of those struggles to the game. Once the codebook was finalized, each reflection paper was coded for each instance students expressed each code. Inter-rater reliability was established by two independent raters coding twenty percent of the reflection papers and revealed substantial agreement with kappa over .700 on each code.

Results

In the following analyses, we report d for effect sizes. According to Cohen (1988), an effect size *d* of 0.20 corresponds to a small effect, 0.50 to a medium effect, and 0.80 to a large effect. We excluded two participants because their scores on the content knowledge test were statistical outliers. This resulted in a final sample of $N = 43$. Table 1 shows the means and standard deviations by condition and measure.

Prior checks

We checked for differences between conditions on the pretests. A MANOVA found no significant differences between conditions on the sense-making pretest ($F < 1$), perceptual-fluency pretest, $F(1,42) = 1.020$, $p = 0.318$, or the content knowledge pretest ($F < 1$).

TABLE 1 Means (standard errors) for each test by measure, condition, and test time. All measures are on a scale from 0 to 1.

Measure/ condition	Pretest	Intermediate test	Posttest
Sense-making test			
Control	0.565 (0.184)	0.560 (0.284)	0.575 (0.290)
Support.	0.596 (0.208)	0.596 (0.280)	0.596 (0.248)
Perceptual-fluency test			
Control	0.850 (0.253)	0.983 (0.075)	0.967 (0.103)
Support	0.913 (0.150)	0.927 (0.173)	0.957 (0.115)
Content knowledge test			
Control	0.243 (0.180)	0.329 (0.203)	0.264 (0.169)
Support	0.286 (0.161)	0.329 (0.195)	0.304 (0.194)

Pretest-to-posttest learning gains

To address RQ2, we used repeated measures ANOVAs with test-time (pretest, intermediate test, post-test) as the repeated, within-subjects factor and test scores as dependent measures. The ANOVA model for RQ2a found no significant gains of sense-making competencies ($F < 1$). The ANOVA model for RQ2b found significant learning gains of perceptual fluency, $F(2,41) = 3.188$, $p = 0.046$, $d = 0.276$. The ANOVA model for RQ2c found no significant gains of content knowledge ($F < 1$).

Effects on representational-competency support on learning outcomes

To address RQ3, we used repeated measures ANCOVAs with condition as the between-subjects factor, test-time (intermediate test, posttest) as the repeated, within-subjects factor, pretest scores as the covariate, and scores on the intermediate test and the posttest as dependent measures. The ANCOVA model for RQ3a that tested the effect of condition on sense-making competencies revealed no significant effect ($F < 1$). The ANCOVA model for RQ3b that tested the effect of condition on perceptual fluency found no significant effect, $F(1,42) = 1.796$, $p = 0.188$. The ANCOVA model for RQ3c that tested the effect of condition for content knowledge found no significant effect ($F < 1$).

To explore whether the null effects were related to students' prior content knowledge or prior representational competencies, we added an interaction of pretest with condition to the original ANCOVA models. There were no significant interactions between condition and pretest for sense-making competencies, perceptual fluency, nor content knowledge ($F < 1$).

Students' experiences of visual representations within the game

To address RQ4, we conducted a qualitative analysis of students' reflection papers. We identified several themes related to students' general impressions, difficulties with visual representations, and game critiques.

With respect to *general impressions of the game*, we identified two major themes. First, students expressed liking the game because it was enjoyable (e.g., "have fun and learn at the same time" and "more fun to learning about chemistry"). Second, they suggested that the game was a helpful learning experience (e.g., "it [the game] taught me about different types of line spectra and what they mean") that was relevant to the chemistry course (e.g., "it was interesting to learn how light can be used to analyze chemicals," and "it made me realize how our base understandings of chemistry can be applied to something so grand and daunting as analyzing absorption spectra in stars").

With respect to *difficulties* with visual representations in the game, we identified two major themes. First, students mentioned being distracted by visual components of the game that related to the game narrative as opposed to the learning content (e.g., "there's just too much [...] I'm not sure what's important" and "flying through planets is [...] visually stimulating [... but] completely irrelevant"). Second, students mentioned being confused about specific visual representations, such as the electromagnetic spectrum (e.g., "I'm not sure I could replicate them [the visual representations] on my own" or "I don't remember the exact procedure or purpose"). This confusion ranged from not understanding why celestial bodies emit spectra (e.g., "I still don't feel like I understand why a star or planet emits a certain type of spectrum.") to not gaining a deeper understanding of electromagnetic spectra from the game (e.g., "I don't feel like I deepened my understanding of electromagnetic spectra or its importance in the study of outer space."

With respect to *critiques of the game*, we identified two major themes. First, students mentioned that it was "too easy to click through activities" without "having to learn what we're doing or why we did it" and without having to think deeply about the visual representations within the game. For instance, students mentioned they would just click through the electromagnetic spectra without being engaged in learning when, why, and how to use them (e.g., "it was a lot of clicking and guessing for me" and "all I'm doing is matching up the colors and locations of [lines]"). Second, students mentioned that there was not enough explanation and feedback in the game in general (e.g., "I really like the illustrations of stars, nebulas, and other cosmic objects, but without a better explanation of them, just a simple one would do, I'm not really getting as much understanding as I could.") or related to specific visual representations within the game (e.g., the game lacked a definition of "what the energy/light spectr[a] really are" or once a student had found two matching spectra, she was wondering "now what").

We also noted that none of the students' reflection papers mentioned the prompts delivered as part of our intervention in the support condition.

Discussion

Building on the results from Study 1, we investigated whether representational-competency supports would enhance students' benefit from the visual representations in *At Play in the Cosmos*. To this end, we compared students playing the game without support to students playing the game with sense-making and perceptual-fluency supports, which were delivered in the form of prompts. In response to RQ2, results showed significant pretest-to-posttest learning gains only for perceptual fluency—a type of representational competency that allows students to quickly and effortlessly use information shown by the visual representations. However, we found no evidence of pretest-to-posttest learning gains that students learned content knowledge or sense-making competencies from the game. Further, in response to RQ3, we found no evidence that representational-competency support enhanced students' learning of sense-making competencies, perceptual fluency, or content knowledge. Finally, in response to RQ4, the results suggest that students had difficulties focusing on the conceptual aspects of the visual representations because they were distracted by other visual elements of the game, and that they struggled to understand the concepts depicted by the visual representations. Students attributed these difficulties to the game encouraging them to click through visual features without providing conceptual explanations or feedback on how the visual representations depict concepts.

The pattern of results regarding learning gains is in line with our interpretation of the single-case study that the game design aligns with design principles of perceptual-fluency supports by engaging students in inductive pattern-matching processes. Indeed, students' comments in the reflection papers noted that they could easily click through the game without deeply considering the visual representations and concepts they depicted. This might explain the lack of learning of sense-making competencies. The game's focus on inductive pattern-recognition processes might have interfered with effortful, verbal explaining of conceptual information that characterizes sense-making processes. Students' comments in the reflection papers speak to this interpretation when they attributed their difficulties in understanding the visual representations to lack of definitions, explanations, and feedback during gameplay – the features that prior research has shown to support sense-making processes (Seufert, 2003; Bodemer et al., 2005).

With respect to RQ3, we see two possible explanations why our representational-competency supports were ineffective at supporting sense-making competencies. First, it is possible that the sense-making support was ineffective because it may have been incompatible with the use of the visual representations in the game. The visual elements of the game engaged students in more intuitive interactions and seemed to have detracted students from thinking deliberately about how they interacted with the visual representations or why. Students' comments from the reflection papers that the game involved a lot of clicking, guessing, and matching speaks to this interpretation. Hence, when the sense-making support prompted students to deliberately think and reflect on relations between the visual representations and the content, the game's pull toward intuitive interactions may have detracted from the sense-making processes that the sense-making support intended to engage students in. Second, a related explanation is that students may have intended to make sense of the visual representations but did not receive sufficient information from the game to do so effectively. Students' comments about the game lacking explanations and feedback is in line with this interpretation. Third, it is possible that delivering the sense-making support via prompts on screens that were displayed in between missions in the game (rather than integrated during game play) rendered them ineffective. Students may have needed additional reminders to engage in sense-making processes during game play.

We see four possible explanations why our representational-competency supports were ineffective at supporting perceptual fluency. First, it is possible that because the game incorporated design principles for perceptual-fluency supports, it already supported perceptual fluency for all students, maximizing the game's capacity of promoting perceptual fluency. Therefore, the additional perceptual-fluency support that prompted students to engage in inductive pattern-recognition processes may not have had any additional effectiveness. The finding that students in all conditions showed pretest-to-posttest gains in perceptual fluency supports this interpretation. Second, it is possible that the method of delivering the perceptual-fluency support outside the game was not maximally effective, as discussed above. Third, it is possible that without any gains in sense-making competencies, perceptual-fluency support cannot fall on fruitful ground: to benefit from perceptual-fluency support, students need to first understand the meaning of the visual representations (Rau, 2018). Finally, the perceptual-fluency test was comprised of three items and had low reliability given the lack of variance in students' scores. Although we saw learning gains across the three test times, it is possible that we were unable to find differences across the conditions due to a ceiling effect.

Given that representational-competency support failed to support sense-making competencies and perceptual fluency, it is not surprising that it failed to enhance students' learning of content knowledge. If, as indicated by prior research both sense-making competencies and perceptual fluency are necessary for students' learning of content knowledge from visual representations (Rau, 2017a), then the lack of students' learning of sense-making competencies may explain their lack of learning of content knowledge. It seems that a focus on perceptual fluency with the visual representations by itself is not sufficient to enable students to learn content from the visual representations. Unless students can make sense of the visual representations, they may not understand the underlying concepts. However, our content measure had poor reliability due to the majority of the students' inability to correctly answer the questions. Thus, it is possible that this lack of learning gains as well as lack of differences across conditions results from measurement error. Indeed, in a follow-up study with revised measures, we saw content learning gains as a result of interacting with the game paired with representational-competency supports (Herder and Rau, 2022).

Taken together, the main finding from our research is that the game did not support students' learning, even though students found it enjoyable and saw its merit in the context of the course. Our results show that the game supported students' acquisition of perceptual fluency but fell short of supporting their sense-making competencies. Students' reflection papers indicate that their difficulties in making sense of the game visual representations impeded their learning of the underlying concepts.

General discussion

We set out to investigate whether a lack of representational competencies might be an issue in students' learning from educational video games that are highly visual by definition. Our single-case study showed that even a high performing student had difficulties making sense of visual representations in a game that seemed to primarily encourage inductive pattern-recognition processes that lead to perceptual fluency with visual representations. We reasoned that supporting students' representational competencies via prompts might alleviate these issues. A class experiment revealed similar issues as the single-case study, showing that the game supported perceptual fluency but not sense-making competencies. Further, we found that the representational-competency supports were ineffective. Qualitative analyses lend credibility to our interpretation of both the single-case study and the class experiment that a lack of sense-making competencies accounts for students' lack of benefits from the game.

Altogether, these findings suggest that sense-making competencies that enable students to map visual features of visual representations to concepts are an important component of learning with visual representations in games. This finding parallels prior research on structured learning environments that has established the importance of sense-making competencies for learning with visual representations (Ainsworth, 2006; Rau, 2017a). Further, our findings suggest that perceptual fluency alone is not sufficient at supporting students' learning with visual representations within games, again paralleling prior research on structured learning environments (Kellman et al., 2008; Rau, 2017a). Contrasting with prior research on structured learning environments, our findings indicate that delivering representational-competency supports in the form of prompts may not be effective in the context of games. It is possible that due to their more immersive nature, video games require more integrated ways of supporting representational competencies during game play. Thus, future research should examine alternative implementations of representational-competency supports. Further, it is possible that games that are designed in ways that align more with one type of representational competencies (in our case, perceptual fluency) cannot be tweaked to support a different representational competency (in our case, sense-making competencies). In this case, it might be advisable to support a given representational competency through other means (e.g., in our case, supporting sense-making competencies via a reflective problem-solving activity before students play the game).

Limitations

Our findings must be interpreted in light of the following limitations. First, the single-case study took place within the broader context of an astronomy course, so we were unable to distinguish between aspects of the student's learning that were due to the game and aspects that were due to other experiences within the course. While Simon provided information about what he thought he was learning from the game versus the rest of the course, we did not have any measures that may have disambiguated his actual learning from the game from the rest of the course. Future research could address this limitation by adding tests immediately after game play, as was done in our class experiment.

Second, the single-case study was meant to serve as an initial exploration of the themes related to learning with visual representations in the game. Despite the focus on one participant, Simon was an interesting candidate because he was a high-performing student in the class and had extensive video game experience. We reasoned that if even he had difficulties with the visual representations in the game, then other lower-performing students may exhibit similar if not more difficulties. However, we cannot make claims about unstudied students based on the single-case study. Thus, future research could investigate cases of lower-performing students learning with visual representations in games.

Third, the class experiment had a relatively small sample size. It is possible that the representational-competency supports had effects that were smaller than what was detectible. Thus, future research should replicate our findings with larger sample sizes.

Fourth, the class experiment was our first attempt at creating measures to assess the constructs of perceptual fluency, sense-making competencies, and astronomy content within the context of an educational video game. Our content measure and perceptual-fluency measures, in particular, had poor reliability. Further, our perceptual-fluency measure was comprised of only three items. Despite showing learning gains, we may have encountered a ceiling effect that may have contributed to the lack of differences across conditions. To address this limitation, future research should use improved measures.

Fifth, across our studies, we focused on a particular game, *At Play in the Cosmos.* As any game, it incorporates specific disciplinary visual representations in specific ways to support students' game play and learning. In particular, throughout this article, we repeatedly emphasize the game's alignment with perceptual-fluency supports. While we think this is not unusual because many games aim to engage students intuitively through visual means, we readily acknowledge that other games may incorporate design features that are more likely to engage students in reflective, conceptual thinking that encourages sense-making processes. Therefore, future research should investigate representational competencies in the context of a larger variety of educational games.

Conclusion

Even though educational video games are highly visual, we are not aware of research that has investigated the role of representational competencies for students' learning with visual representations in games. The present article takes a first step toward addressing this gap. We found that a lack of a specific type of representational competency, namely students' difficulties in making sense of visual representations within the game, seemed to impede their learning of content knowledge from the game. While we acknowledge that a lack of sense-making competencies may not be the only issue that accounts for the students' failure to learn content knowledge from the game, we consider sense making of visual representations a prerequisite to their learning from the game because the purpose of the game was to familiarize students with the use of visual representations for disciplinary problem solving. At the very least, our findings suggest that representational competencies may be an important ingredient to students' learning within educational video games that warrants further research.

Data availability statement

The datasets presented in this article are not readily available because of IRB restrictions. Requests to access the datasets should be directed to corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by University of Wisconsin—Madison IRB 2018-0662 and 2018-1131. The patients/participants provided their written informed consent to participate in this study.

Author contributions

TH conducted the studies and analyses as well as most of the writing activities. MR served as the academic advisor to TH and oversaw all study activities and writing activities. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.919645/full#supplementary-material

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Moving beyond the language–Visualizing chemical concepts through one's own creative expression

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The aim of the study was to explore university students' interpretations of chemical content in the form of physical constructions of atomic nuclei. Playdough was chosen as the means for expression, since it provided the students with the task of choosing the number, form, size, shape, and distance of particles. Data was collected in the form of photographs, written explanations as well as *ad hoc* notes. Data from 64 students was analyzed using the three levels of analysis as presented by Hedegaard and framed within the theories of models. Results show that students' choices gave rise to 34 variations of the atomic nuclei. The analysis provided two different categories: models with close resemblance to the teaching model and models with less resemblance to the teaching model. Results show the limitations of verbal and written communication and add to the discussion concerning students' interpretations of the multitude of atomic models used in teaching. The method was indeed a beneficial tool both for students, who could explore the composition of atomic nuclei and isotopes, and for teachers, who could connect their teaching to students' interpretations of scientific content since the method brings a new level of detail to discussions.

KEYWORDS

chemistry education, atomic nuclei, sub-microscopic level, models of science, playdough, creative

Introduction

The challenges facing chemistry teachers and learners are many and vary in their nature. The first challenge that a chemistry teacher may encounter is that the material world may seem self-evident to learners, so self-evident that it may in fact not even require an explanation (Tytler, 2000). The second challenge lies in what Vygotsky (2004) may have correctly stated when he theorized that "imagination is based on our experiences and creativity is a combination of experiences." This conclusion is supported by decades of research showing the difficulty that learners face when trying to imagine the sub-microscopic world (Garnett and Hackling, 1995). Vygotsky's conclusion suggests that for us to imagine something, we already need to have some experience of the phenomenon at hand. This is indeed a challenge for chemistry, as chemical phenomena are explained on the non-visual sub-microscopic level, a level that is difficult to provide experiences of. Our traditional way of introducing chemistry becomes the third challenge; that is, in chemistry, abstract concepts are defined using other, equally abstract, concepts in our explanations (Taber, 2019). Furthermore, the atom has been suggested to be a precursor model, i.e., fundamental for further concept formation in chemistry (Koerber and Osterhaus, 2019). Something that highlights the importance of understanding concept formation and learners' interpretation of this specific concept. Most studies concerning the atom have focused on electrons, electron shells or orbitals (Taber, 2005; Stefani and Tsaparlis, 2009) but not atomic nuclei, their composition, repulsions, forces, weight and shape. This study was designed to fill this gap in the literature. It is also here assumed that learner's interpretation of atomic nuclei may influence their perception of the entire atom. The present project was designed to explore a method for problem-solving that makes use of students' expressions of the sub-microscopic level, whereby the learners are provided with as much creative self-expression as possible.

Theoretical framework

Models of science and science education

The definition of the word *model* used here is the one derived from the work of Acevedo-Díaz et al. (2017): *A model is a simplified representation of an object, phenomena, process, idea, or system of a physical reality that is created to explain, predict, or communicate natural science*. Models can then be further differentiated into scientific and educational models, where scientific models have been categorized as being composed of historic models and scientific models (Taber, 2019). Historic models are no longer used within the scientific community but are seen as important for education since they are part of our cultural history. Scientific models are the ones currently used by the scientific community, and they are also transformed into educational models, models that are adapted to be suitable for learners at different educational levels. Educational models can in turn be categorized into curricula models, expressed models, and individual models. Educational models can be defined as consensus models, meaning that scientists, textbook-writers, and other members of an educational community have agreed on the level of the simplifications made. These consensus models then become expressed models when used by the teacher in teaching (Taber, 2019). The individual then interprets the expressed models, and these become individual models (Gilbert et al., 2001). In this process of interpretation, it becomes important for teachers, who work with educational models, to be explicit concerning the nature of a model. A framework designed to help teachers work with models was described by Gilbert (2004), who suggested that the different aspects of modeling should include an understanding that a model is not a replica of the world; it is an interpretation, meaning that there can be many different models in use for the same phenomena. Models are used as tools for supporting conceptual understanding, solving problems or predicting outcomes of processes. Even if the model is perceived as an object, the model can be an interpretation of an "idea, a system, an event or a process" (Gilbert, 2004). As research progresses, new models are created leading to models becoming superseded and eventually seen as historic models. This multitude of historic models introduced to learners often as a way to introduce the cultural history of science may in fact not always be helpful, as research shows that teachers and textbooks in some cases present inaccurate hybrid models that are combinations of different historical models (Justi and Gilbert, 2000).

Models as tools for teaching

The actual process of how to support students' own modeling has also been described by Justi and van Driel (2006) as beginning with initial observations of a phenomenon, where a few specific parts of the phenomenon at hand are chosen, and a model is initially produced, then later manipulated, and finally the limitations of the model discussed.

Another suggestion, more focused on analyses of the teaching models themselves, was made by Glynn and Duit (1995) who described six different steps for introducing models to students, beginning with the introduction of a target model and followed by an overview of the teaching model. These six steps are relatively similar to the steps suggested by Justi and van Driel (2006) with identification of the relevant aspects of the models, "finding similarities, mapping similarities, identification of where the analogy breaks down and drawing conclusions of the target model." Indeed, types of systematic use of models can be done with three different kinds of intentions (van Joolingen, 2004), which are communication, analysis, or explanation: a model as a way of communication is where the intention is for students to create their own models to express their ideas; for analysis, the intention is to analyze the properties of the model itself or its usefulness in explanation, and models used for explanation involve the intention for students to recreate models to explain results or make predictions.

Research into the development of individual models is abundant and researchers have performed meta-analysis to categories the different types of individual models that have been found. One of these meta-analysis was performed by Talanquer (2006) here learner's interpretations was categorized into the empirical assumptions; continuity, substantialism, essentialism, mechanical causality, and teleology. Assumptions that in combination with the following heuristics: association, reduction, fixation, and linear sequencing were found to be the basis of many of the individual interpretations. Another approach is to find and explore precursor models, i.e., individual models that are seen as fundamental for building further understanding of a subject area (Pantidos et al., 2022). The atom has been suggested to be one of the precursor models (Koerber and Osterhaus, 2019) something that makes research into students understanding of the atom an important field. Traditional methods using educational models for visualizing different aspects of the atom such as different types of 2 and 3-d models are commonly used where a sense of scale is provided using verbal or written communication. Today research points toward the importance of multimodal teaching approaches including body language (Pantidos et al., 2022) and better support for student using inscriptional stories as a new way to move from the everyday world to abstractions (Pantidos et al., 2022).

The type of modeling that is the focus of the present study is a model for communication or students' own models used as a way of expression. Here, students construct a model in order to express their own ideas, which is a type of modeling used as means to gain insight into student ideas (Nersessian, 2002; Halloun, 2006) and to promote metacognition (Gilbert and Justi, 2016). This type of modeling provides an opportunity to work with a content on different levels (Gilbert, 2004): tangibly and concretely using 3-D material; verbally involving speech and writing where model discussions can use metaphors and analogies; visually with the help of drawings, diagrams, animations, illustrated stories and so on, as well as with gestures or bodily representations; and symbolically using formula equations.

Expressed models are composed of concepts and relationships that can be temporal, spatial, and causal relationships. The analysis of student-generated models can be made using appearance, literal similarity, tightness (closeness of source and the target), and with what has been described as true analogy (where the composition of the target cannot be transferred but the relationships can) (Duit, 1991).

Creative expressions in science education

Today many schools are culturally diverse and multilingual (Wilmes et al., 2018). A situation that has placed focus on the need to provide learners with multiple ways of accessing and expressing knowledge, especially using non-lingual modes (Roth and Lawless, 2002). Researchers have argued for an expansion of the concept of literacy to include visual (graphs and images), spatial (episodic movement), gestural (hand and body movement), auditory (sound effects and music), tactile (sensory hands on), oral (speech), and written modes (Williams and Tang, 2020). In this context science is viewed as a specialized language, something that may become an additional challenge for learners at all ages. Research shows that gestures and body language support learners both in learning (Cervetti et al., 2015; Pantidos and Givry, 2021) as it can promote moving between spoken language and thought (Bracey and Zoë, 2017), fill gaps in language (Korkmaz and Unsal, 2017), be used as pedagogical scaffolds (Santau et al., 2010), as well as communicating understanding (Siry and Martin, 2014). In the present study, student-generated models was designed to be expressed in the form of playdough creations. Combining creative expression with science is as old as science itself and can be seen in stone carvings dating back to 3,500 before christ (BC) that display lunar cycles and calculations (Steele, 2000). Research shows that creative expressions in science education have many advantages such as providing connections between different subject content (Herro and Quigley, 2016) and placing science in a real-world context (Gilbert et al., 2011). Creative expressions are also important for visual thinking, structures, interpretation of 3-dimensional aspects of phenomena, combining both processes and concepts in expression (Begoray and Stinner, 2005). They can also be a way to integrate learners' concepts and canonical science (Scott et al., 2011) and become foundations for new pedagogies (Braund and Reiss, 2019), and a ways to express knowledge beyond written or spoken language for second language learners (Aubusson et al., 2006).

Models in chemistry

The use of teaching models cannot be avoided when teaching and learning chemistry, especially since many of the explanations in chemistry are based on a sub-microscopic level. The tools that teachers can use for providing their students with experiences on this non-visual level are the use of analogy and models; all of which by necessity are macroscopic in their nature. The words used for describing the sub-macroscopic level were not all newly invented as our understanding of this level developed. Instead, some of the words used are also macroscopic in nature and may lead to unwanted analogy formation. In the Swedish language, for example, the word *shell* (skal) is the word also used for different fruit peels such as an orange peel and apple peel or an eggshell. The word *nuclei* (kärna) is the same as the word used for kernels, which can lead many students toward fruit analogs in connection to the atom. Other analogs found in connection with the atom are that the atom is seen like a ball, or a solar system (Harrison and Treagust, 1996). This particular problem, using a macroscopic view of the sub-microscopic level, can derive from many different sources, such as, macroscopic word use, the learning process itself where children connect new experiences to previous macroscopic ones, or a lack of ways to provide experiences of the sub-microscopic world. Indeed, research shows that it is not uncommon to find students who believe that atoms can be viewed in a normal microscope or that the illustration that they see in textbooks and other media are real images of the atom (Papageorgiou et al., 2016).

When turning toward research concerning the learning process itself, it shows that young children's learning of the concept of *small* (atoms and molecules) begins with the use of analogy (Adbo and Vidal Carulla, 2020), where for example pieces of crushed sugar seen through a magnifying glass are described as ice blocks. The development of a sense of scale and an understanding of the sub-microscopic world can be enhanced by zooming-in videos that visualize the transition between the macroscopic and the sub-microscopic level. A sense of scale can be provided if the zooming-in video is perceived as occurring at constant speed; the difference in perceived time between the different levels of organization then gives an understanding of scale to the extent that 5-year old children describe atoms initially as meatballs, and then recognizing that the analogy is not enough, the children conclude that these are not meatballs, they just look like meatballs; the word *atom* was then introduced. The sense of scale is seen through comments, such as, "They are everywhere in everything." In summary, the concept of atom at that point in time did include shape, 3-dimensionality, and a sense of scale (Adbo and Vidal Carulla, 2020).

The aim of the present study was to move beyond language and provide students with as much creative self-expression as possible to express their own models of selected atomic nuclei. The study aimed in particular at exploring:

- What do the students' expressed models look like when they are given the opportunity to move beyond spoken language?

- In what way can creative visualizations contribute to contemporary science education?

Materials and methods

Context

The participants in this study were 64 students taking the first of two chemistry courses in a university course during a so-called foundation year, which provides preparatory education of science content that is equivalent to the upper secondary level. The requirements for admission to the foundation year are a completed upper secondary level program that is preparatory for higher studies. The foundation year provides the basic natural science courses required for entrance to university level in natural science for those students who wish to obtain higher grades or add courses that were not completed in previous studies. Several of the students included in this study, therefore, had previous experience in chemistry at this level. All students included had formal chemistry at lower secondary school, students age 13–16, something that contain the structure of matter, atoms, electrons, and nuclear particles. At the beginning of the course the atom was reintroduced to the students. The teaching model for the general atom in use within this course was the one in **Figure 1**. This model includes protons and neutrons depicted in a way that attempts to show the three-dimensional structure of the nucleus. Electron movements are communicated as probability clouds (marked with gray color). The mass of all particles in the form of atomic mass units (u) and the charge of all particles are included in the model. There is also a small difference in size between electrons and protons, a difference that by no means is close to the perceived reality but a difference, nonetheless.

Data collection

The students were asked to build a selection of atomic nuclei using play dough and choose different colors for the different sub-atomic particles included. Additional instructions were:

1. Build the following atomic nuclei: The most common form of Hydrogen, Helium, Carbon and Oxygen and take a photo of it.
2. Draw the nucleus.
3. Provide a written explanation to the built nuclei and calculate their masses in u.

The students were also provided with a periodic table that included atomic number and atomic mass.

The choice of using playdough was made since it provides ample creative freedom for working in three dimensions, without restrictions on size and shape. The students were also asked to provide a written explanation to their different nuclei, calculate the mass of each nucleus using units (u), draw their nuclei, and take a photo of each nucleus. Information that was used in the interpretation of students' constructions. The students worked in groups of 2–4 students, but each student made his or her own nuclei. Notes of *ad hoc* discussions were collected while the teacher circulated in the room. The only other instruction the students were provided was to use one color for each of the particles. The fact that the playdough was colored was misleading, but an issue that could not be resolved. Each student had at least three different colors of playdough to choose from.

To meet ethical considerations, consent forms were collected from all students. All data collection and data storage are in compliance with general data protection regulation (GDPR) according to the european union (EU) standards (2016).

Data analysis

Data in the form of construction from playdough, written explanations and *ad hoc* field notes was analyzed independently by two researchers using Hedegaard's three levels of qualitative analysis (Hedegaard, 1995) where the first level is called the commonsense interpretation. At this level of interpretation data from the 64 students were merged into, individual, consecutive series of atomic nuclei. The second level of analysis, called situated interpretation, was then applied to the data set. In this level of analysis, students written explanations and common structural and functional patterns of the models were in focus. Especially, the differences between the teaching model and the student expressed model were analyzed for literal appearance and tightness and the images was then sorted into two different categories; models with close resemblance to the teaching model and models with less resemblance to the teaching model. Representational series of images for each set of deviations were selected. The third level of analysis, called thematic and conceptual interpretation, was performed here with analytical focus on identifying general connections between the findings and the existent research literature. The analysis did not include body language or social interactions.

Results and discussion

Due to the diversity of the student group and the number of atomic nuclei models available to students today, it is only the teaching model in use within this course that can be addressed and the conclusions regarding teaching models can only be drawn from students' models. When comparing the teaching model to students expressed model, no difference between the different student groups could be detected, i.e., meaning that there was no difference between the students that had previously studied chemistry at upper secondary school level and those who had not.

Results are presented in the form of photos of the students' expressed models and categorized into two major categories, one with close resemblance (**Figure 2**) to the teaching model and one with less resemblance to the teaching model (**Figure 3**). The construct of individual students' series was maintained within the categories since it provided information of student reasoning when creating nuclei of different sizes with different types of interactions between the subatomic particles. The models were built on a single occasion, proving a cameo-shot of the diversity of student's interpretations and considerations. The series of categorized images that were found in the dataset here referred to as: close resemblance and less resemblance, represent the different variations of playdough models, deriving from the 64 students participating in the project. Models with close resemblance are presented in **Figure 2** and models with less resemblance in **Figure 3**. The category with close resemblance to the teaching model included models that were correct regarding written explanations, number of protons and neutrons in the playdough model, and mass was provided in a correct manner. Even though the answers were in close resemblance with the teaching model, 16 different series of nuclei were found in the assembly of the constructed model. Of the 64 students included in the study 70% of the students' models was found in category: close resemblance. In the category: less resemblance (**Figure 3**) the students included an incorrect number of sub-atomic particles, ignored the size differences of the particles or added particles not relevant to atomic nuclei. A total of 30% of student models were found in this category. Results deriving from the series of atomic nuclei (H, He, C, and O) show in total 32 different variations.

Analysis of the category: Close resemblance

In this category the series with close resemblance toward the teaching model of the atomic nuclei concerning the number of protons, neutrons and their respective mass, show 16 different variations in the placement of protons and neutrons (**Figure 2**). In general, the differences between the students' models and the teaching model depend on what specific feature (Lakoff and Johnson, 1987) the student focusing on at the time. This approach of working with one or a few features at a time shows how the students used the models as a form of visual thinking (Begoray and Stinner, 2005) in integrating different experiences into science (Scott et al., 2011).

The overall shape of protons and neutrons was also a feature that became important as it contributed to the overall shape of the of the nuclei. The shapes of protons, neutrons, and electrons were either circular leading to there being space in-between them (for example, C5 in **Figure 2**), or they were shaped as wedges leading to no space in-between them (for example, C8 and C15). The protons and neutrons could also be loosely assembled (for example, C7) or close together (for example, C2). Different students used different entailments when building their nuclei, which led to nuclei that were 2 or 3-dimensional, tetradic (for example C1), flat (for example, C5), round (C15), square (C10 and C14), circular (C13), linear (C12), linear-curved (C13), triangular (C6), donut-shaped (C8), and star-shaped (C7).

One group of students saw the construction of atomic nuclei as a continuous repetition of helium nuclei (C12), and the students explained that "*the carbon and oxygen nuclei are made of three and four helium nuclei.*" These models hold no or little visual resemblance to the teaching model, but they do make sense when focusing on one specific feature, such as number of protons and neutrons. If the focus was only on producing the correct number of protons and neutrons, then

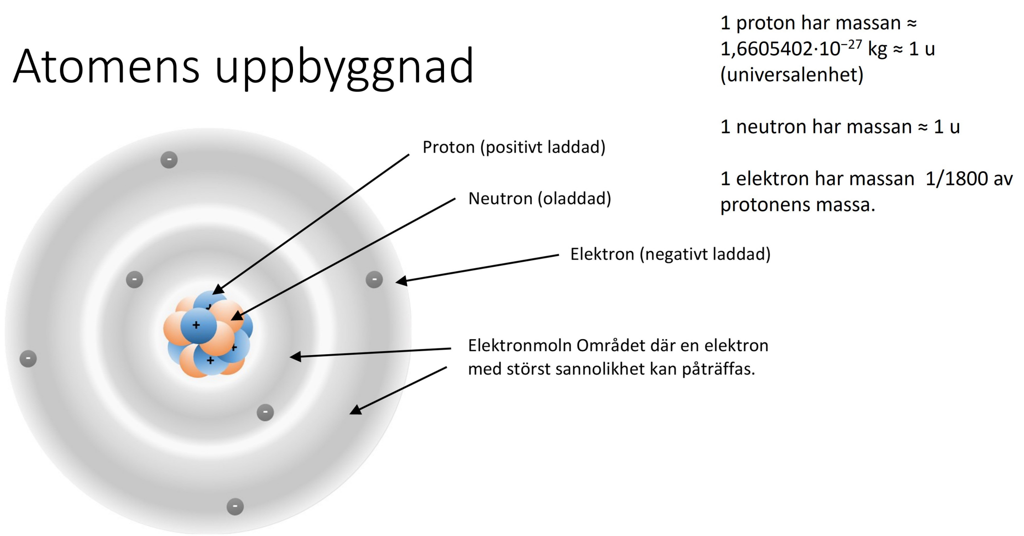

FIGURE 1
The teaching model used for the students included in this study.

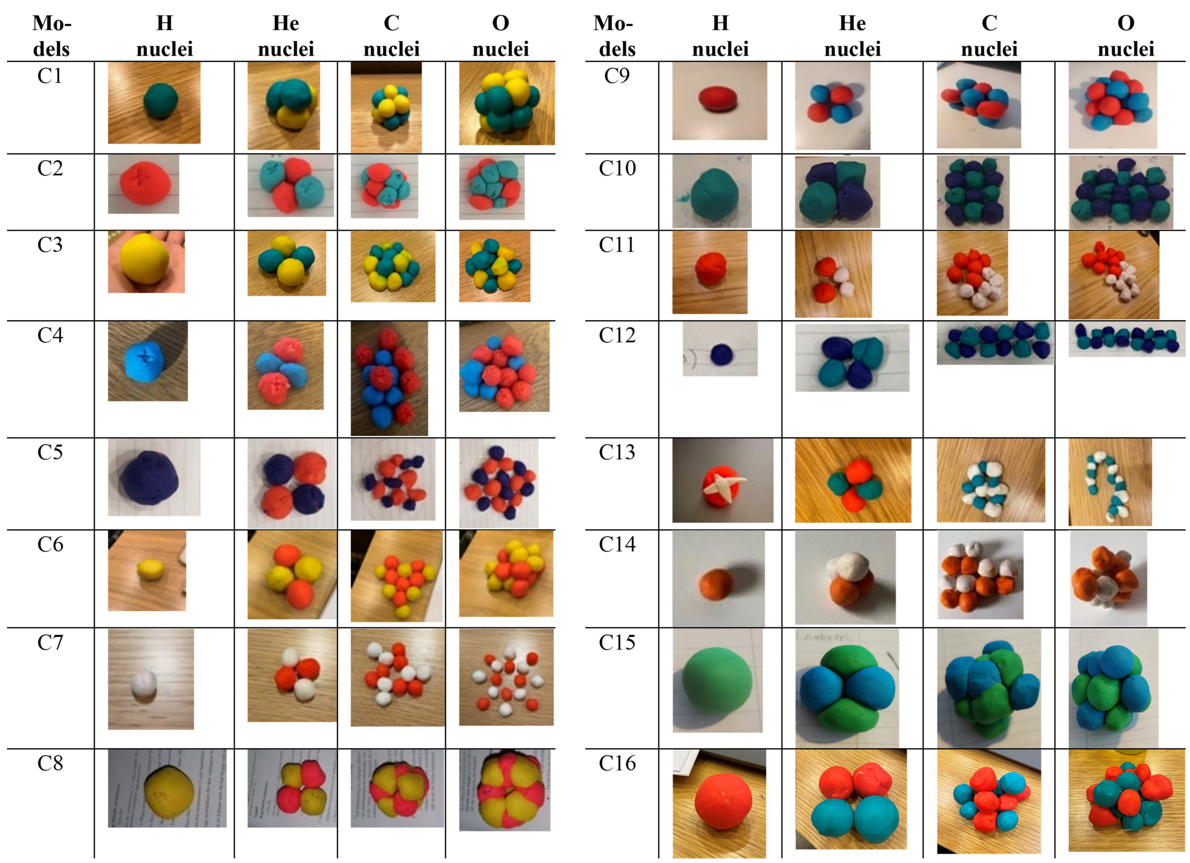

FIGURE 2
Models with close resemblance to the teaching model regarding written explanations, a correct number of protons and neutrons in the playdough model, and mass was provided in a correct manner. Series of atomic nuclei in the order: Hydrogen (H), Helium (He), Carbon (C), and Oxygen (O). One student in each row (C1–C16) and the different versions of the nuclei are found in the columns.

FIGURE 3
Models with less resemblance to the teaching model. Series of atomic nuclei in the order: Hydrogen (H), Helium (He), Carbon (C), and Oxygen (O). One student in each row (L1–L16) and the different versions of the nuclei are found in the columns.

the student may not have considered other aspects such as structure and repulsion; one example is C11. If C12 placed focus only on repulsions but not shape, then linear nuclei could also be a reasonable result. These series point toward the students at least initially using one or a few features at the time when working with the teaching models for the atom. This result shows the importance of giving careful attention to teaching models that simultaneously include all relevant features surrounding atomic nuclei.

All these results point to the importance of moving beyond the use of language. Some examples stand out; a student wrote, "*Helium has two protons and two neutrons in the nucleus*" which is an answer that could have been deemed correct until the student built a nucleus (round ball) and then attached two protons to it (L7 in Figure 3). Several of the students provide correct answers regarding the number of protons and neutrons, but built models with a different number of particles. The opposite also occurs, where the model looks reasonable, but the written answer was incorrect. This finding shows the flexibility of models in use during the learning process.

Although the teacher pointed out to the students on several occasions that they should only build the nucleus and not the atom, totally 16% of the students added electrons to their play-dough models.

Analysis of the category: Less resemblance

In this category student expressed model deviates from the teaching model in that it did not include the correct number of protons or neutrons, electrons were added, size differences were ignored or particles not relevant to atomic nuclei was added (Figure 3). The addition of electrons placed focus on size differences between the subatomic particles. Size and scale are inevitable problems when teaching chemistry, as the actual distance cannot be displayed using the normal variety of teaching models available to teachers. Despite this problem, teaching models do show some size difference, and even if not realistic, many of the students did not take this difference into account (L16) but instead placed the visual similarity on distance between the electron and the nuclei (see for example, L2). Most students that added electrons to their nuclei provided explanations that confirmed that this was their intention. Some also included an electron trajectory; one example is L2 with "*one electron trajectory and one electron and one proton*." The addition of electrons did provide variations in the form of shells and the placement of electrons. Some placed electrons on one side of the nucleus (L6); it is difficult to draw a conclusion about the reasons behind this construction, but it is nonetheless an important feature for teachers to address. For some students, the electrons were evenly spread out in different shells or placed closely around the atom. Several of the students placed the electron directly onto the proton in the hydrogen nucleus (L5 and L16), but the distance between electrons and the nucleus increases when the students build larger nuclei, which is a placement that may stem from students trying to depict the small size of the first two atoms and possibly recognizing that space occupied by electrons. The atomic nuclei in Series L1–L6 in Figure 3 contained the same kinds of deviations as seen in the category: close resemblance.

Series L7–L16 in Figure 3 includes the models that deviates the most from the teaching model. This category includes student models were the number of particles either did not match the number of particles in their written explanations (L8–L11) or the number of neutrons in the nuclei was incorrect (L12 and L15). Some included additional particles not found in the teaching model (L7), added protons and electrons in same sizes (L16) or added protons and neutrons of different sizes to their models (L13). One student placed the neutrons in a circle around a core of protons (L14). Of the 64 series in total 17% were included into series L7–L16.

Analysis of their written answers

The detailed analysis of the results from the atomic nuclei in Figure 2 shows how uncertain the students were, even those who had built a model with close resemblance to the teaching model (here, the hydrogen nuclei). They expressed doubts concerning their construction; for example, "*Is it only one ball? It seems too easy*." In the category of less resemblance some students used the word atom for their construction of the atomic nuclei or built an atom and then referred to it as an atomic nucleus. Analysis of the written and verbal explanations for the hydrogen atom (see Table 1) shows the difference in word use. Only eight variations in explanations were found amongst the 64 students, a result that shows how similar students' explanations were, a result that may suggest that definitions/explanations were rote learned.

TABLE 1 A summary and categorization of all students written explanations regarding the hydrogen nucleus.

Categories of answers	Percentage of answers
Uses word hydrogen atom or atom in their answers instead of nucleus/nuclei	
1. *"A hydrogen atom weighs, 1u".*	8%
2. *"The hydrogen atom is made of 1 proton and has the mass of 1,008 u".*	
Uses the word hydrogen instead of nucleus/nuclei	
1. *"Hydrogen is made of 1 proton and then has the atomic mass of 1u".*	11%
2. *"Hydrogen has only one proton and has the mass of 1u".*	
Used the word hydrogen nucleus or the nucleus of the hydrogen atom	
1. *"The hydrogen nucleus is composed of one proton, the mass is 1u".*	33%
2. *"The hydrogen nucleus is made of only one proton. 1u = 1.66 × 10^{-27} kg". "The most common form of the hydrogen nucleus is made of one proton and no neutrons. It weighs 1u".*	
Does not provide the word nucleus or nuclei or atom in their answers	
1. *"1 proton 1u"*	25%
2. *"It is made of 1 proton with a mass of 1u".*	
Uses only the word nucleus or atomic nucleus	
1. *"The nucleus is composed of 1 proton with a total mass of 1.007276 u".*	5%
2. *"The atomic nucleus is made of only one proton 1u".*	
Includes electrons into their nucleus/nuclei	
1. *"1 proton and one electron. The mass is 1u".*	9%
2. *"1 proton and one electron, Mass = 1u".*	
Includes electron orbitals and shells	
1. *"One electron orbital and one electron and one proton the mass of the atom is 1u".*	6%
2. *"It is composed of 1 proton in the nucleus and 1 electron in the shell and has the mass of 1,008 u".*	
More deviant explanations	
1. *"Is made from one atomic nucleus and one proton in the shell and it weighs 1u".*	3%
2. *"One helium atom is made of 1 proton. The mass is 1u (1.44 × 10^{-27})".*	

These results of the playdough constructions can depend on several different reasons, such as a mix-up of words or how the task was formulated; for example, a task that included weight might have given the impression that the electron should be included in the expressed model since the weight of the electron was included in the teaching model. Additionally, it is not uncommon in textbooks to represent both the atomic nuclei and the atom as one circular 3-dimensional ball depending on what phenomena the author is addressing. These types of mixing of teaching models were nonetheless an issue that became visible when the students were provided with the opportunity for creative expression in this form.

Conclusion

The result of this study shows the importance of the mode of expressions provided to students. Written explanations provided eight categories or variations while the playdough constructions opened for choices in assembly of nucleic particles and as a result the number of variations increased. The use of one feature at a time, such as only considering number of particles with no regard for 3-dimensionality, place focus on the importance of not only allowing for the exploration but also on the importance of the teacher to provide a holistic view where all relevant features are taken into consideration. This approach to problem-solving concepts, that is, giving the student a form of creative freedom to express the atom and atomic nuclei, provided teachers with student-generated models suitable for discussion using the framework for models (Gilbert and Justi, 2016).

Moving beyond verbal and written language did indeed provide a level of detail to students' interpretations of concepts that would otherwise have been difficult to reach. Variations to the method, for example, by asking students to build an oxygen atom and then changing it to a nitrogen atom or building a nitrogen atom and changing it to a carbon-14 isotope, could be tasks that would place more focus on isotopes than the problems used within this study.

Limitations to the study

Data collection includes 64 students, a number that does not provide saturation of the data set. The results presented here is a cameo-shot of students' interpretations and consideration expressed only in the form of playdough models and written explanations. The design of the study did not include data collection and analysis of body language such as gestures something that may have delimited the results. Also, a more in-depth analysis would have been possible if discussions and social interactions had been recorded.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

Ethical review and approval was not required for the study involving human participants in accordance with the local legislation and institutional requirements. The participants provided written informed consent to participate in the study.

Author contributions

Both authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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