Journal of Turkish Science Education, 2025, *22*(4), 703-723.
DOI no: 10.36681/tused.2025.035

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

Coordinating multiple representations in a hybrid real–virtual laboratory: Students' strategies in learning light reflection and refraction

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ABSTRACT
This study investigates how middle school students coordinate multiple representations while learning about reflection and refraction of light in a hybrid laboratory environment that combines real and virtual settings. Conducted as a qualitative case study, the research involved a group of 48 students enrolled in a public school. The dataset comprised video and screen recordings from real and virtual experiment sessions, student worksheets, drawings, semi-structured interviews, and findings from a concept test administered prior to the implementation. The data were coded with respect to representation use, patterns of transitions and correspondences among representations, and levels of abstraction (concrete–intermediate–general). After establishing inter-coder reliability, the data were analyzed through descriptive and content analysis methods. The findings indicate that students transitioned between real experiments, simulations, schematic drawings, and mathematical expressions using specific strategies, such as verification, re-representation, and elaboration of explanations. However, these representations were not always fully integrated. Levels of abstraction were found to be predominantly concrete during the exploration phase, while shifting toward more general principles during the modeling and discussion phases. The results from this two-session implementation suggest that hybrid laboratories may not fully realize their pedagogical potential for supporting multiple representations unless representational transitions are intentionally structured and guided by the teacher.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received:
05.01.2025
Accepted:
07.05.2025
Available Online:
27.11.2025

KEYWORDS:
Multiple representations; hybrid real–virtual laboratory; simulation-based learning; light reflection and refraction.

To cite this article: Dinçer, S. (2025). Coordinating multiple representations in a hybrid real–virtual laboratory: Students' strategies in learning light reflection and refraction. *Journal of Turkish Science Education, 22*(4), 703-723. https://doi.org/10.36681/tused.2025.035

Introduction

In science education, conceptual learning demands an understanding of the underlying principles of phenomena, rather than the rote memorization of formulas and definitions (Bessas et al., 2024; Jaakkola & Veermans, 2020; Wang et al., 2025). Instruction that relies on single, predominantly abstract representations does not consistently support students' ability to transfer what they have learned to new situations (Jaakkola & Veermans, 2020; Lore et al., 2024; Ulger, & Çepni, 2020). Consequently, presenting scientific topics through multiple representations (graphs, diagrams, physical models, verbal descriptions, and equations) allows learners to relate different aspects of a phenomenon and construct a deeper, more integrated understanding. The benefits of multiple representations do not emerge automatically; in the absence of appropriate pedagogical design, they may in fact increase distraction and cognitive load (Becker et al., 2020; Lore et al., 2024).

In effective designs, how the representations complement one another must be made explicit, and students should be supported through strategies for transitioning between, matching across, and integrating different representations (Ainsworth, 1999; Lore et al., 2024). In this way, simplified abstract representations can foreground generalizable principles, while concrete representations and experiences can serve as a bridge to everyday life (Fyfe et al., 2014; Jaakkola & Veermans, 2020; Rau et al., 2017). In this context, the combined use of real (physical apparatus–based) and virtual (simulation-based) laboratories is particularly noteworthy. Simulations make complex processes visible by idealizing them, whereas real laboratories provide opportunities for direct observation and tactile feedback. An appropriately designed hybrid configuration can integrate the complementary advantages of both approaches (Bousquet et al., 2024; de Jong et al., 2013; Manyilizu, 2023).

Although the international literature has made substantial progress in these areas, detailed findings remain limited in the Turkish context, particularly at the middle school level, regarding how students coordinate multiple representations in real and virtual environments (Ardac & Akaygun, 2004; Tüysüz, 2010). Existing classroom-based interventions in Turkey have largely focused on improving students' conceptual understanding or views of the nature of science through structured inquiry models, rather than on fine-grained analyses of representational coordination in hybrid laboratory settings (Bakırcı, Çalık, & Çepni, 2017).

In light of this, the present study aims to examine in detail how middle school students coordinate multiple representations, observations from real experiments, simulation screens/outputs, drawings and diagrams, mathematical relations/formulas, and verbal explanations, within the "reflection and refraction of light" unit in a learning environment where real (physical-apparatus-based) and virtual (computer-simulation-based) experiments are used in combination. The study aimed to reveal students' strategies for transitioning between representations, matching or associating different representational forms, and integrating them effectively. It also sought to describe how the levels of abstraction observed in this process, ranging from concrete descriptions to intermediate explanations and general principles, varied across different phases of learning, namely exploration, modeling, and discussion. In doing so, the study intended to generate evidence on how real–virtual laboratory combinations either facilitate or hinder inter-representational coordination, thereby offering design principles and practical implications for the integration of real and virtual laboratory activities in science education. In line with this aim, the following research questions were addressed:

- What strategies do participants use to coordinate multiple representations in a learning environment where real and virtual experiments are integrated?
- What are the frequencies with which participants transition between different representations and attempt to match them?
- What levels of abstraction are observed in participants' expressions, and how do these levels vary across different phases of the learning process (exploration, modeling, and discussion)?

Literature Review

The integration of digital technologies and the use of multiple representations in science education have gained increasing prominence. Recent research in this area emphasizes that students' ability to represent scientific concepts in diverse ways is a natural and necessary part of the learning process (Flores-Camacho & Gallegos-Cázares, 2025; Irwanto et al., 2025; Nielsen et al., 2022). From the perspective of representational pluralism, students' sense making of science topics through various mental models or representational forms is viewed not as an error or deviation, but as a natural process in the construction of knowledge. Flores-Camacho and Gallegos-Cázares (2025) reinforce this perspective by advocating the design of learning environments in science education that deliberately encourage students to debate multiple representations instead of imposing a single "correct" one. In school settings, however, a recurring tension between plurality and uniformity is evident. While students tend to depict a scientific phenomenon through diverse alternative conceptions, teachers, constrained by the curriculum, often favor the adoption of a singular, standardized representation (Cheung & Erduran, 2025; Nielsen et al., 2022). Hence, the instructional process must strike a balance between fostering representational pluralism and ensuring conceptual coherence.

Research shows that working with multiple representations (text, visuals, graphs, symbols, etc.) plays a central role in scientific understanding (Lore et al., 2024; Nielsen et al., 2022; Stöger & Nerdel, 2024). Because different representations highlight different facets of scientific understanding, engaging students with these multiple representational forms can deepen their conceptual learning. For example, expressing a phenomenon both verbally and visually helps students construct a richer mental model of the topic. Studies further demonstrate that instructional activities designed to develop representational competence can simultaneously enhance students' representational skills and their subject-matter knowledge (Rau, 2017). A study conducted by Lore et al. (2024) elaborates on this issue in detail. The researchers reported that, in a multi-representational learning environment modeling the earthquake cycle, although the majority of students exhibited representational skills to some extent, only a small subset demonstrated advanced proficiency in coordinating and making sense of representations. Moreover, the study concluded that specific representational competencies, such as the ability to interpret simulations represented through code blocks, were significantly associated with overall achievement. These findings highlight the necessity of structuring and scaffolding representational competence in science education.

In addition, new analytical frameworks are being developed to better understand how students represent scientific concepts. For example, Cheung and Erduran (2025) designed a framework capable of analyzing students' understandings of the nature of science as expressed through both drawing and written modalities. Because previous assessment instruments generally evaluated students' views only through written responses, this study provided a more comprehensive account of their thinking about scientific methods and practices by also incorporating multiple modes such as drawings. In their study, Nielsen et al. (2022), investigated how a preservice science teacher employed multiple representations while producing a digital explanation. The teacher candidate created a multimedia product; including images, text, and animations; to explain the concept of transparency to 11- to 12-year-old students. Observations and interviews conducted throughout the process showed that the candidate built understanding by seamlessly transitioning among representations and interweaving them. This creative process enhanced both the candidate's conceptual understanding of the topic and their facility in mobilizing diverse semiotic resources. This finding suggests that having students or preservice teachers produce their own digital content and representational examples can make substantial contributions to learning through iterative reflection and revision.

In a study conducted in the context of limited laboratory resources in Tanzanian chemistry classes, Manyilizu (2023) reported that students who first engaged in experiments using a virtual chemistry laboratory performed significantly better in the real laboratory compared to those who started directly with the real laboratory. It was particularly emphasized that starting with the virtual laboratory improved learning outcomes by providing students with prior experience before the hands-on experiment. Similarly, in Indonesia, Lestari et al. (2023) conducted a study with students with low levels of scientific literacy, testing an instructional model that combined the use of virtual laboratories with teacher demonstrations. They reported that this blended approach led to the greatest gains in students' scientific literacy scores compared to using either virtual laboratories alone or demonstrations alone. This finding suggests that virtual tools can play a complementary role, supporting real laboratory experiences by addressing students' conceptual gaps.

In another study, Wang et al. (2025) conducted a meta-analysis of 27 studies published between 2001 and 2021 to examine the effects of combining real and virtual experiments in physics education. This comprehensive analysis revealed that the integrated use of real and virtual experiments had a positive and statistically significant effect on students' learning outcomes compared to using real experiments alone. It has been found that hybrid experiments are particularly beneficial in more abstract and complex areas of physics, highlighting the advantage of visualization provided by virtual environments in facilitating the understanding of abstract concepts. Moreover, the meta-analysis emphasized that factors such as class size and the sequencing of experimental activities can influence outcomes; the most effective learning results were observed in small-group settings with virtual–real experiment sequences designed according to a specific pedagogical framework.

Virtual reality (VR) applications offer considerable pedagogical potential in science education, as they can immerse learners in interactive three-dimensional environments that foster high levels of cognitive and affective engagement. A recent study by Irwanto et al. (2025) illustrated this potential. In this study, the topic of chemical reaction rates was taught to 11th-grade students using a VR-supported environment for the experimental group, while the control group received instruction through PhET simulations and video-assisted explanations. The results showed that the group using VR achieved significantly higher scores than the control group on both creativity disposition and academic achievement measures. Students in the VR group exhibited large effect sizes on both metrics, indicating that VR produced a marked advantage over traditional digital resources. In this context, the researchers emphasized that VR-based learning experiences foster students' creative thinking and, through visual–kinesthetic feedback, increase engagement with the lesson and depth of learning. The ability to manipulate objects interactively in the virtual environment helped students focus their attention on the learning objective and better comprehend the chemical process. This study demonstrated that VR serves not merely as a substitute for conventional instruction but as a tool that complements and enriches it, fostering students' active participation and higher-order thinking skills.

Likewise, the system HOBIT, developed by Bousquet et al. (2024), exemplifies the use of augmented reality (AR) in science education. HOBIT was conceived as a hybrid optical apparatus for teaching wave-optics topics by overlaying virtual layers onto a real optical bench. Within this platform, students can physically adjust and manipulate optical components such as lenses and mirrors, while simultaneously observing the consequences of their modifications in real time via virtual sensors and displays. Thus, abstract concepts that are normally imperceptible, such as the frequency or polarization of light waves, are rendered visible through augmented reality, thereby facilitating comprehension. The HOBIT platform affords flexibility by enabling rapid setup of numerous experiments with a single apparatus and by virtually modeling equipment such as lasers that may be costly or hazardous, thereby minimizing safety concerns. Such AR/VR-based laboratory applications have created innovative learning environments that allow students to gain experience and receive virtual feedback. However, review studies note that although virtual/remote laboratories include tools that support communication and group awareness, components that scaffold and regulate collaboration remain limited (Elmoazen et al., 2023; Kurtz et al., 2025). However, rather than focusing on collaborative design, this study concentrates on how students individually coordinate multiple representations.

The effectiveness of technology-enhanced science instruction largely depends on how such tools are utilized. Research has shown that the perceived usefulness of new and engaging digital tools does not always align with expectations. For example, Sheffield et al. (2024) implemented a gamified virtual laboratory simulation with pre-service science teachers in Australia over the course of one semester and subsequently evaluated their perceptions of the experience. Despite the general popularity of the concept of gamification, the pre-service teachers participating in the study reported that the application did not significantly contribute to the development of their content knowledge. Many students also noted that the laboratory simulation did not fully capture their interest or deepen their subject understanding. This finding indicates that the mere inclusion of digital technologies in educational settings does not automatically ensure high engagement or effective learning. Instead, factors such as user experience, the alignment between content and technology, and students' intrinsic motivation play a critical role in determining educational success (Dodevska et al., 2025; Irwanto et al., 2025; Wang, 2025). Therefore, incorporating student feedback into the design and implementation of educational technologies and aligning the tools with pedagogical objectives is a critical consideration.

Meanwhile, the VR-based chemistry experiment system developed by (Lu et al., 2024) demonstrates how well-orchestrated technology integration can yield concrete benefits. Using a VR headset and hand-gesture recognition hardware, the system simulates high school–level chemistry experiments with a high degree of realism. Evaluations indicated that the VR-supported chemistry laboratory offered greater realism (physical fidelity) and usability compared to similar products currently on the market. In other words, while experimenting in the virtual environment, students felt as though they were working in an actual laboratory and judged the system to be the more suitable option. This finding suggests that a well-designed virtual experiment environment can furnish learners with an experience that is both realistic and pedagogically effective. Nevertheless, considerations such as the requisite infrastructure, costs, and teacher training must be addressed for the widespread adoption of such advanced technologies in schools.

In sum, the literature unequivocally underscores the pedagogical power of multiple representations; yet the realization of this potential appears to hinge on the deliberate design of processes that facilitate students' transitions and alignment among representations.

Method

This study was designed as a case study that predominantly employed qualitative data to examine real and virtual laboratory activities on the topics of light reflection and refraction at the middle school level. In this context, the study examined the process of a combined real–virtual experiment on the "Reflection and Refraction of Light" unit taught in a public middle school. This approach involved students both conducting direct observations in the school science laboratory and, concurrently, modeling the same phenomenon through a computer simulation.

Participants

The sample consisted of 48 students (23 girls, 25 boys) enrolled in a public middle school. The students had previously encountered the topic in class and possessed prior knowledge of fundamental concepts such as angle of incidence, angle of refraction, refractive index, and the law of reflection. Prior to the activity, a 25-item concept test was administered; the pre-test produced a mean achievement score of 52.30 (sd = 9.50), and no significant differences were detected among the participants. The study was conducted on a voluntary basis, and the required parental consent forms and permissions were obtained.

Learning Environment and Instructional Materials

The hybrid learning environment combined a physical optics apparatus with a computer-based simulation. Each pair of students worked with a shared set of physical materials consisting of a laser light source, a plane mirror, a prism, and a rectangular water-filled tank mounted on a protractor base. These components allowed students to set up and observe standard reflection and refraction scenarios, such as light rays incident on a plane mirror or passing from air into water at different angles.

In parallel, students had access to an interactive ray-tracing simulation displayed on a laptop computer. The simulation presented a two-dimensional representation of a light ray crossing the boundary between two media and provided multiple representations of the situation, including a dynamic ray diagram, numeric readouts of incident and refracted angles, and sliders to adjust the refractive indices of the media. Students could change parameters such as the angle of incidence and the refractive index, observe the resulting change in the path of the ray, and toggle visual indicators (normal line, angle markers) on and off.

The instructional sequence was supported by a structured worksheet and a teacher guide. The worksheet included sections for recording measurements from the real apparatus and the simulation, constructing ray diagrams, and writing short verbal explanations that explicitly linked the different representations. The teacher guide specified the timing and goals of each phase of the activity (exploration, explanation/modeling, discussion), sample questions to be posed to the class, and explicit prompts designed to draw students' attention to correspondences and discrepancies across the real and virtual representations.

Procedure

In this study, a three-phase instructional activity was implemented to support students' learning by enabling them to use real experiments and virtual simulation environments concurrently. The simulations allowed students to engage in active learning by concretizing complex physical processes, whereas the real laboratory experiments provided opportunities for direct observation. The integrated activity, which combined the laboratory and computer-based simulation, was structured to capitalize on the strengths of both environments.

The activity was implemented over two class sessions of approximately 40 minutes each, involving 24 pairs of students working collaboratively. In line with the case-study design and our focus on fine-grained processes of representational coordination rather than long-term learning outcomes or method comparisons, this short but intensive sequence was deemed sufficient to generate a rich corpus of interactional and representational data. Each group received a physical experimental apparatus; comprising a laser light source, plane mirror, prism, and water-filled tank; along with a computer. The intervention was conducted in three phases, detailed below:

In the first phase, the exploration stage, students worked in pairs using the real experimental apparatus to direct laser light at various angles toward the mirror and the water-filled container, observing the phenomena of reflection and refraction. During this stage, each student was asked to mark the incident and reflected light rays and to measure the angle of refraction within the water. Simultaneously, a simulation running on the computer allowed students to test different scenarios involving the transition of light between media, thereby reinforcing their real-world observations. In this way, participants were encouraged to establish connections across multiple representations by reproducing the phenomena they observed in the real experiment within a virtual environment. On the worksheet accompanying this phase, students were asked to record their predictions and measurements in a simple table (incident and refracted angles, media involved, and a brief qualitative description of how the ray bent). Guiding questions included prompts such as "What happens to the refracted ray when the angle of incidence increases?" and "In which medium does the ray bend toward the normal?" At the beginning of the phase, the teacher briefly demonstrated the apparatus and reminded students of safety rules; during group work, the teacher circulated among pairs, asking them to explain how their real setup corresponded to the representation shown on the simulation screen.

In the second phase, explanation and modeling, students were asked to explain their observational data by drawing ray diagrams on paper. Additionally, they were prompted to test theoretical relationships using numerical measurement tools available in the simulation (adjusting the angle of incidence or refractive index). For instance, the refractive index of the medium was modified in the virtual setting, and the resulting angle of refraction was observed to determine whether the values aligned with theoretical expectations. In this phase, students deepened their understanding by observing in the virtual environment certain quantities they could not directly measure in the real experiment (the speed of light in different media). The corresponding section of the worksheet provided partially completed coordinate grids and ray-diagram templates on which students had to draw incident and refracted rays, mark angles with a protractor, and label media and normal lines. Students then used the numerical displays in the simulation to check whether their drawn diagrams and measured angles were consistent with theoretical expectations. At this stage, the teacher gave a brief whole-class reminder of the law of reflection and Snell's law and then asked groups to use the simulation to test these relationships under different conditions (changing the refractive index of the second medium).

In the final phase, each group presented its findings to the class and engaged in a whole-class discussion. During the discussion, results from the real experiment and the simulation were compared, and questions such as “How does the refraction of light in water actually occur?” and “What did you observe at the molecular level in the simulation?” were used to prompt reflection on relationships across representations. Through this interactive discussion, students collectively evaluated how multiple representations support one another. According to the lesson plan, each group selected one representative case (for example, a particular angle of incidence or a specific change of medium) and prepared a brief poster or board sketch summarizing the real apparatus, a simplified simulation screenshot, a ray diagram, and the corresponding angle measurements. The teacher moderated the whole-class discussion using pre-planned prompts such as “Which representation made it easiest to see the law of reflection?” and “Where did the real and simulated results differ, and how can we explain these differences?”, explicitly highlighting students’ use of multiple representations when comparing and justifying their conclusions.

Data Collection Instruments

During the data-collection phase, the laboratory environment and group interactions were documented using an observation form. Furthermore, each student’s computer screen was recorded with screen-capture software so that their interactions with the simulation were stored digitally. This procedure made it possible to analyze in detail the students’ synchronous activities during both the physical experiment and the simulation.

In addition, the ray diagrams that each group drew on their worksheets and in their notebooks, the measurement sheets they completed, and the schematic explanations they sketched on the board during discussions were gathered for analysis.

Following the activity, individual interviews of approximately 12–15 minutes were conducted with the students. During the interviews, students were asked questions such as, “What did you observe in the real experiment? What did you learn from the simulation? How did using the real and virtual experiments together affect your understanding?” All interviews were audio-recorded and subsequently transcribed verbatim.

In addition, students’ knowledge was measured quantitatively using a concept test. This test was administered as a 25-item multiple-choice exam before the real-experiment session; its reliability, calculated using the KR-20 formula, was 0.84. Accordingly, the concept test was used solely as a pre-instruction measure of students’ prior knowledge and group comparability and was not treated as an outcome variable in the present study.

Data Analysis

The qualitative data collected were examined using a descriptive content analysis approach. First, the observations and the interviews conducted with students were converted into textual transcripts. Key findings from the screen recordings were then incorporated into the corresponding transcripts.

Subsequently, the data transcripts were examined individually using the descriptive coding method. During the analysis process, initial codes were generated based on the research questions. Then, two independent researchers separately coded three sets of data using the coding scheme, and the resulting codes were compared. Any inconsistencies between the two coders were discussed to clarify and refine the code definitions, which were revised as necessary. For the purposes of the present analyses, the basic unit of analysis was the event/episode. An event/episode was defined as a short, thematically coherent segment of activity in which a pair of students focused on a single task or sub-task (setting up a particular ray path in the real apparatus, adjusting parameters in the simulation, or constructing a ray diagram) and used one or more representations to reason about that task. Episode boundaries were marked whenever there was a substantive shift in task goal (for instance, moving from manipulating the apparatus to drawing a diagram or from drawing to verbally explaining results) or a change in the dominant representation being used. In practice, this meant that a continuous sequence of student talk and action from the moment a new representational goal was introduced until the group transitioned to a different representation or task was treated as one event/episode.

Once the code definitions were finalized, the entire data set was coded according to the final code list with the aid of statistical software. To assess inter-coder agreement, 27.00% of the data set was independently re-coded by a second coder, and Cohen's Kappa coefficient was calculated. The resulting Kappa value of 0.82 indicates a high level of reliability between coders.

The main themes and subcodes that emerged from the coding process were analyzed. This process, along with the relationships among the research questions, data sources, and analysis procedures, is summarized in Table 1.

Table 1

Relationship among research questions, data sources, and analysis procedures

RQ	Data Source	Analysis Approach	Indicators / Outputs
RQ1. Which strategies do students use to coordinate multiple representations?	In-class observation notes; screen recordings; semi-structured interviews; student drawings / documents	Thematic / descriptive coding (strategy categories)	Strategy repertoire; category frequencies; illustrative representation examples and brief excerpts
RQ2. What are the frequencies of transitions and matching between representations?	Screen recordings + discourse transcripts	Sequential coding analysis	Stage-specific transition matrices (explore – model – discuss) for comparison
RQ3. What are the levels of abstraction and how do they change across stages?	Interview / discourse transcripts; drawings / diagrams	Level coding: Concrete – Intermediate – General principle; distribution by stage	Percentages for each level; sample excerpts; stage × level cross-tabulations
Additional quantitative measure	25-item multiple-choice test	Used solely to assess students' prior knowledge; not employed to address the research questions	

Findings

Descriptive content analysis conducted to address the first research question revealed that students employed five main strategies when establishing connections between the real and virtual experiments: Visual–Schematic Matching, Verbal–Conceptual Explanation, Mathematical/Geometrical Analysis, Experiment–Simulation Comparison, and Hypothesis Testing/Verification. On average, students used 3.60 (sd = 1.10) strategies in combination. Visual–Schematic Matching emerged as the most frequently used strategy. Descriptive statistics related to these strategies are presented in Table 2.

To examine the co-occurrence patterns of the strategies, a co-use matrix was constructed. The findings related to this pairing are presented in Table 3, which displays the frequencies with which pairwise combinations of the five strategies were reported by the same student.

When Table 3 is examined, the highest co-occurrence is observed for the pair Visual–Schematic Matching and Verbal–Conceptual Explanation (35/48; 72.90%). This is followed by Visual–Schematic and Mathematical/Geometrical Analysis (31/48; 64.60%), and Visual–Schematic and Experiment–Simulation Comparison (29/48; 60.40%). All cell values are upper-bounded by the minimum of the marginal frequencies of the two respective strategies. In summary, the co-occurrence patterns indicate that Visual–Schematic Matching most frequently appears together with Verbal–Conceptual Explanation and Mathematical/Geometrical Analysis. This suggests that, in coordinating representations, students often move from visual anchors toward verbal explanation and quantitative validation.

Table 2

Descriptive statistics on participants' strategy use by learning phase

Strategy	f	Exploration ($\bar{x}$; sd)	Modeling ($\bar{x}$; sd)	Discussion ($\bar{x}$; sd)
Visual–Schematic Matching	43	2.10 (0.90)	1.40 (0.70)	1.20 (0.60)
Verbal–Conceptual Explanation	39	0.80 (0.60)	1.50 (0.85)	1.90 (0.90)
Mathematical/Geometrical Analysis	34	0.60 (0.50)	1.70 (0.90)	1.10 (0.70)
Experiment–Simulation Comparison	31	1.00 (0.70)	1.20 (0.80)	1.30 (0.70)
Hypothesis Testing/Verification	26	0.40 (0.50)	1.00 (0.70)	1.50 (0.80)

Note: x̄; sd represent the mean and standard deviation of the number of coded events per student.

Table 3

Co-occurrence matrix of strategies (pairwise combinations reported by individual students)

	Verbal–Conceptual Explanation	Mathematical/ Geometrical Analysis	Experiment–Simulation Comparison	Hypothesis Testing/Verification
Visual–Schematic Matching	35	31	29	24
Verbal–Conceptual Explanation	-	28	27	22
Mathematical/Geometrical Analysis	28	-	23	21

To address the second research question, instances of transitions between representations, operationalized as a change in the dominant class of representation, and matching, defined as the concurrent and meaningful use of two representations within the same episode, were descriptively grouped. These events were analyzed both as the mean number of occurrences per student (events per student; n = 48) and as total occurrences.

Based on the mean values calculated for each learning phase, transition frequencies were found to be highest during the exploration phase (x̄ = 4.00, sd = 1.20), followed by the modeling phase (x̄ =2.50, sd = 1.13) and the discussion phase (x̄ =1.50, sd = 1.72). Matching events were most frequent in the modeling phase (x̄ =4.20, sd = 1.11), followed by the discussion (x̄ =3.50, sd = 1.70) and exploration (x̄ =2.00, sd = 1.80) phases. The total number of events corresponding to these means was 192 (exploration), 120 (modeling), and 72 (discussion) for transitions, and 96 (exploration), 202 (modeling), and 168 (discussion) for matching events, yielding an overall total of 384 transitions and 466 matching events.

All directional transitions were grouped in detail and presented in Table 4. According to Table 4, when all phases are considered collectively (f = 384), the most prominent transitions during the exploration phase were from Real to Simulation (f = 66) and from Simulation to Real (f = 56), followed by transitions from Real to Drawing/Diagram (f = 36) and from Simulation to Drawing (f = 40). During the modeling phase, increased frequencies were observed in the transitions from Drawing to Mathematics (f = 41) and from Simulation to Mathematics (f = 22). Transitions toward verbal representations appeared to be relatively limited ($f_{\text{Mathematics–Verbal}}$ = 18; $f_{\text{Real–Verbal}}$ = 8).

Table 4

Distribution of directional transitions between representation types (all phases; total f = 384)

Source – Target	f	Source – Target	f
Real - Simulation	66	Simulation - Real	56
Real - Drawing/Diagram	36	Drawing/Diagram - Real	12
Simulation - Drawing/Diagram	40	Drawing/Diagram - Simulation	15
Drawing/Diagram - Mathematics	41	Mathematics - Drawing/Diagram	24
Simulation - Mathematics	22	Mathematics - Simulation	10
Mathematics - Verbal	18	Verbal - Mathematics	10
Real - Verbal	8	Verbal - Real	6
Drawing/Diagram - Verbal	10	Verbal - Drawing/Diagram	10

The overall distribution of matching events across pairs of representations (f = 466) is presented in Table 5. Examination of the table reveals that the highest frequencies occur for the Drawing–Mathematics pair (f = 140) and the Real–Simulation pair (f = 130). These are followed by Simulation–Drawing (f = 78) and, at a lower frequency, Mathematics–Verbal (f = 28); matches involving Real/Verbal and Simulation/Verbal combinations are comparatively infrequent.

Table 5

Frequency of matching between representations; representation types (undirected; total f = 466)

Matched pair	f	Matched pair	f
Drawing – Mathematics	140	Real– Drawing	36
Real– Simulation	130	Simulation – Mathematics	24
Simulation – Drawing	78	Real– Mathematics	12
Mathematics – Verbal	28	Real– Verbal	8
Drawing – Verbal	4	Simulation – Verbal	6

Note: Matching is undirected; it refers to the simultaneous, side-by-side use of two representations for the same finding.

The directional transitions between representations observed during each learning phase are presented in Table 6. During the exploration phase (f = 192), the highest flows were observed in the transitions from Real to Simulation (f = 43) and from Simulation to Real (f = 38). Transitions from Real to Drawing (f = 24) and from Simulation to Drawing (f = 27) indicated a shift from observational data to diagrammatic representation. The highest row totals at this phase were from Simulation (71) and Real (69) sources.

In the modeling phase (f = 120), the most prominent flows were from Drawing to Mathematics (f = 23) and from Simulation to Mathematics (f = 12), with a reverse transition from Mathematics to Drawing (f = 14) also recorded. Row totals were highest for Simulation (f=32) and Drawing/Diagram (f=32), indicating these as central sources of representational activity.

During the discussion phase (f = 72), a clear orientation toward verbal representations was observed, with transitions such as Mathematics to Verbal (f = 8), Real to Verbal (f = 4), and Drawing to Verbal (f = 4), indicating a moderate level of bidirectional flow toward and from verbal explanation.

In summary, the findings indicate that the exploration phase was characterized by intensive transitions between observational and digital representations, whereas in the modeling phase the use of matching along the Drawing–Mathematics axis increased notably. This pattern suggests that, while students moved across multiple representations in the early stages, at later stages they tended to place representations side by side, shifting toward a form of coordination focused on verification and quantitative relationships.

Table 6

Directed transition matrix by learning phase (revised format; total frequency = 384)

Source \ Target	Real	Simulation	Drawing/Diagram	Mathematics	Verbal	Total
Explore						
Real	0	43	24	0	2	69
Simulation	38	0	27	6	0	71
Drawing/Diagram	8	10	0	11	3	32
Mathematics	0	2	6	0	5	13
Verbal	1	0	3	3	0	7
Total	47	55	60	20	10	192
Modeling						
Real	0	13	8	0	2	23
Simulation	12	0	8	12	0	32
Drawing/Diagram	3	3	0	23	3	32
Mathematics	0	6	14	0	5	25
Verbal	2	0	3	3	0	8
Total	17	22	33	38	10	120
Discussion						
Real	0	10	4	0	4	18
Simulation	6	0	5	4	0	15
Drawing/Diagram	1	2	0	7	4	14
Mathematics	0	2	4	0	8	14
Verbal	3	0	4	4	0	11
Total	10	14	17	15	16	72
Grand total	74	91	110	73	36	384

To address the third research question, students' utterances were coded to examine both the levels of abstraction exhibited in their statements and how these levels varied across stages. The coding showed that participants were capable of producing statements at more than one level. Specifically, 60.40% of participants (29/48) articulated at least one Concrete/Descriptive-level statement, 50.00% (24/48) produced an Intermediate/Conceptual-level statement, and 35.40 % (17/48) offered an Abstract/Theoretical-level statement.

When phase-based means (unit = occurrences per student; n = 48) were examined, the discourse pattern was found to follow a systematically increasing trajectory of abstraction throughout the process. In the exploration phase, Concrete/Descriptive statements were more frequent ($\bar{x}$ =3.80, sd = 1.40), whereas Intermediate/Conceptual ($\bar{x}$ = 1.40, sd = 0.92) and Abstract/Theoretical ($\bar{x}$ =0.60, sd = 0.43) statements were more limited. In the modeling phase, the focus shifted to the Intermediate/Conceptual level ($\bar{x}$ = 3.60, sd = 1.20), the mean frequency of Abstract/Theoretical statements increased ($\bar{x}$ =1.80, sd = 0.90), and Concrete/Descriptive statements decreased ($\bar{x}$ = 1.90, sd = 1.16). In the discussion phase, Abstract/Theoretical discourse increased markedly ($\bar{x}$ =3.20, sd = 1.30), Intermediate/Conceptual statements remained at a moderate level ($\bar{x}$ =2.50, sd = 1.13), and Concrete/Descriptive statements were at the lowest level ($\bar{x}$ =0.90, sd = 0.60). This distribution indicates that students progressed from observation-based descriptions to conceptual framing and, subsequently, to the formal expression of general optical principles.

The analysis of sequential transitions between abstraction levels (f_{total} = 294 transition events) supports this finding. The most frequently observed directions were Concrete - Intermediate (f = 88) and Intermediate - Abstract (f = 72), while the reverse transitions occurred less frequently ($f_{Intermediate\text{-}Concrete}$= 36; $f_{Abstract\text{-}Intermediate}$ = 41; $f_{Concrete\text{-}Abstract}$= 29; $f_{Abstract\text{-}Concrete}$ = 28). Accordingly, the analysis indicates that as the process progressed, students' discourse exhibited a gradual increase in the level of abstraction, predominantly following a Concrete - Intermediate - Abstract pattern, with theoretical and generalizing statements becoming noticeably more frequent in the final phase.

Discussion

In this study, five core strategies employed by students in a learning environment that combined real and virtual experiments were identified. These strategies were thematically categorized as: Visual–Schematic Matching, Verbal–Conceptual Explanation, Mathematical/Geometrical Analysis, Experiment–Simulation Comparison, and Hypothesis Testing/Verification. The fact that participants frequently employed more than one strategy concurrently, at rates above the average, was interpreted as an indication that, when working with multiple representations, they tended not to follow a singular or linear pathway, but rather showed a tendency to integrate multiple representations within the same learning episode. This pattern is largely consistent with the literature on learning with multiple representations, which conceptualizes representational competencies in terms of linking, sense making, and conceptualization (Becker et al., 2020; Lore et al., 2024; Stöger & Nerdel, 2024). In particular, recently developed models of representational competence highlight as critical students' abilities to gather evidence from multiple representations and use this evidence to construct explanations (Flores-Camacho & Gallegos-Cázares, 2025; Nielsen et al., 2022).

Despite this coherent pattern, the findings should also be evaluated from alternative perspectives. Specifically, the central role of visual–schematic matching, and its sequential or simultaneous coupling with verbal–conceptual explanation and mathematical/geometrical analysis, suggests that students typically structure their coordination of representations along a "visual anchor -verbal explanation - quantitative validation" pathway. This finding is consistent with studies suggesting that visual representations provide a perceptual anchor and are particularly functional for understanding abstract processes such as those in optics (Bousquet et al., 2024; Jiang et al., 2025). However, representation theories also emphasize that such visual centrality is not invariably advantageous; in the absence of appropriate scaffolding, students may focus on surface features and overlook underlying conceptual relations, and the use of multiple representations may even increase cognitive load and hinder learning (Jaakkola & Veermans, 2020; Lore et al., 2024; Stöger & Nerdel, 2024). Therefore, although the diversity of strategies observed in this study can be regarded as a positive indicator of the depth of representational coordination, it should not be directly interpreted as evidence that all students achieved equally meaningful or deeply integrated understanding.

Secondly, students' use of multiple strategies may not necessarily reflect fully autonomous or spontaneously developed representational flexibility; rather, it can also be attributed to the guiding influence of the designed instructional activities (Rexigel et al., 2024; Skulmowski, 2022). Recent studies employing multiple, dynamically interrelated representations have shown that students typically follow the linking opportunities provided by researchers, and that their repertoire of strategies is strongly shaped by the structure of the activities and the accompanying instructions (Lore et al., 2024; Rau, 2017). Consistent with this view, CKCM-based interventions in Turkish middle school science classrooms have similarly demonstrated that carefully sequenced instructional designs can strongly shape how students mobilize evidence and engage with the epistemic dimensions of science (Bakırcı, Çalık, & Çepni, 2017). In this regard, the present findings successfully demonstrate the potential of the design to support representational coordination; however, they leave open the question of whether students would employ these strategies with the same level of flexibility in more loosely structured contexts.

Third, the incorporation of the Experiment–Simulation Comparison and Hypothesis Testing/Verification strategies is highly encouraging, as it shows that students engage in evidence-based comparison and model-testing processes between empirical findings and simulation outputs; this outcome is consistent with perspectives that regard multiple representations not merely as "more than one display" but as epistemic tools (Bousquet et al., 2024; Flores-Camacho & Gallegos-Cázares, 2025). At the same time, pluralistic and pragmatic approaches discussed in the philosophy of representation and the science education literature emphasize that the use of multiple representations or strategies does not inherently imply "better" understanding; what matters is how these representations are used, what kinds of inferences they afford, and for what purposes students select them (Jaakkola & Veermans, 2020). From this perspective, beyond the sheer number of coded strategies, the quality of strategy use and the ways in which students justify their choices of particular combinations of representations emerge as critical areas of analysis.

Fourth, previous research has indicated that the impact of multiple representations is closely related to learners' prior knowledge and level of expertise. Some studies have shown that additional representations are particularly beneficial for students with higher levels of competence, whereas for those with lower proficiency, they may increase cognitive complexity and thereby hinder learning (Stöger & Nerdel, 2024; Tóthová & Rusek, 2025). Although the students in this study had relatively homogeneous and moderate levels of prior knowledge, the assumption that the observed diversity of strategies translated into equally deep conceptual gains for all learners should be approached with caution. Qualitative data may reveal that although some students formally employed multiple strategies, they did not exhibit deep conceptual integration in their explanations. This highlights the need for a more detailed analysis of representational competencies.

Fifth, some empirical studies on multiple representations (Ainsworth, 1999; van der Meij & de Jong, 2006) reported that even when students are presented with several representations, they often systematically engage with only one or two of them, while disregarding the others. Although the above-average use of strategies in this study suggests that the design encouraged students to activate various representations, it remains important to distinguish between students who genuinely preferred to use multiple strategies and those who interacted with different representations only superficially due to task requirements.

The contribution of this study lies in showing that, within a combined real–virtual laboratory setting, students can work not only with individual representations but also with coherent clusters of strategies. However, when generalizing these findings to other contexts and subject domains, the decisive role of both the strong scaffolding provided by the design and the characteristics of the student population must be carefully considered.

In sum, the present findings highlight the considerable potential of representational coordination, yet they also show that the effects of multiple representations must be examined in light of factors such as design quality, students' representational competencies, cognitive load, epistemic goals, and individual differences. Within this framework, instructional design should adopt visual–schematic representations as an initial anchor and link them, in a stepwise fashion, to explicit verbal explanations and quantitative validation tasks, while simultaneously subjecting this structure to critical evaluation for each learner.

In this study, the patterns of transitions between representations showed that, particularly during the exploration phase, transitions in the Real–Simulation direction and flows from Real/Simulation to drawing/diagram representations were highly concentrated. This pattern aligns with studies in science and physics education that emphasize the "complementary epistemic roles" of real and virtual laboratories (Rau, 2020; Wörner et al., 2022). While virtual environments serve to make otherwise unobservable processes in optics visible, to rapidly manipulate parameters, and to provide idealized conditions, real laboratories offer important insights into the nature of scientific knowledge through measurement errors, experimental constraints, and direct physical interaction. Hybrid optical setups and augmented reality–based platforms similarly aim to create a rich representational ecology for conceptual understanding by integrating physical manipulation with digital or simulation-based representations. In this context, the high frequency of Real–Simulation transitions suggests that students used these two sources not as mutually exclusive, but rather as complementary and mutually validating tools for knowledge construction. This finding is consistent with previous research indicating that the combined use of virtual and real laboratories can enhance conceptual learning and transfer more effectively than either environment used in isolation (Lestari et al., 2023; Wang et al., 2025).

However, interpreting this pattern solely as an indicator of "ideal complementarity" may be a one-sided reading. A high frequency of transitions between representations does not always signify deep conceptual integration. At times, it may reflect more superficial scanning behaviors, such as complying with task instructions, rapidly shifting visual attention across screens, or struggling to determine which representation is more explanatory. The literature on multiple representations emphasizes that random or excessively frequent switching between representations can increase cognitive load and make it more difficult for students to focus on core conceptual relationships (de Jong, 2010; Schnotz & Bannert, 2003). Therefore, the frequent Real–Simulation transitions observed in this study gained meaning only through a structured activity design; however, it should also be acknowledged that, in different contexts, similar arrangements may yield nothing more than "representational clutter" if they are not accompanied by appropriate pedagogical guidance (Renkl & Scheiter, 2017; Rexigel et al., 2024).

The pronounced prominence of Drawing–Mathematics matching in the modeling phase indicates that drawings and diagrams functioned as a bridge for students, enabling them to translate concepts such as refraction, reflection, and refractive index into quantitative models through ray diagrams and measurements. This finding is consistent with empirical evidence suggesting that, when appropriately integrated with targeted tasks, diagrams facilitate students' transitions to symbolic and mathematical representations (Stöger & Nerdel, 2024; Volkwyn et al., 2020). At the same time, this pattern also implies that the activity steered students toward a particular representational sequence. Hence, it underscores the need to design representational coordination flexibly, so that it accommodates not only a single normative flow but also the alternative pathways and explanations students may construct on their own.

The limited transitions and matchings between verbal representations and other forms suggest that students struggle to translate visual and quantitative findings into clear, coherent, and well-reasoned scientific explanations. This outcome parallels studies indicating that learners who work with multiple representations often require additional scaffolding to convey their models and calculations in the language of scientific argumentation (Lore et al., 2024; Nielsen et al., 2022; Stöger & Nerdel, 2024). Such a result, however, should be viewed not merely as evidence of a "deficiency," but also as a natural consequence of a design predominantly centered on visual-quantitative coordination.

The findings of this study indicate that transitions between representations are broad and frequent during the exploration phase, whereas matching becomes more pronounced and elaborated in the modeling and discussion phases. This trajectory was interpreted as consistent with the "initial flexible circulation, subsequent structured integration" perspective proposed in the literature (Giardino, 2017; Naftaliev & Yerushalmy, 2011). In the initial stages, students move across different representations to familiarize themselves with the phenomenon from multiple angles; in later stages, they juxtapose selected pairs of representations, particularly Real–Simulation and Drawing–Mathematics, to compare, verify, and generalize. At the same time, philosophical and didactic approaches that emphasize representational plurality argue that forcing all representations into a fully unified conceptual framework is not always necessary or realistic, and that different representations may, in certain contexts, offer partially incompatible yet productively complementary perspectives (Flores-Camacho & Gallegos-Cázares, 2025; Paillusson & Booth, 2025). From this perspective, the observed patterns among Real, Simulation, Drawing, Mathematical, and Verbal representations should not be interpreted merely as an attempt to converge toward a single, coherent model. Rather, they may also reflect students' processes of exploring, comparing, and negotiating among different epistemic resources.

In conclusion, the patterns of transitions and correspondences observed in this study suggest that a well-structured real–virtual laboratory design can support students' strategic movement across representations. However, the educational value of such movement does not stem solely from increasing the number or frequency of representational transitions, but from integrating these transitions with conceptual reasoning, verbal explanation, and critical comparison.

Findings related to levels of abstraction indicate that students generally exhibited a gradual progression in their discourse throughout the learning process, moving from Concrete/Descriptive to Intermediate/Conceptual, and finally to Abstract/Theoretical levels. The dominance of observation-based descriptive expressions during the exploration phase, the emergence of conceptual frameworks and quantitative relationships in the modeling phase, and the increased emphasis on general principles and theoretical formulations in the discussion phase all suggest that students' use of representations and discourse forms was progressively restructured in alignment with the instructional process. The concentration of transitions particularly between the Concrete–Intermediate and Intermediate–Abstract levels aligns with theoretical perspectives that define learning with multiple representations as a process of meaning intensification through sequential re-representation across different representational forms (Duval, 2006; Yao, 2022).

The literature emphasizes that in environments where visual, verbal, and symbolic representations are used in combination, effective learning occurs not through single-step shifts between representational forms, but through gradual transformations of this kind. Each act of re-expression is argued to strengthen students' epistemic awareness, modeling competencies, and pursuit of conceptual coherence (Rau et al., 2021; Stull et al., 2012). The fact that the findings make this stepwise progression visible both in the representations employed and in the level of discourse supports the conclusion that the designed real–virtual laboratory activity is aligned with key principles of learning with multiple representations (Ainsworth, 2006; Kapici et al., 2019; van der Meij & de Jong, 2006). However, interpreting this trajectory solely as a linear and universal success narrative carries the risk of overlooking several important nuances. First, the general trend observed across levels of abstraction is based on averages; when individual student pathways are examined, it becomes evident that there are also back-and-forth transitions, partial leaps, and even occasional regressions among the Concrete, Intermediate, and Abstract levels. In the literature on multiple representations, such "returns" are not necessarily viewed as indicators of deficiency, but rather as instances where students re-negotiate meaning and strengthen their representational understanding. From this perspective, while the Concrete–Intermediate–Abstract model provides a normative framework, the inherently dynamic and reconstructive nature of learning must also be acknowledged.

The observed pattern of abstraction was interpreted not only as a process arising from students' own cognitive initiative, but also as a reflection of the strong guidance embedded in the instructional design. The structure of the activity, with its focus on observation and description during the exploration phase, quantitative relations during the modeling phase, and generalization during the discussion phase, renders the systematic progression from Concrete to Abstract at least partly an outcome that "bears the imprint" of the design. This raises the question of the extent to which processes of re-articulation are shaped or "imposed" by the design, and whether students would construct a similar ladder of abstraction independently in a more open learning environment. In this regard, the findings call for a dual reading that points both to the effectiveness of the design and to the context sensitivity of abstraction.

The relative weakness of bridges grounded in verbal representations points to a critical area for improvement in supporting students to transform abstract and theoretical knowledge into clear, coherent, and well-justified scientific explanations. The comparatively frequent use of visual and mathematical representations suggests that students are willing and to some extent competent in working with these forms; however, they experience difficulties in extending this work to the level of scientific explanation and argumentation. This finding is consistent with previous studies indicating that students often experience difficulties translating models and calculations into scientific discourse, written explanations, and evidence-based reasoning (Hsu et al., 2015; Kulgemeyer, 2018). In future instructional designs, it is therefore important to include tasks, particularly during the discussion phase, that explicitly require students to verbalize and articulate their representational coordination.

It should also be emphasized that the observed increase in abstraction levels should not be equated with the assumption that more abstract concepts are inherently better. Several studies have pointed out that, particularly for students with lower levels of prior knowledge, excessive abstraction may lead to conceptual disconnection, while maintaining concrete and contextually grounded explanations is critical for the sustainability of learning (Fyfe et al., 2014; Jaakkola & Veermans, 2018). From this perspective, expressions at the Concrete level are not expected to vanish entirely during the discussion phase; instead, Abstract-level explanations should be legitimized by tying them to concrete examples and observation-based evidence. The marked decline in Concrete-level utterances observed in the present findings has therefore been interpreted, on the one hand, as evidence of successfully achieving conceptual abstraction and, on the other, as a possible sign that the bridges of meaning may have weakened for some students.

In this context, the observed pattern indicates that, when appropriately structured, combined real–virtual laboratory settings can support students in moving from descriptions grounded in concrete observations to progressively more sophisticated conceptualizations and, ultimately, to more general and abstract formulations of optical principles.

Conclusion and Implications

This study investigated how students utilized multiple representations, transitioned between them, and progressed in their levels of abstraction while learning about the reflection and refraction of light in a hybrid (real and virtual) laboratory environment. The findings suggest that students were not passive recipients randomly engaging with different types of representations. Instead, they developed selective strategies—purposefully emphasizing certain types of representations while downplaying others.

The transition patterns observed across the exploration, modeling, and discussion phases indicate that the hybrid environment offered representational variety; however, this variety alone did not guarantee representational integration. In particular, while many students demonstrated ease with concrete observations and visual representations, they appeared to require additional support in systematically connecting these to mathematical relationships and overarching scientific principles.

The findings suggest that incorporating multiple representations into a hybrid laboratory environment should be viewed not merely as technological enhancement but as a deliberate instructional-design endeavor aimed at fostering representational coordination. To enable students to establish meaningful transitions among real experiments, simulations, drawings, and symbolic expressions, these representations must be sequenced according to a coherent pedagogical logic, their interrelationships made explicit, and tasks provided that prompt students to interrogate those connections. The results also underscore the pivotal role of teacher guidance: explanations that clarify the purpose of each representation, questions that elicit verbal articulation of inter-representational links, and classroom orchestration that brings diverse representational uses into discussion all serve to strengthen students' strategic deployment of representations. For example, during whole-class discussions teachers can ask questions such as "How does the angle you measured with the real apparatus correspond to the angle displayed in the simulation?" or "Can you sketch a ray diagram that matches what we just observed on the screen and explain how you know the two representations correspond?". In addition, a short consolidation activity in which students produce a summary poster that combines a sketch or photograph of the real setup, a hand-drawn ray diagram, and key numerical values taken from the simulation can make these connections more visible and actionable for classroom practice.

In this regard, the study proposes that the effective use of multiple representations in hybrid environments should be addressed at three levels. First, learning activities should be designed not on the basis of an implicit expectation that students will independently establish relations among representations, but so as to incorporate explicit transitions and re-representation tasks. Second, teacher education should focus on fostering a professional awareness that enables teachers to analyze the epistemic functions of representations, potential misconceptions, and appropriate transition points. Third, assessment should be enriched with tools that attend not only to the correctness of answers, but also to how students transform across representations, how they reference one representation through another, and which combinations of representations they use to warrant abstract principles. When such a holistic approach is adopted, the potential of hybrid laboratory implementations to generate more coherent learning experiences that strengthen students' representational competence and support their conceptual understanding and levels of abstraction becomes more evident.

Limitations and Future Research

The findings of this study should be interpreted in light of certain methodological and contextual limitations. First, the research was conducted in a single school with a limited number of students within a specific socioeconomic and institutional context. This limits the generalizability of the identified representational strategies and abstraction patterns to different types of schools, student profiles, or cultural settings. Future research should conduct comparative studies across diverse regions, school types, and heterogeneous samples to better capture the context sensitivity and potential common patterns of representational coordination in hybrid learning environments.

The research design focused on providing a detailed description of representational processes rather than testing the effects of the hybrid learning environment within a causal framework. The absence of a control group or direct comparisons with alternative instructional settings does not permit strong claims that the hybrid environment is "more effective" or "more advantageous." Future studies employing experimental and quasi-experimental designs that compare different representational sequences, tool combinations, or instructional scenarios would enable a more systematic examination of how the observed strategies relate to learning outcomes. Furthermore, the intervention spanned only two 40-minute sessions, which constrains the extent to which we can draw conclusions about the stability or longer-term development of students' representational strategies.

Although the data sources are rich, the analyses are based on the coding of specific types of interactions and products. Since the coding schemes were developed in line with the research questions, other dimensions of representational coordination (affective responses, epistemological beliefs, technological literacy) were not directly addressed in this study. Furthermore, due to the qualitative nature of the coding, interpretive subjectivity cannot be entirely eliminated, even though reliability coefficients are reported. Future research is needed that integrates process data (video, screen recordings, eye-tracking, concurrent think-aloud protocols, etc.) with micro-analytic techniques and employs coding schemes tested by different research teams. Such pluralistic data and researcher designs would allow representational strategies to be characterized with greater nuance.

The hybrid environment and tools employed in this study are confined to a particular simulation design, activity set, and form of teacher guidance. Alternative simulation interfaces, representational options, feedback types, or orchestration styles could produce meaningful differences in students' strategic choices. Consequently, future research should compare hybrid-environment designs and systematically determine which features most effectively support transitions, matching, and integration among representations. Adaptive systems and dynamic task designs grounded in learner modeling, in particular, offer a productive avenue for developing hybrid learning environments that are sensitive to individual representational profiles.

Finally, the present study modeled only to a limited extent the quantitative relationships among conceptual learning, representational coordination, and levels of abstraction. It did not examine how representational strategies influence long-term retention, transfer, or performance in other subject areas. Future investigations should track students' representational development over time through longitudinal designs and developmental analyses, and more comprehensively test the links between representational strategies and achievement, reasoning modes, and the ability to evaluate scientific models. Such work would broaden the findings reported here and provide a stronger basis for both the theoretical grounding of hybrid laboratory practices and the creation of evidence-based design principles.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability

Data will be made available on request.

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