Teacher-Mediated and Student-Led Interaction with a Physics Simulation: Effects on the Learning Experience

Maria Ioanna Magkouta[1 [0000−0002−3377−1835]], Jérémy La Scala[1 [0000−0002−8057−7787]], Juan Carlos Farah[1 [0000−0002−2477−4196]], Emily Michailidi[2 [000−0003−1094−9407]], and Denis Gillet[1 [0000−0002−2570−929X]]

[1] École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
{maria-ioanna.magkouta,jeremy.lascala,juancarlos.farah,denis.gillet}@epfl.ch
[2] University of Crete, Greece
e.michailidi@uoc.gr

Abstract. Computer simulations are often used as support material for science education, as they can engage students through inquiry-based learning, promote their active interaction in the experimentation phase, and help them visualize abstract concepts. For instance, interactive simulations developed by the PhET Interactive Simulations Project are being increasingly used in K–12 physics education. These simulations provide different levels of interaction to scaffold how students are exposed to the content embedded in the simulations. In a classroom setting, students can interact directly with the simulation (changing the parameters themselves) or indirectly via the teacher, who controls the simulation in front of the class (guiding the interaction through questions). Although researchers have investigated the effects of differences in interaction levels on learning outcomes, fewer studies explore how indirect interaction with the simulation compares to when students interact directly with the simulation. To address this question, we conducted a quasi-experimental study with 34 primary school students, examining the effects of direct versus indirect interaction using a simulation on sound propagation. Students in both groups were asked to produce drawings and explanations to assess their understanding of the material both before and after our intervention. A quantitative analysis comparing the learning outcomes of the two conditions did not yield significant differences, suggesting that both groups achieved comparable short-term learning gains. However, our findings suggest that there could be cognitive understanding differences between conditions. We discuss implications for further research on how to best integrate simulations into science lessons at the primary school level.

Keywords: Science Education · Computer Simulation · Inquiry-Based Learning · Physics · Primary School.

1 Introduction

Computer simulations are essential tools in science education, replicating real-world systems to facilitate inquiry-based learning (IBL). Particularly integrated into physics education, simulations play a crucial role in facilitating IBL, helping learners experiment with variables, observe outcomes, and eventually understand scientific phenomena [8,21]. However, research on IBL shows that students often require support, especially in interpreting the outcome of a simulation [2]. While previous studies have explored the guidance provided by simulations and accompanying software, the role of teachers in guiding students through IBL with simulations remains relatively unstudied [18]. This gap in the literature underscores the need to investigate the specific forms of guidance offered by teachers within the context of simulation-based inquiry. To address this gap, this paper presents a quasi-experimental study focused on the different forms of guidance provided during simulation-based inquiry, specifically in the context of physics education for 10-year-old students. We compare teacher-facilitated (indirect) interaction with the simulation versus students' in-pair (direct) interaction with the simulation. By categorizing guidance from both sources, we aim to better understand the complexity of integrating simulations into inquiry-based science learning.

2 Background and Related Work

2.1 Inquiry-Based Learning Model in Science Education

The perspective that science encompasses the integration of knowledge and practices promotes inquiry-based methods. These methods offer learners the chance to participate in scientific practices to develop and enhance their understanding of science [16]. Indeed, inquiry-based instructional models actively engage the learner in following a research approach to understanding a new concept, akin to those undertaken by researchers in scientific studies, rather than merely receiving scientific facts and theories passively as static information [21]. One well-known model for structuring the inquiry process is the BSCS 5E Instructional Model [7]. Each element of the model (Engage, Explore, Explain, Elaborate, Evaluate) represents one phase of instruction. Compared to traditional instruction, research reports better learning outcomes, more advanced reasoning ability, and enhanced procedural abilities [7,29].

2.2 Simulations in Science Education

Computer simulations have become elemental educational tools, especially in the domain of science education [3]. This is because, for students to understand a concept better, practical work (tasks in which the learner interacts and examines objects and materials) cannot be separated from science education [20]. Simulations can be used as an addition to other forms of instruction, aiding a learner's comprehension of scientific concepts [15]. Additional advantages of their use pertain to the restrictions that exist in the physical laboratory: (i) they can be used easily, without the need for real equipment, which can be difficult to find or impractical to use, (ii) they can provide structured experiments that are not feasible to do physically, e.g., microscopically depict the movement of the molecules when sound propagates, (iii) taking measurements and changing variables becomes an easy task in contrast with a real lab condition, (iv) students can be autonomous and explore the simulation on their own pace, not being restricted in the classroom setting [11,22,32]. These interactive environments can engage students in experimenting and can thus support classroom instruction with virtual laboratories. Regarding research on conceptual change, simulation-based learning environments are suitable for showcasing the conditions of conceptual change [9,12]. As described by Finkelstein et al. [10], simulations provide visually dynamic representations of physics principles that are physically accurate. Those visualized features facilitate the assimilation of new information with existing knowledge, fostering a deeper conceptual understanding of scientific phenomena [5]. In addition, computer simulations are effective in altering students' preexisting alternative ideas [15], enhancing the acquisition of intuitive domain knowledge, and fostering a clearer understanding of concepts [13].

2.3 Inquiry-Based Model through Simulations

The use of IBL with computer simulations is recognized as a promising approach to enhance science learning and instruction [24]. According to Trundle and Bell [30], integrating computer simulations with inquiry-based instruction can promote cognitive dissonance and induce conceptual change. Modern technology-driven methods for science education provide computer simulations that create opportunities for students to engage in IBL environments aiming at ameliorated learning experiences [27,28]. Despite their advantages, the pedagogy, through which simulations are integrated into the learning process and the included instructional strategies, both play a pivotal role in their overall effectiveness [25]. Learners should be actively involved in the steps of inquiry, experimentation, and discovery, as well as when interacting with simulations [18].

Although existing research has focused on the guidance for inquiry learning using virtual laboratories, which is already provided by the computer software itself [17], there is a lack of research investigating the role of the teacher in the process [31]. It is unclear what the most effective way is for teachers to guide the students when using a simulation in an inquiry learning process, despite its importance in the successful implementation of the process [18].

Drawing from the cognitive load theory, the limits of the cognitive capacity of the human brain force us to make decisions about which information to keep [8]. When introduced to a new environment (simulation), the amount of information to which the learner is exposed also encompasses the understanding of the elements of the simulation; thus, the extrinsic cognitive load is charged. This load can be removed with the appropriate guidance. According to de Jong and Lazonder [8], five forms of guidance for inquiry learning with simulation exist:

the process constraint, performance dashboard, prompts, heuristics, scaffolds, and direct presentation of information.

We will focus on the scaffolds through worksheets and on the process constraint through teacher-mediated interaction with the simulation. The choice of these two forms of guidance is made due to their appropriateness for the IBL approach. Scaffolds, particularly structure-providing scaffolds, are well-suited for students who lack the proficiency to perform processes independently [8]. Similarly, process constraints aim to reduce the complexity of the inquiry learning process by limiting the number of options students need to consider. The teacher's role in implementing process constraints helps simplify the interface of the simulation and directs students' attention to the domain knowledge to be acquired.

2.4 Research Questions

In this study, we aim to explore the impact of different interaction modalities on student learning outcomes when using a physics simulation. Specifically, we investigate the following research questions: (i) *How does teacher-mediated interaction with a physics simulation compare to student-led interaction in terms of learning outcomes?* (ii) *Is there a significant difference in learning gains between teacher-facilitated and student-led interactions with the simulation?* By addressing these questions, we seek to understand the effectiveness of instructional strategies in enhancing conceptual understanding of physics.

3 Methods

3.1 Participants and Context

We conducted a quasi-experimental study, with a pretest evaluation of the students' prior knowledge as a baseline and a posttest evaluation of their learning experience during a module in physics related to sound propagation. Participants were 34 primary school students from two classes of the largest public school in Rethymnon, Crete. Each class was randomly assigned to a different condition: control or treatment, with 17 participants per group. In the control group (*Group A*), the teacher handled the simulation on behalf of the students, while in the treatment group (*Group B*), the students managed the simulation themselves. Group A consisted of 6 females and 11 males (mean age = 10, SD = 0.0001), while Group B consisted of 5 females and 12 males (mean age = 10, SD = 0.0001). All participants demonstrated fluency in Greek.

3.2 Overarching Pedagogical Scenario

The intervention was included in a narrative-driven educational experience lasting 90 minutes, where students were immersed in a storyline centered around the exploration of the properties of sound. The narration was structured according to the 5E Inquiry-based model, meaning that each part of the story was related to one phase of inquiry. Initially, students in both conditions were introduced to the context of the narrative, which revolved around two children beginning a journey to understand the characteristics of sound. This storyline involved encounters with historical scientists who contributed to the understanding of sound, namely Galileo Galilei, Ernst Chladni, and Robert Boyle. The students' mission was to understand the properties and characteristics of sound while helping the scientists within the story. The narrative was created and visualized using the Book Creator application [6], pages of which are demonstrated in Fig. 1.

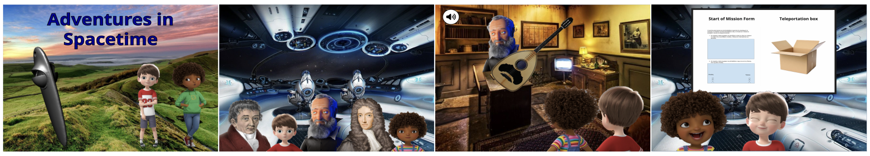

Fig. 1. Sample Pages from the E-book Used

3.3 Sound Propagation

Our intervention included fundamental scientific concepts about sound, with particular emphasis on the properties of frequency and amplitude at both microscopic and macroscopic scales. Key concepts explored include the required conditions for sound propagation and the dynamic oscillatory behavior of constituent molecules. Understanding students' misconceptions about sound propagation is crucial for developing effective teaching materials. Following the inquiry-based methodology, we aimed to build upon students' existing ideas and expand their understanding. Hrepic et al. [14] identified four general mental models encompassing students' ideas on sound:

- **Wave Model:** Sound is perceived as a vibrational motion of particles within the medium, triggered by the source. Without the medium, sound cannot exist or propagate.
- **Independent Entity Model:** Sound or sound particles are viewed as self-standing entities that propagate independently through the space between the medium particles.
- **Intrinsic Model:** Sound propagation is associated with particles of the medium moving away from the source in the direction of sound propagation. The motion of the particles towards the listener constitutes the perception of sound.
- **Dependent Entity Model:** Sound propagation occurs due to the motion of medium particles, which create sound as they move through the space between them.

3.4 Interactive Simulation

As part of the exploration phase of the 5E Inquiry model, a simulation developed by the PhET Interactive Simulations Project, namely *Intro to Waves* [23] was used to visualize and experiment with the sound properties of frequency and amplitude on a microscopic level. According to Maulidah and Prima [20], PhET as a virtual laboratory for learning about waves and sounds demonstrates positive outcomes for both cognitive development and science laboratory settings. The simulation interface allowed students to engage in several interactive functionalities. Both experimental and control groups were given worksheets containing prompts for documenting the measurements through their interaction with the simulation. The differentiation occurred at the level of the interaction with the simulation.

3.5 Procedure

For the experimental group, students were transferred to the computer classroom where they interacted directly with the simulation. Working in pairs, they utilized computers to observe the interface, manipulate the parameters, and record measurements. Verbal instructions with visual supports displayed on the interactive board on how to use the simulation were given in the beginning and worksheets were provided to document their observations and measurements. In contrast, the control group engaged in the simulation with the teacher as a proxy. That is, the simulation was projected on the interactive board of the classroom, allowing for simultaneous whole-class interaction. The difference in the condition is visually presented in Fig. 2. The teacher acting as a facilitator, controlled the simulation, changed the parameters, and engaged the students in taking measurements. For example, when changing the frequency from high to low, the teacher started by focusing the attention of the students on the movement of the molecules and continued by measuring the change with the tool provided by the simulation. In this case it was a chronometer, measuring the number of oscillations performed by the molecule. Similar worksheets were provided to document their observations. The control case is a common modality for schools having no computer rooms or tablets, or when teachers want to avoid interrupting the flow of a course by moving to a different location.

3.6 Instruments and Data Analysis

To assess the short-term learning gains, a pre-posttest approach was utilized. Both groups completed a pretest to estimate their baseline knowledge before engaging with the material, evaluating their familiarization with microscopic representations and their perceived interaction of the sound with the molecules. Posttests evaluated comprehension and representation of sound propagation, amplitude, and frequency concepts. The questionnaire was developed through a multi-stage process that involved a literature review, item generation, and expert consultation. Drawing on established theories and the model used in the

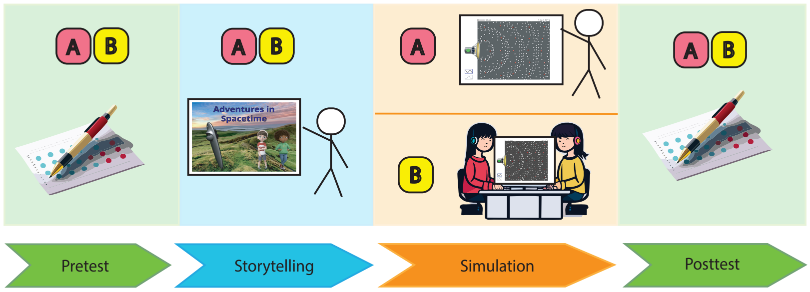

Fig. 2. Experimental Protocol: Control (A) vs. Experimental (B) Group. Both groups undergo pretests, storytelling, and posttests. Group A experiences indirect, teacher-mediated interaction, while Group B has direct, student-led interaction.

simulation, we identified key constructs and developed a set of questions for the pretest and the posttest to assess them. The pretest questionnaire consisted of three questions evaluating preexisting knowledge on (i) representing microscopically the air molecules, (ii) requiring molecules for sound to propagate, and (iii) conceptualizing the interaction of the sound waves with air molecules. The posttest questionnaire consisted of ten questions. Four of these questions were about sound characteristics (three of which were the same as those in the pretest), three were about amplitude, and three were about frequency. The questionnaire consisted of drawings, open-ended questions, and one multiple-choice question. Sample questions from the questionnaire are depicted in Fig. 3 and all the material used in this study is available online (`https://osf.io/uv5hk`) [19].

Our results were analyzed using mixed methods. Quantitative analysis employed independent t-tests to compare posttest scores between groups, using Jamovi statistical software [1], while qualitative analysis of students' drawings was conducted using NVivo software to identify emerging patterns. We quantitatively assessed the students' level of understanding of a concept using a five-point scale. This evaluation was conducted by two independent coders to ensure objectivity and reliability. The coding was based on the scale created by Sözen and Bolat [26] in their study on determining the misconceptions of primary school students related to sound transmission through drawing. To ensure the reliability and validity of our findings, we followed a double-coding approach. Two researchers were tasked with independently coding the data according to the established guidelines. Initially, we calculated the inter-annotator reliability using Cohen's weighted kappa coefficient, which resulted in a substantial agreement of 0.886.

Text responses were also analyzed. For this analysis, stop words were removed from student responses, which were then concatenated, tokenized, and stemmed, resulting in one text response per student. Student responses were

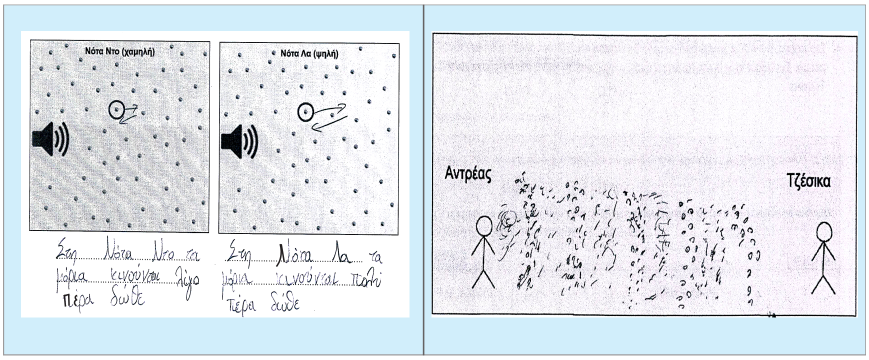

Fig. 3. Example Questions: (Left) *Question.* What happens to the air molecules when a low note is played compared to a high note? Draw and describe their movement. *Sample Answer.* Low Note: The molecules move a little bit from side to side. High Note: The molecules move a lot from side to side. (Right) *Question.* Draw how you think sound travels from person A to person B when person A speaks to person B.

then vectorized using a TF-IDF vectorizer and compared to each other using cosine similarity. The distributions of the pairwise cosine similarities for each group were then compared using a Mann-Whitney U test.

4 Results

4.1 Short-Term Learning Gains Analysis

Independent t-tests were conducted to assess the short-term learning gains of the experimental and control groups. Initially, we aimed to determine if the two groups exhibited similar levels of preexisting knowledge, particularly regarding their cognitive capability of representing microscopic concepts. This served as the baseline for the interaction with the simulation. We observed a significant difference between the pretest results of the experimental (student-led) and control groups (teacher-mediated) ($p < 0.001$). To gain further insights into the specific areas of strength of the experimental group based on the pretests, a qualitative analysis was conducted on students' drawings. It was observed that the experimental group predominantly depicted air molecules as dots (microscopic representation), whereas the control group tended to represent air as lines (macroscopic representation). Upon comparing the responses to the same set of questions in the posttest, no significant difference was found between the experimental and control groups ($p = 0.495$). Similarly, when analyzing the total post-test scores of both groups, no significant difference was observed ($p = 0.493$). Consequently, significant pre-post differences were detected between both groups ($p = 0.047$). These results are depicted in Figs. 4–5. Finally, both the experimental (p = 0.009) and control (p = 0.001) groups demonstrated learning gains after the intervention.

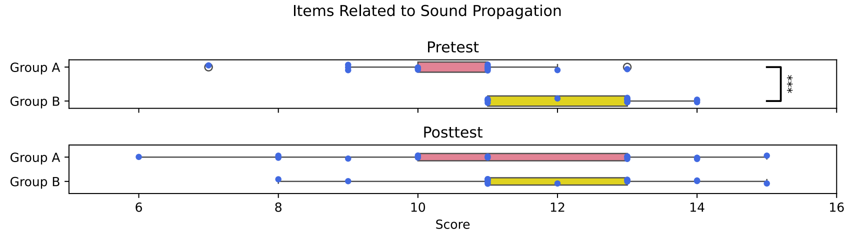

Fig. 4. Scores in pretest and posttest items related to sound propagation.

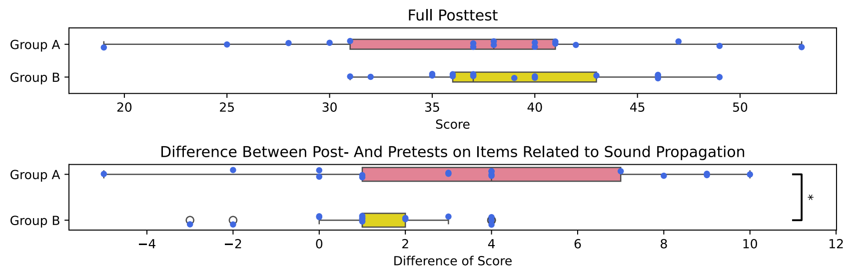

Fig. 5. Differences between post and pretest items related to sound propagation, and differences in total score of posttests.

4.2 Text Analysis

Following the initial analysis, a secondary examination of results was conducted by quantitatively analyzing the qualitative data. Transcripts of written responses from both groups were obtained, and comparisons were made with each group's answers. To minimize the redundancy, responses were concatenated, allowing each student to be compared to all other students within their respective group, once. Stop words were removed from the answers using the Greek *stop-words* corpus provided by NLTK [4]. The results revealed a notable disparity in the similarity of the answers between the control and experimental groups, with the experimental group demonstrating greater similarity (U = 6888.0, $p < 0.001$).

The analysis employed a cosine similarity metric for both groups. The results are visually represented in Fig. 6.

Additionally, a secondary exploratory analysis focusing on the frequency and uniqueness of the words in each group was conducted. After the removal of the stop words, we extracted the words that were used in one group only. The frequency of each word was computed and used to produce the two word clouds shown in Fig. 7. This analysis revealed different words being used more frequently and uniquely in each group, suggesting potential interpretations related to the presence or absence of the teacher. These variations in word usage could indicate different levels of engagement, understanding, or interaction dynamics within the groups, potentially influenced by the teacher's role in the learning process. For example, in Group A (teacher-mediated interaction), students prominently used the word *movement* (in Greek, in a formal way), which was the exact word used in the script by the teacher when explaining the simulation. In contrast, in Group B (student-led interaction) students used unique, more informal words to convey their understanding. For instance, they used the word *thick* to describe the sound produced from a low note, indicating a less scientific but alternative approach to expressing their comprehension.

5 Discussion

The primary objective of this quasi-experimental study was to examine the impact of different types of guidance in utilizing a simulation within an inquiry-based teaching module focused on sound propagation. Specifically, we wanted to compare the effects of direct interaction with the simulation versus indirect interaction facilitated by the teacher as a process constraint.

Direct interaction with the simulation, particularly when the interface is unfamiliar to students, amplifies cognitive demands [31]. In this condition, students must comprehend the mechanisms of the simulation, followed by a subsequent phase of directing their attention toward the predefined learning objectives [18]. This was the case for the experimental group, which, unlike the control group, only received scaffolding in the form of worksheets, without any process constraints. Indirect interaction with the simulation, mediated by the teacher, served to facilitate the learning process by constraining the complexity and cognitive load inherent in direct interaction. By limiting the number of options and directing student attention toward specific learning goals, the use of process constraints aimed to enhance learning effectiveness, while the scaffolding tool, present in both groups, aimed to facilitate the learning process by structuring the activity [8]. Using the indirect interaction of students with the simulation as a process constraint and the worksheets distributed to the students to document the observations and the measurements of the simulation as a scaffolding tool, the cognitive load that is added from the extrinsic engagement with the simulation is reduced, facilitating ample cognitive space for the assimilation of novel concepts, thereby ensuring their optimal reception and integration by learners [8]. In this condition, the teacher decided on which parameter to change

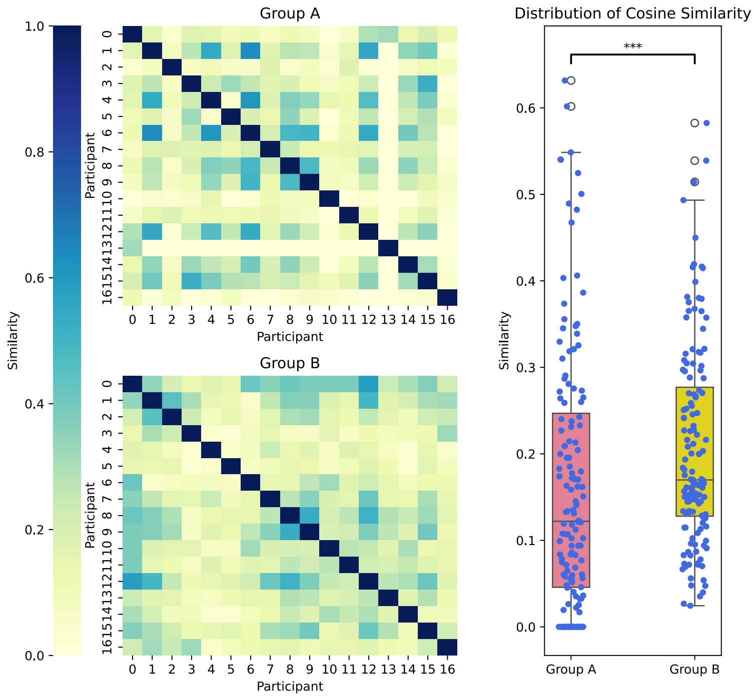

Fig. 6. Pairwise cosine similarity of the written answers between students of each group. The plot on the right shows the distribution of the cosine similarity for each group.

and which value to try, following the questions of the worksheets. This approach facilitated a more focused engagement with the learning objectives, potentially leading to improved learning outcomes.

The study represents a contribution to the field by exploring the interplay between different forms of guidance and cognitive load in the context of utilizing simulations within IBL modules in primary school physics education. While prior research has predominantly focused on the guidance provided by simulations themselves [22], this study offers a novel perspective by emphasizing the role of the teacher as a constraint on cognitive load in this context. By employing indirect interaction with the simulation, the study suggests how cognitive load can be effectively managed to enhance the learning outcomes. This shift in focus toward integrating simulation more effectively within the framework of

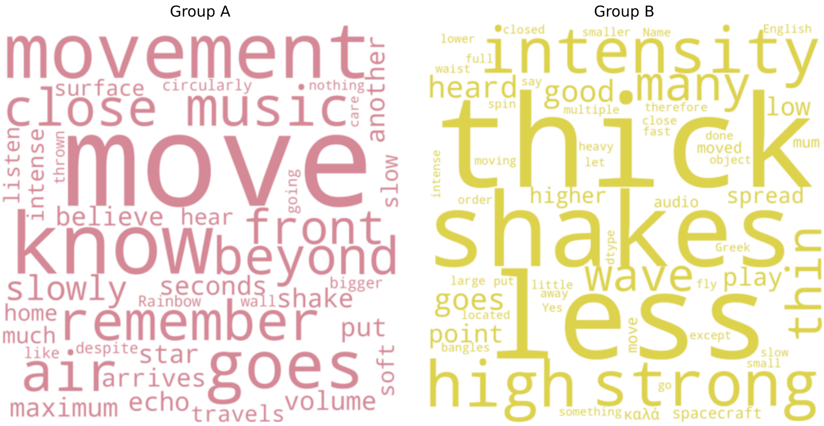

Fig. 7. These word clouds depict the frequency of the words unique to each group.

IBL emphasizes the importance of considering pedagogical approaches beyond the simulation itself.

The results highlight the efficacy of both student-led and teacher-mediated interaction with the simulation. Both groups demonstrated significant short-term learning gains, indicating the effectiveness of the simulation within an inquiry-based methodology. This suggests that while direct interaction with simulations can be beneficial, integrating process constraints facilitated by the teacher can further enhance learning effectiveness by managing cognitive load. Thus, future studies should delve deeper into understanding the co-factors (students' misconceptions or familiarization with the simulation) which may influence the effectiveness of the different types of guidance given when using simulations in inquiry-based contexts.

The interpretation of the results of the two exploratory analyses conducted, with a focus (i) on the alignment of responses within each respective group and (ii) on the frequency and uniqueness of the words used in each representative group, offer valuable insights.

The distinct differences in word usage between the two groups highlight the influence of instructional style on students' language and conceptualization. The control group, guided by the teacher, tended to echo the formal terminology used during instruction, which might reflect a more structured and uniform comprehension shaped by the teacher's framing. Conversely, the experimental group, operating independently, demonstrated a tendency to use more informal and varied language, indicating a personalized and perhaps more intuitive grasp of the concepts. Our second exploratory analysis further supports the findings from the initial analysis regarding in-group similarity in terminology usage. The experimental group, where students interacted primarily with their peers, exhibited a greater tendency to use common and informal terminology characteristic of their age group. This observation aligns with the expectation that peer interactions foster a more homogeneous linguistic environment, reinforcing students' use of familiar and colloquial language. This diversity in language usage can be attributed to the dual influence of the teacher's formal vocabulary and the students' informal reinterpretations. These findings underscore the importance of text analysis in educational research. By examining the qualitative data quantitatively, we can reveal differences in student understanding and interaction patterns that are shaped by the instructional context.

Despite the insights gained from this study, certain limitations impeded further analysis. Notably, the divergent pretest scores between the control and experimental groups hindered direct comparison of the level of complexity added to students' drawings. However, both groups ultimately achieved comparable short-term learning gains, underscoring the effectiveness of both instructional approaches. For future research ventures, we aim to explore the effects of varying cognitive load reductions on learning outcomes. Given the role of prior knowledge as a cognitive load reducer, investigating the impact of indirect simulation interaction in contexts with and without prior knowledge could yield valuable insights, on the effective use of science simulations. Specifically, conducting parallel studies with matched populations, one with prior knowledge and one without, could elucidate the differential effects of indirect interaction on learning gains. Furthermore, it is imperative to acknowledge the importance of sample size in detecting subtle differences resulting from instructional interventions. Larger sample sizes are essential for detecting meaningful variations in learning outcomes, particularly in the context of simulation-based inquiry learning. Furthermore, our study primarily examined short-term learning gains rather than focusing on conceptual change. However, conceptual change is often the desired outcome. To achieve this, we propose conducting multiple measurements that incorporate the time variable to assess long-term learning effects.

6 Conclusion

This study investigated the effects of different guidance approaches in utilizing simulation-based inquiry learning for teaching sound propagation. By comparing direct and indirect interaction with the simulation, operationalized by teacher-mediated process constraints, we aimed to investigate their impact on learning outcomes. The two different types of guidance used in this study were scaffolds and process constraints, with the second being present only in the control group condition. Despite encountering limitations in comparing the two groups because of discrepancies in their pretests, our findings revealed comparable short-term learning gains across both instructional approaches. In conclusion, this study underscores the significance of wisely integrating simulations within IBL frameworks and highlights the need for careful consideration of guidance strategies to optimize learning outcomes. By addressing the identified limitations and refining instructional approaches, educators can utilize simulations to foster meaningful and effective learning experiences within physics teaching and beyond.

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