Analysis of Interaction Patterns in Augmented Reality-Based Physics Learning

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Abstract. Augmented Reality (AR) has been increasingly integrated into physics education, providing an immersive and interactive learning experience. While numerous studies have examined AR's impact on conceptual understanding, engagement, and motivation, limited research has explored the dynamic interaction patterns that emerge when AR is used over multiple learning sessions. This study investigates the evolving interaction patterns among students, teachers, and AR technology in a physics learning environment. Specifically, it examines how student-student, student-teacher, and student-AR interactions change across six AR-enhanced learning sessions on magnetism. A qualitative research approach was employed, involving 36 high school students from West Kalimantan, Indonesia. Data were collected through video-recorded classroom observations, interaction mapping, and field notes. Interaction frequency analysis and qualitative coding were applied to assess engagement trends and learning strategies over time. The findings indicate that student-student interactions fluctuated, with a noticeable decrease in session three, followed by a recovery in later sessions. Student-teacher interactions increased progressively, suggesting a growing reliance on teacher guidance as learning tasks became more complex. Meanwhile, student-AR interactions remained relatively stable, with peaks at the beginning and end of each session, indicating initial exploration and final knowledge validation phases. This study highlights the temporal dynamics of collaborative learning in AR-supported environments, emphasizing the need for strategic integration of AR and teacher scaffolding. The results provide valuable insights for designing more effective AR-based instructional strategies that sustain meaningful student engagement over multiple sessions.
Keywords: Augmented reality, Interaction patterns, Physics education.

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1. Introduction

In recent years Augmented Reality (AR) has been applied in physics learning because it can help students to understand the abstract and the complex concept (Arymbekov et al., 2024; Bakri & Dwijayanti, 2022; Nusroh et al., 2022). The use of AR technology offers a more immersive and interactive learning experience. Students can visualize and directly interact with scientific phenomena that are difficult to observe in a typical classroom setting (Li et al., 2024). A number of studies have been conducted where it has been concluded that the use of AR in learning can not only improve the conceptual understanding of the students but also strengthen their engagement in the learning process and enhance academic motivation (Mokmin et al., 2024; Wang, 2022).

Although AR research has come a long way, the majority of current studies continue to examine whether it can enhance various aspects involved in student learning outcomes, engagement, and motivation, while overlooking the possibilities of investigating the nuances of interactions that arise when AR is applied in learning environments. Existing studies in this area primarily assess the effect of AR through short-term interventions aimed at improving conceptual understanding. However, they have not examined the long-term impact of AR systems on students' interaction patterns with peers, teachers, and the AR system itself. Moreover, the aspects of collaboration between students, the facilitative role of teachers and influence of the level of student dependence on AR in the learning process have not been comprehensively investigated.

Additionally, studies on the dynamics of interaction in AR-assisted physics learning remain limited. An analysis of collaborative learning theory highlights the essential role of peer interactions in knowledge construction (O'Donnell & King, 2014; Schoor et al., 2015; Yücel & Usluel, 2016); however, empirical evidence is needed to demonstrate how these interactions evolve over time in AR-based learning environments. The role of teachers inside AR supported learnings is also further simplified as of the role of facilitator (Diegmann et al., 2015; Lin & Tsai, 2021). There is limited research on how teacher-student interactions develop over multiple sessions as more students engage with AR tools (Cheng & Tsai, 2019; Martín-Gutiérrez et al., 2015). Furthermore, while the use of AR might improve the ability of students to explore independently, the temporal trends of student AR interactions during learning sessions is still to be systematically studied.

The existing research gap has not been fully addressed. Therefore, this study contributes to the advancement of research by conducting a longitudinal analysis of interaction patterns in AR-based physics learning environments. Unlike previous studies that primarily focus on user engagement and the transmission of conceptual information, this research provides a dynamic exploration of the evolving interactions among students, teachers, and AR over an extended period. Additionally, this study introduces a methodological approach for analyzing temporal interaction trends within each learning session, offering insights into how and when students transition between AR engagement, peer discussions, and teacher guidance. The findings of this analysis are expected to inform the optimal design of AR-based instructional settings and other collaborative learning components.

The following key research questions guided this study:

- How do student-student interactions fluctuate across different learning sessions, and what factors contribute to variations in collaboration?
- How does student-teacher interaction frequency change across multiple AR-enhanced sessions, and at what points do students seek the most guidance?
- What are the temporal trends in student-AR interactions within a session, and how do students transition between AR engagement and peer discussions over time?

2. Method

This study employs a qualitative approach, involving six 90-minute learning sessions on the topic of magnetism for 12th-grade students. The participants consisted of 36 high school students from a school in West Kalimantan, Indonesia, a physics teacher, and a four-member classroom observation team tasked with documenting interactions throughout the learning process.

An instructional approach enhanced with Augmented Reality (AR) supports the learning process and helps students grasp physics concepts, particularly magnetism. AR was integrated at three key stages: (1) Concept Exploration (0-30 minutes), where students used AR to visualize and interact with magnetic fields, magnetic forces, and related concepts; (2) Discussion and Clarification (30-60 minutes), where students engaged in discussions with peers and the teacher to clarify their understanding based on their AR experiences; and (3) Application in Problem-Solving (60-90 minutes), where students applied their understanding to answer questions or solve problems related to magnetism, using AR as a reference tool.

Through multiple methods, data was collected. Classroom observations were conducted using video recordings to capture the sequence of interactions and processes among students, teachers, and AR involved in learning. In addition, verbal and non-verbal cues of interaction during the learning sessions, such as field notes and interaction mapping were recorded to identify patterns of interaction.

Interaction frequency analysis was used as the study for data analysis, and counted times that there are student-student, student-teacher and student-AR interactions in each learning session. Qualitative coding also applied to video transcripts in order to identify themes and analyze student engagement patterns and learning strategies.

3. Results and Discussion

Instructional Media: Augmented Reality Application

The augmented reality (AR) system was developed using Vuforia as the AR software development kit and Blender for three-dimensional model creation. The application adopts a marker-based approach, in which students scan predefined markers using Android devices to render virtual objects in real time within a physical environment.

This AR application was designed to enhance students' conceptual understanding of magnetic fields, magnetic forces, and electromagnetic phenomena. Several visualizations are presented in Figure 1, including: (a) the Lorentz force, illustrating the interaction between a moving electric charge and a magnetic field; (b) a simple electric motor model, depicting key components such as the rotor, stator, commutator, and magnetic field source; (c) an illustration of the right-hand rule to determine the direction of magnetic force; and (d) the magnetic field surrounding a current-carrying wire.

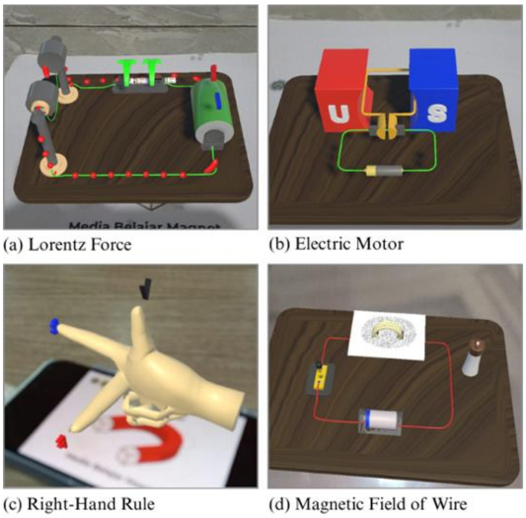

Figure 1. Augmented reality visualizations in physics education.

Interaction Frequency Across Sessions

To analyze student interaction patterns, data were collected from six learning sessions, each lasting 90 minutes. Figure 2 presents a stacked bar chart illustrating the distribution of student-student, student-teacher, and student-AR interactions across the sessions.

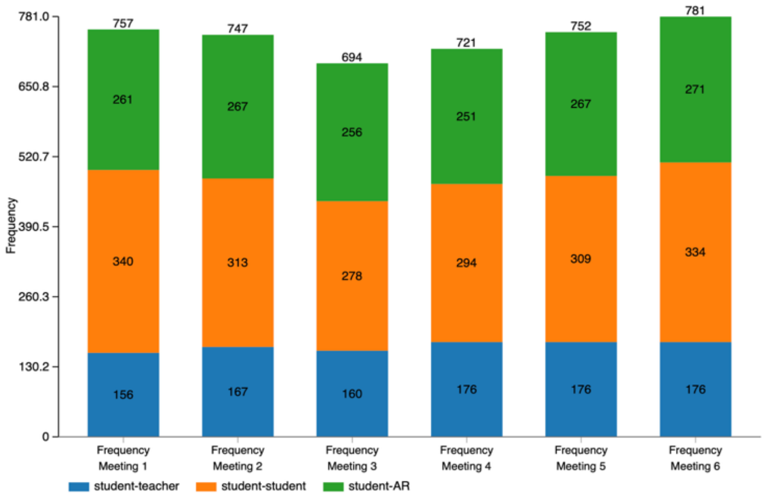

Figure 2. Frequency distribution of student-student, student-teacher, and student-AR interactions across six learning sessions.

The data show that student-student interactions fluctuated dipping down in session 3 and rising again in sessions 4 through 6. This variation suggests that students were initially engaged, however challenges in collaboration emerged midway through the sessions, requiring them to adapt. Student-AR interactions remained fairly stable, but showed a slight increase in the later sessions, likely due to an increased level of familiarity with AR devices. Consistently, student to teacher interaction was the least, however, it was slightly higher after session 3, showing that students needed guidance as they progressed in learning.

There was a fluctuating pattern of student-student interactions in which the level of interaction in session 3 dropped significantly before it increased again in the following sessions. The observed spike in collaborative learning pattern suggests that there was an engagement with collaborative learning, which then decreased during the course of tasks, marking a decrease in engagement in the learning process. This finding is in line with previous research on collaboration in technology-based learning environments which reveals some sort of temporary plateaus on the way to a plateau as students learn to adapt (Doyle & Nagle, 2019; Lämsä et al., 2018). This can be understood as an increase in the engagement with subsequent sessions, implying that the strategies the students have developed were facilitating an increased work with peers in AR mediated learning, but continued cooperation in AR mediation will be necessary.

Interaction Trends Over Six Sessions

To further examine interaction trends, Figure 3 presents a line graph depicting the interaction frequency trends of student-student, student-AR, and student-teacher interactions over the six sessions.

The graph indicates a temporary decline in student-student interactions during session 3, followed by an increase in later sessions. Student-teacher interactions significantly increased as the time went by, while student-AR interactions stayed constant with slight fluctuations. However, where the trend indicates that students primarily need to collaborate with peers, they relied more on AR and teacher support at different stages in the learning process. Session 3 could be where we observe a dip in student-student interactions if there is an increase in cognitive load or complexity of the learning tasks and additional scaffolding was needed support.

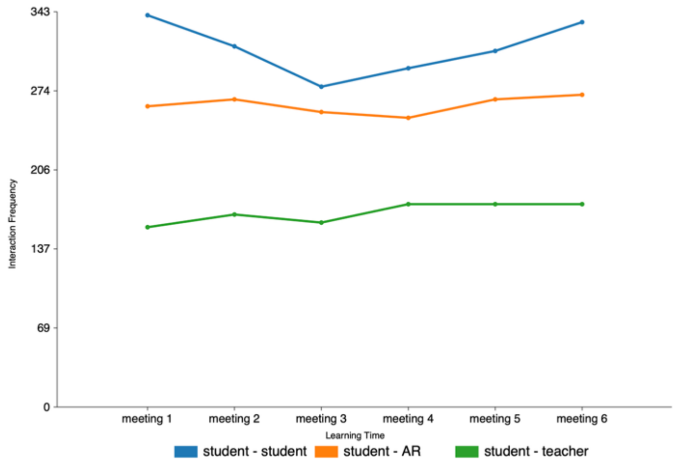

Figure 3. Frequency distribution of student-student, student-teacher, and student-AR interactions across six learning sessions.

Interactions between students and teachers were at the lowest level but increased with time in the following sessions. Overall, this pattern showed that students used AR technology and collaborative assistance from their peers to a greater extent in the early stages of studying but leaned on teacher engagement mostly while dealing with more complex concepts. Prior work emphasizes the importance of teachers in the process of AR-based learning, through their role as scaffolders, highlighting the role of teachers in supporting students in more abstract conceptual problem-solving tasks. Teacher scaffolding in AR environments helps boost students' spatial and conceptual understanding in mathematics education (Nikimaleki & Rahimi, 2022). Teacher involvement is active and encourages collaboration and engagement, making them key partners in co-constructing knowledge (Hunuk & MacPhail, 2023). Furthermore, a dual scaffolding framework reveals that the teacher's support is crucial for maintaining students' collective learning during AR-enhanced tasks (Hou & Keng, 2021). The increase in student-teacher interactions indicates that as students develop a deeper understanding, they progressively seek more focused and structured guidance, reinforcing the teacher's role as a facilitator in AR-supported learning environments.

Temporal Trends in Student-AR Interactions Within a Session

To analyze interaction patterns within a single learning session, Figure 4 displays the frequency distribution of student interactions over 15-minute intervals throughout a 90-minute session.

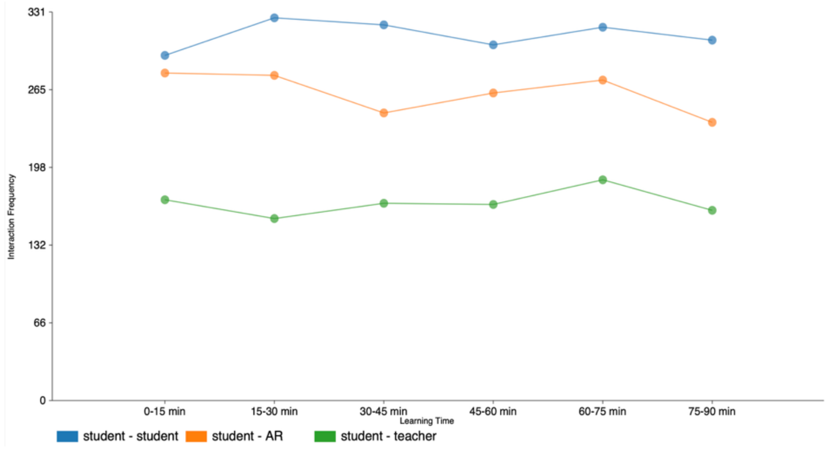

Figure 4. Temporal distribution of student-student, student-AR, and student-teacher interactions within a single 90-minute session.

Student-AR interactions began high (15-30 mins), decreased slightly (30-45 mins), and increased again (60-75 mins). At the same time, student-student interactions remained high throughout the session, while student teacher interactions peaked in the middle of the session. The AR simulation dipping shows a trend that students started the session off engaging heavily with the AR simulations but as they went deeper into the problem space, they moved on to peer discussions to work the problem. Towards the end of the session, the higher number of in student AR interactions suggests that students repeated AR content to check their understanding before wrapping up the task. The increase in student-teacher interactions in the middle of the session indicates that students wanted to get clarifications after they had explored the task, discussed it with peers and reached some conclusions.

The within-session interaction data reveal a distinct pattern of AR usage. Students engaged most with AR tools in the first 30 minutes, followed by a shift towards peer collaboration. In all of the research conducted thus far with AR integration in education, AR has been suggested to be a two-stage learning process where students first use AR tool to visualize concept before finally transferring into peer discussion in order to clarifying and summarizing what was learned. By exploring digital content that helps facilitate understanding of concepts, students initially provide motivation and confidence as they are engaged in this process independently before having the opportunity to engage in collaborative dialogue. Regarding various contexts such as vocational education, STEM learning, or university level AR/VR adoption, it has been uncovered that AR works as a cognitive scaffold, as well as a catalyst for meaningful peer interaction (Acosta et al., 2019; Jdaitawi et al., 2022; Petrov & Atanasova, 2020; Tan et al., 2024).

Students engage with AR at the end of their learning sessions to validate their knowledge, as it reinforces conceptual understanding. Multiple studies confirm that blended learning methods together with AR-based learning environments help students to improve their comprehension through multiple digital resource interactions which lead to better knowledge retention and conceptual understanding (Ashraf et al., 2022; Harahap et al., 2019). Research shows that model students engage better using AR in educational and commercial settings when they repeatedly interact with it because understanding improves (Ganesan & Kumar, 2024). The research demonstrates why it is essential to merge AR with blended learning methods during instructional planning in order to support optimal student educational outcomes.

4. Conclusion

This study examined the dynamic interaction patterns among students, teachers, and Augmented Reality (AR) technology in an AR-enhanced physics learning environment. Through a longitudinal analysis of six learning sessions, the findings reveal that student-student interactions fluctuate over time, with a temporary decline in session three before recovering in later sessions. This suggests that students initially engage in collaborative learning but may require additional scaffolding to maintain interaction consistency.

Student-teacher interactions show a progressive increase, indicating that as learning tasks become more complex, students seek more structured guidance. This highlights the evolving role of teachers from facilitators to active contributors in the AR learning process, reinforcing the importance of well-designed scaffolding strategies. Meanwhile, student-AR interactions remain relatively stable, peaking at the beginning and end of sessions, suggesting that students use AR for both exploration and knowledge validation.

This study highlights the importance of designing AR-based learning environments that integrate peer collaboration, teacher facilitation, and technological support. Future research should explore additional factors influencing these interaction patterns, such as students' prior knowledge, cognitive load, and motivation. By understanding the temporal dynamics of AR-supported learning, educators can develop more effective instructional strategies that sustain meaningful engagement and improve learning outcomes in technology-enhanced education.

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