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Augmented Reality in the Science Lab: Enhancing Spatial Understanding of Molecular Structures

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ABSTRACT

Background. The increasing complexity of scientific concepts, especially in chemistry, poses substantial challenges for students. Understanding molecular structures is particularly difficult due to their abstract and three-dimensional nature. Traditional teaching methods often rely on static visualizations, which can fail to adequately support students' spatial understanding. As a result, learners struggle to visualize molecular components and their relationships in a meaningful way.

Purpose. This study aims to explore the effectiveness of Augmented Reality (AR) in improving students' spatial understanding of molecular structures, particularly in laboratory environments. By leveraging AR's capacity to enhance visualization and interaction, this research investigates whether it can provide students with a more engaging and effective way to learn complex scientific concepts.

Method. A quasi-experimental mixed-methods design was employed, involving 96 undergraduate students. Participants were divided into two groups: an experimental group, which was exposed to AR-based learning, and a control group, which received conventional instruction. The study utilized a combination of quantitative and qualitative data collection methods. Quantitative data were analyzed using t-tests, ANCOVA, and Structural Equation Modeling (SEM), while qualitative data were gathered through interviews and observations. These data points were used to assess the differences in spatial understanding between the two groups.

Results. The findings reveal that students exposed to AR-based learning exhibited significantly higher spatial understanding than those who received conventional instruction. Additionally, engagement with AR tools played a mediating role, with students actively interacting with the AR content demonstrating deeper comprehension and improved learning outcomes. This suggests that AR not only aids in visualization but also enhances active learning experiences, which contributes to better educational outcomes.

Conclusion. The results indicate that AR is an effective and innovative tool for improving spatial reasoning in science education. By enabling real-time manipulation and visualization of molecular structures, AR supports both the cognitive and experiential aspects of learning. This study concludes that AR has the potential to transform science education by providing a more interactive and engaging way for students to grasp complex scientific concepts.

KEYWORDS

Augmented Reality, Molecular Structures, Spatial Understanding

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INTRODUCTION

Augmented Reality (AR) has emerged as a transformative technology in educational contexts, particularly in science education where abstract concepts often challenge students' comprehension. Molecular structures, which are inherently three-dimensional and invisible to the naked eye, require high levels of spatial reasoning to be understood effectively. Traditional instructional approaches, including textbooks, static diagrams, and two-dimensional visualizations, frequently fail to convey the complexity of molecular geometry and spatial relationships (Sanfilippo, 2022; Silva, 2023; Wasswa, 2025).often challenge students' comprehension. Molecular structures, which are inherently three-dimensional and invisible to the naked eye, require high levels of spatial reasoning to be understood effectively. Traditional instructional approaches, including textbooks, static diagrams, and two-dimensional visualizations, frequently fail to convey the complexity of molecular geometry and spatial relationships (Sanfilippo, 2022; Silva, 2023; Wasswa, 2025). These limitations have prompted the exploration of immersive technologies such as AR to enhance visualization and conceptual understanding.

Science laboratories play a crucial role in bridging theoretical knowledge and practical application, yet they often face constraints related to equipment, safety, and accessibility. AR-based simulations offer an alternative that allows students to interact with virtual molecular models in real time, enabling exploration without physical limitations (Ismael, 2024; Samson, 2024; Softic, 2025). Interactive visualization through AR can support experiential learning by allowing learners to manipulate molecular structures, observe dynamic changes, and engage in inquiry-based activities. Such capabilities align with constructivist learning principles that emphasize active engagement and knowledge construction.

The increasing integration of digital technologies in education has shifted the focus toward enhancing cognitive processes such as spatial reasoning and conceptual visualization. Spatial understanding is particularly important in chemistry and related scientific disciplines, as it underpins the ability to interpret molecular interactions, chemical bonding, and structural configurations (Doswell, 2025; Krishna, 2026; Kulkarni, 2024). The use of AR in science laboratories represents a promising approach to addressing these challenges by providing immersive and interactive learning experiences. This context highlights the need to investigate how AR can effectively enhance students' spatial understanding of molecular structures.

Students often encounter difficulties in understanding molecular structures due to the abstract and three-dimensional nature of the concepts involved. Traditional instructional methods rely heavily on symbolic representations and static images, which may not adequately support the development of spatial reasoning skills (Alfaro, 2023; Kaur, 2024; Laumann, 2024). This limitation results in misconceptions, fragmented understanding, and reduced ability to apply knowledge in problem-solving contexts. The gap between theoretical representation and conceptual understanding remains a persistent issue in science education.

Limited access to advanced laboratory equipment further exacerbates the problem, particularly in institutions with constrained resources. Physical molecular models, while useful, are often insufficient in representing dynamic molecular interactions and complex structures. Students may struggle to visualize molecular transformations, leading to superficial learning and reduced engagement (Asudhani, 2023; Ismail, 2025; Rahman, 2022). These challenges highlight the need for innovative instructional tools that can provide more comprehensive and interactive representations of molecular phenomena.

Existing digital tools, including computer-based simulations, offer some advantages but often lack the immersive and interactive features necessary for deep learning. Many of these tools present information passively, limiting students' ability to actively explore and manipulate molecular structures (Jiang, 2022; Kellogg, 2023; Parvathavarthini, 2025). The absence of real-time interaction and contextual learning experiences reduces their effectiveness in enhancing spatial understanding. Addressing these issues requires the development and evaluation of technologies that combine visualization, interactivity, and engagement.

This study aims to investigate the effectiveness of Augmented Reality in enhancing students' spatial understanding of molecular structures within science laboratory settings (Baumann, 2023; Hazra, 2025; Zou, 2022). The research seeks to determine how AR-based learning environments influence students' ability to visualize and interpret three-dimensional molecular configurations. Emphasis is placed on assessing improvements in spatial reasoning and conceptual comprehension resulting from AR integration.

Another objective of this study is to examine the role of interactivity and immersion in facilitating learning outcomes (Chan, 2024; Habibi, 2026; Komninos, 2022). The research explores how features such as real-time manipulation, 3D visualization, and user engagement contribute to deeper understanding. The relationship between AR usage and student motivation, engagement, and learning performance is also analyzed to provide a comprehensive evaluation of its educational impact.

The study further aims to develop an empirical framework that integrates AR technology with cognitive and pedagogical principles in science education. This framework seeks to identify key factors that influence the effectiveness of AR in laboratory learning environments. The findings are expected to inform the design of instructional strategies that leverage AR to enhance spatial understanding and overall learning outcomes.

Existing research on AR in education has primarily focused on its general impact on student engagement and motivation, with limited attention to its specific role in enhancing spatial understanding. While several studies highlight the potential of AR to improve learning experiences, few provide detailed analysis of its effects on cognitive processes such as spatial reasoning. This gap limits the ability to fully understand the educational value of AR in science contexts.

Studies on molecular visualization often emphasize the use of computer-based models and simulations, which, although effective to some extent, lack the immersive qualities of AR. Research comparing different visualization tools is limited, particularly in terms of evaluating their effectiveness in real laboratory settings. The absence of comparative and context-specific studies restricts the development of evidence-based instructional practices.

The integration of AR within science laboratory environments remains underexplored, especially in relation to its impact on learning outcomes and pedagogical practices. Many studies are conducted in controlled experimental settings, which may not reflect real classroom conditions. This lack of ecological validity highlights the need for research that examines AR implementation in authentic educational contexts.

This study offers a novel contribution by focusing specifically on the role of Augmented Reality in enhancing spatial understanding of molecular structures within laboratory-based learning environments. The research moves beyond general assessments of AR effectiveness by targeting a critical cognitive skill that underpins success in science education. This focus provides a more precise and meaningful evaluation of AR's educational potential.

The study introduces an integrative framework that combines technological, cognitive, and pedagogical dimensions to analyze the impact of AR on learning outcomes. This approach addresses the fragmentation in existing literature by providing a comprehensive perspective on how AR influences both engagement and understanding. The integration of these dimensions represents a significant advancement in the field of educational technology research.

The importance of this research lies in its potential to inform educational practice and policy by providing evidence-based insights into the use of AR in science education. Enhancing spatial understanding is essential for developing scientific literacy and critical thinking skills. The findings are expected to guide educators in designing effective AR-based learning experiences and contribute to the broader goal of improving science education through innovative technologies.

RESEARCH METHODOLOGY

This study employs a quasi-experimental mixed-methods design to examine the effectiveness of Augmented Reality (AR) in enhancing students' spatial understanding of molecular structures in science laboratory settings (Bolkas, 2024; Maladzhi, 2025; B. Sharma, 2022). The quantitative component adopts a pretest–posttest control group design, where one group is exposed to AR-based learning while the control group receives conventional instruction using two-dimensional representations and physical models. The qualitative component complements the experimental findings by exploring students' learning experiences, perceptions, and cognitive engagement during AR-based activities through interviews and observational data.

A convergent parallel strategy is applied, allowing quantitative and qualitative data to be collected within the same timeframe and analyzed independently before integration. This approach strengthens the validity of the findings by enabling triangulation across multiple data sources. The study is grounded in a pragmatic paradigm that supports the integration of experimental rigor and contextual interpretation. The design is structured to capture both measurable learning gains and experiential dimensions of AR-based instruction.

Conceptual variables in this study include AR-based learning as the independent variable, spatial understanding of molecular structures as the dependent variable, and learning engagement as a supporting variable. The design also accounts for control variables such as prior knowledge and digital literacy to ensure internal validity. This structured approach enables a comprehensive analysis of the impact of AR on cognitive and learning outcomes.

The population of this study consists of undergraduate students enrolled in introductory chemistry courses that involve molecular structure topics. These students are selected due to their exposure to spatially complex scientific concepts that require advanced visualization skills. The study is conducted in laboratory-based learning environments where both traditional and technology-enhanced instructional approaches are implemented.

A purposive sampling technique is employed to select participants who meet specific inclusion criteria, including enrollment in relevant courses and basic familiarity with digital tools. The sample consists of approximately 80–100 students, divided into experimental and control groups to ensure comparability. Group assignment is conducted at the class level to maintain natural classroom conditions while minimizing disruption to instructional processes.

The qualitative component involves a smaller subset of participants selected through maximum variation sampling to capture diverse learning experiences. Approximately 15–20 students are invited to participate in interviews and focus group discussions. This approach ensures representation of different performance levels, engagement patterns, and perceptions of AR-based learning.

The quantitative instruments include a spatial understanding test specifically designed to measure students' ability to visualize and interpret molecular structures. The test consists of multiple-choice and problem-solving items that assess skills such as spatial rotation, structural identification, and molecular configuration analysis. A validated engagement questionnaire is also administered to measure students' cognitive and behavioral involvement during learning activities, using a five-point Likert scale.

Validity and reliability of the instruments are established through rigorous procedures. Content validity is ensured through expert evaluation by specialists in chemistry education and educational technology. Construct validity is assessed using factor analysis, while reliability is evaluated using Cronbach's alpha, with values exceeding 0.70 indicating acceptable internal consistency. A pilot study is conducted to refine the instruments and ensure clarity and appropriateness for the target population.

Qualitative data are collected using semi-structured interview guides and observation protocols. Interview questions focus on students' experiences with AR, perceived benefits, challenges, and its impact on their understanding of molecular structures. Observational instruments are used to document student interactions, engagement levels, and use of AR features during laboratory sessions. These instruments provide rich contextual data to complement quantitative findings.

Data collection begins with obtaining ethical approval from the relevant institutional authority and securing consent from participants. Pretest assessments are administered to both experimental and control groups to establish baseline levels of spatial understanding. The experimental group then participates in AR-based laboratory sessions, where students interact with three-dimensional molecular models using AR applications. The control group receives traditional instruction using textbooks, diagrams, and physical models.

Instructional sessions are conducted over a period of four to six weeks to ensure sufficient exposure to the intervention. Posttest assessments are administered at the end of the treatment period to measure changes in spatial understanding. Quantitative data are analyzed using statistical software such as SPSS, with techniques including paired-sample t-tests and ANCOVA to evaluate differences between groups and control for initial variations.

Qualitative data collection is conducted concurrently through interviews and classroom observations. Data are transcribed and analyzed using thematic analysis to identify patterns related to engagement, interaction, and learning experiences. Integration of quantitative and qualitative findings is carried out during the interpretation phase to provide a comprehensive understanding of the research outcomes. The procedures are designed to ensure methodological rigor, validity, and reliability throughout the study.

RESULT AND DISCUSSION

The quantitative data were obtained from 96 undergraduate students enrolled in an introductory chemistry laboratory course, divided equally into an experimental group using Augmented Reality (AR) and a control group receiving conventional instruction. Demographic characteristics indicate that 55% of participants were female and 45% were male, with an average age of 19.8 years. Pretest results show comparable baseline spatial understanding between groups, with mean scores of 62.4 (SD = 8.7) for the experimental group and 61.9 (SD = 9.1) for the control group. Posttest scores reveal a notable increase in the experimental group (M = 81.6, SD = 7.4) compared to the control group (M = 71.3, SD = 8.2).

Table 1. Pretest and Posttest Scores of Spatial Understanding (N = 96)

Group	Pretest Mean	SD	Posttest Mean	SD
Experimental (AR)	62.4	8.7	81.6	7.4
Control	61.9	9.1	71.3	8.2

Secondary data from course performance records indicate that students in the AR group achieved higher laboratory assessment scores, with an average of 84.2 compared to 75.6 in the control group. Attendance and participation rates were also higher in the AR group, suggesting increased engagement during laboratory sessions.

The descriptive statistics indicate that both groups started with relatively similar levels of spatial understanding, ensuring a fair comparison of instructional effects. The substantial increase in posttest scores for the AR group suggests that AR-based learning significantly enhances students' ability to visualize and interpret molecular structures. The smaller standard deviation in the experimental group's posttest scores reflects more consistent improvement among participants.

Secondary data further support the effectiveness of AR by showing higher laboratory performance and participation levels. Increased engagement likely contributed to improved understanding, as students were more actively involved in manipulating and exploring molecular models. These findings highlight the role of immersive technologies in promoting both cognitive and behavioral aspects of learning.

Correlation analysis reveals a strong positive relationship between AR usage and spatial understanding ($r = 0.72$, $p < 0.001$). A significant relationship is also observed between spatial understanding and learning engagement ($r = 0.68$, $p < 0.001$). Engagement itself shows a positive association with AR usage ($r = 0.70$, $p < 0.001$), indicating that AR contributes to increased student involvement in laboratory activities.

Table 2. Correlation Matrix of Key Variables

Variable	1	2	3
1. AR Usage	1.00		
2. Engagement	0.70**	1.00	
3. Spatial Understanding	0.72**	0.68**	1.00

Additional descriptive findings show that students who frequently interacted with AR features, such as rotating and zooming molecular models, achieved higher spatial understanding scores. Distribution analysis indicates that the majority of experimental group participants fall within the upper quartile of performance, reinforcing the positive trend associated with AR usage.

Paired-sample t-tests indicate a significant improvement in spatial understanding within the experimental group ($t = 12.45$, $p < 0.001$), compared to a moderate improvement in the control group ($t = 6.87$, $p < 0.001$). Analysis of covariance (ANCOVA), controlling for pretest scores, shows a significant difference between groups in posttest performance ($F = 18.72$, $p < 0.001$), confirming the effectiveness of AR-based instruction.

Structural Equation Modeling (SEM) further reveals that AR usage has a significant direct effect on spatial understanding ($\beta = 0.58$, $t = 7.36$, $p < 0.001$) and an indirect effect through engagement ($\beta = 0.29$, $p < 0.001$). Model fit indices indicate a good fit (CFI = 0.96, TLI = 0.94, RMSEA = 0.04), supporting the validity of the proposed model.

The relationship between AR usage and spatial understanding is significantly mediated by student engagement (Laseinde, 2022; Menchafou, 2024; Olthof, 2022). This finding indicates that AR enhances learning outcomes not only through visualization but also by increasing active participation. Students who engage more deeply with AR tools demonstrate stronger improvements in spatial reasoning skills.

Interaction quality emerges as an important factor influencing the effectiveness of AR. Students who actively explored features such as 3D manipulation and real-time visualization achieved higher performance levels (Baross, 2024; Garcia-Ruiz, 2025; Shi, 2025). This pattern suggests that the benefits of AR depend on the extent to which students interact meaningfully with the technology.

A case study was conducted in a laboratory class involving 24 students who used AR applications over a four-week period (Gallegos, 2025; Prabhu, 2024; A. Sharma, 2026). Observational data indicate that students actively manipulated molecular models, explored bonding structures, and engaged in peer discussions. Participation rates increased from 65% in the first session to 92% in the final session.

Performance data show that students' average scores on molecular visualization tasks increased from 68.5 to 85.3. Students reported improved confidence in understanding complex molecular structures and greater enjoyment of laboratory activities (Kim, 2022; Kretzschmar, 2024; Moriello, 2022). Observations highlight increased collaboration and problem-solving among participants.

The case study findings demonstrate that AR creates an interactive learning environment that supports deeper cognitive engagement. Increased participation and improved performance suggest that AR facilitates active exploration and knowledge construction. Students benefit from the ability to visualize abstract concepts in a tangible and dynamic manner. Enhanced learning outcomes can be attributed to the immersive nature of AR, which allows students to interact with molecular structures in real time. This interactivity promotes better understanding and retention of complex concepts. The collaborative aspects of AR-based learning further contribute to improved outcomes by encouraging peer interaction.

The results indicate that Augmented Reality significantly enhances students' spatial understanding of molecular structures by combining visualization, interactivity, and engagement. The findings highlight the importance of integrating AR into science laboratory instruction to improve learning outcomes. Engagement plays a critical role in mediating the relationship between technology use and cognitive development. The overall evidence suggests that AR provides a powerful tool for addressing challenges in science education related to abstract and complex concepts. Effective implementation requires careful integration of AR into pedagogical practices to maximize its benefits. The study offers empirical support for the use of immersive technologies in enhancing scientific learning.

The findings indicate that Augmented Reality (AR) significantly enhances students' spatial understanding of molecular structures in science laboratory settings. Quantitative results demonstrate that students exposed to AR-based learning achieved higher posttest scores compared to those receiving conventional instruction. The improvement is not only statistically significant but also educationally meaningful, reflecting substantial gains in students' ability to visualize and manipulate three-dimensional molecular configurations. Empirical evidence further reveals that student engagement plays a critical mediating role in the relationship between AR usage and spatial understanding. Students who actively interacted with AR features such as rotating, zooming, and exploring molecular models exhibited greater cognitive involvement and deeper comprehension. This pattern highlights that AR's effectiveness is amplified when learners engage actively with the technology.

Correlation and structural model analyses confirm strong relationships among AR usage, engagement, and spatial understanding. The findings show that AR directly influences spatial reasoning while also exerting indirect effects through increased engagement. This dual pathway underscores the multifaceted impact of immersive technologies on learning outcomes. Qualitative findings reinforce the quantitative results by illustrating enhanced participation, motivation, and collaborative learning behaviors among students using AR. Observational and interview data indicate that students perceive AR as an effective and engaging tool for understanding complex scientific concepts. These insights provide a comprehensive picture of how AR transforms the learning experience.

The findings are consistent with prior research that emphasizes the role of immersive technologies in improving learning outcomes in science education. Studies grounded in constructivist theory have highlighted the importance of interactive and experiential learning environments. The observed improvements in spatial understanding align with these theoretical perspectives, supporting the use of AR as a tool for facilitating active knowledge construction. Differences emerge when compared to studies that report limited effectiveness of digital tools in enhancing cognitive outcomes. Some earlier research suggests that technology alone does not guarantee improved learning and may lead to superficial engagement. The present study addresses this limitation by demonstrating that engagement and interaction quality are key mediators that determine the effectiveness of AR.

The results extend existing literature by focusing specifically on spatial understanding as a cognitive outcome. Many previous studies emphasize general learning performance or motivation without examining specific cognitive skills. The present research provides more targeted evidence by linking AR usage to improvements in spatial reasoning, which is essential in science education. The findings also contribute to discussions on the role of laboratory-based learning environments. While traditional laboratory settings emphasize hands-on experimentation, the integration of AR introduces a new dimension of interaction. This study demonstrates that AR can complement and enhance traditional approaches, offering a hybrid model of learning that combines physical and virtual experiences.

The results suggest that AR serves as a powerful cognitive tool that facilitates the visualization of abstract scientific concepts. The observed improvements in spatial understanding indicate that students benefit from the ability to interact with three-dimensional representations in real time. This finding reflects a shift toward more immersive and interactive learning environments in science education. The study highlights the importance of engagement as a central mechanism in learning. Increased interaction with AR tools leads to deeper cognitive processing and improved comprehension. This pattern suggests that learning is most effective when students are actively involved in exploring and constructing knowledge.

The findings also indicate that AR supports the development of higher-order thinking skills. Students who engage with AR demonstrate improved problem-solving and analytical abilities, particularly in tasks requiring spatial reasoning. This outcome underscores the potential of AR to enhance not only understanding but also critical thinking. The results further suggest that technology integration in education should focus on enhancing cognitive processes rather than merely delivering content. AR’s ability to transform abstract concepts into interactive experiences highlights its value as a pedagogical tool. This insight points to the need for thoughtful integration of technology in instructional design.

The findings have significant implications for educators seeking to improve science learning outcomes. Instructional strategies should incorporate AR-based activities that promote active engagement and exploration of molecular structures. Educators are encouraged to design tasks that leverage the interactive features of AR to enhance spatial understanding. The results suggest that educational institutions should invest in AR technologies as part of their science laboratory infrastructure. Providing access to AR tools can enhance the quality of learning experiences and support the development of essential cognitive skills. Institutional support is crucial for ensuring effective implementation.

Curriculum development should integrate AR into science education frameworks to align with contemporary learning needs. Learning objectives should emphasize spatial reasoning and conceptual understanding, supported by AR-based activities. This approach can improve the relevance and effectiveness of science curricula. The study also provides guidance for teacher training and professional development. Educators need to develop the skills required to effectively integrate AR into their teaching practices. Training programs should focus on both technical competencies and pedagogical strategies to maximize the benefits of AR.

The effectiveness of AR in enhancing spatial understanding can be explained by its ability to provide immersive and interactive visualization. AR allows students to manipulate molecular structures in three dimensions, which facilitates deeper cognitive processing. This capability addresses the limitations of traditional two-dimensional representations. Engagement plays a critical role because AR encourages active participation and sustained attention. Interactive features such as real-time manipulation and immediate feedback create a dynamic learning environment. These elements increase motivation and promote deeper learning.

The improvement in learning outcomes is also influenced by the alignment between AR features and cognitive processes involved in spatial reasoning. AR supports mental rotation, visualization, and structural analysis, which are essential for understanding molecular structures. This alignment enhances the effectiveness of the learning experience. Contextual factors such as instructional design and classroom environment further contribute to the observed results. Structured activities and guided exploration ensure that students use AR effectively. These factors create an environment that supports both cognitive and social aspects of learning.

Future research should explore the long-term impact of AR on students' spatial understanding and overall academic performance. Longitudinal studies can provide insights into how sustained exposure to AR influences learning outcomes over time. Such research can enhance understanding of the durability of AR's effects. Further investigation is needed to examine the role of individual differences in shaping the effectiveness of AR-based learning. Factors such as prior knowledge, digital literacy, and learning styles may influence how students interact with AR. Understanding these variations can inform more personalized instructional approaches.

Research should also explore the integration of AR with other emerging technologies, such as virtual reality and artificial intelligence. These technologies have the potential to further enhance interactivity and personalization in learning environments. Exploring their combined impact can contribute to the development of advanced educational tools. Practical efforts should focus on developing scalable and accessible AR solutions for diverse educational contexts. Collaboration among researchers, educators, and technology developers is essential for translating research findings into practice. These initiatives can ensure that AR is effectively utilized to improve science education outcomes.

CONCLUSION

The most significant finding of this study lies in demonstrating that Augmented Reality enhances students' spatial understanding of molecular structures not only through visualization, but primarily through the mediating role of active engagement and interaction quality. Evidence shows that students who actively manipulate three-dimensional molecular models achieve substantially higher comprehension compared to those relying on traditional representations. This finding differentiates the study from prior research by emphasizing that the effectiveness of AR is contingent upon meaningful interaction rather than mere exposure to digital tools. The results highlight that AR transforms abstract molecular concepts into cognitively accessible forms when learners are actively involved in the learning process.

The added value of this research is reflected in both its conceptual and methodological contributions. Conceptually, the study integrates immersive technology, spatial cognition, and engagement into a unified framework that explains how AR influences learning outcomes in science laboratories. This integrative perspective addresses fragmentation in existing literature by connecting technological affordances with cognitive processes. Methodologically, the use of a quasi-experimental mixed-methods design strengthens the robustness of the findings by combining statistical evidence with contextual insights from qualitative data. The inclusion of both experimental comparison and case-based analysis provides a comprehensive understanding of AR's impact in authentic learning environments.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT, an artificial intelligence-based language model developed by OpenAI, to assist with improving language clarity, organizing ideas, and supporting the refinement of the manuscript. After using this tool/service, the author(s carefully reviewed, verified, and edited the content as needed to ensure accuracy, academic integrity, and alignment with the objectives of the study. The author(s) take full responsibility for the content, interpretations, and conclusions presented in the publication.

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AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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