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Beyond Immersion: A Comparative Analysis of Cognitive Learning Outcomes in Augmented Reality (AR) versus Traditional Laboratory Settings

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ABSTRACT

Background. The integration of Augmented Reality (AR) in education has garnered attention for its potential to enhance student engagement and learning outcomes. While much of the research focuses on the immersive nature of AR, its impact on cognitive learning outcomes compared to traditional laboratory-based learning environments remains underexplored.

Purpose. This study aims to compare the cognitive learning outcomes of students who engage with content in AR environments versus those who participate in traditional laboratory settings. The research seeks to determine whether AR offers significant advantages in terms of knowledge retention, problem-solving, and conceptual understanding.

Method. A mixed-methods design was employed, combining quantitative pre- and post-test assessments to measure cognitive outcomes and qualitative focus group discussions to capture students' experiences. The study involved 200 students, with 100 participating in AR-based learning and 100 in traditional laboratory settings.

Results. The AR group showed a greater improvement in cognitive learning outcomes (23% increase) compared to the traditional laboratory group (14% increase). Students in the AR environment also reported higher levels of engagement, which correlated with their cognitive improvements.

Conclusion. AR-based learning environments offer significant cognitive benefits over traditional laboratory settings, particularly in enhancing conceptual understanding and problem-solving skills.

KEYWORDS

Augmented Reality, Educational Technology, Traditional Laboratory

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INTRODUCTION

The increasing integration of technology in educational settings has opened new avenues for enhancing the learning experience. Among these technological advancements, Augmented Reality (AR) stands out as a transformative tool in educational environments, particularly for subjects that require hands-on, immersive experiences (Álvarez-Marín dkk., 2023; Cao dkk., 2025). Unlike traditional teaching methods, AR has the potential to create highly interactive learning environments that in novel ways. By superimposing digital information allow students to engage with content onto the physical world, AR enables learners to visualize complex concepts and engage with them in real-time, potentially improving cognitive learning outcomes. This has led to widespread adoption of AR across various fields, including science, engineering, and medicine (Khang dkk., 2023; Parvathavarthini dkk., 2025).

In parallel, traditional laboratory settings have long been the cornerstone of experiential learning, particularly in science education, where students are encouraged to manipulate equipment, conduct experiments, and observe phenomena firsthand. Despite its success, traditional laboratory teaching is often limited by resource constraints, time, and safety considerations. Furthermore, the scope of concepts that can be taught in a physical lab setting is often constrained by the available equipment and physical space. As educational institutions seek innovative ways to overcome these limitations, AR technology has emerged as a potential alternative or complement to traditional laboratory learning experiences. However, it remains unclear how these two learning environments AR and traditional laboratories compare in terms of cognitive learning outcomes (Ding dkk., 2026; Hernández-Rodríguez, 2023).

Given this context, understanding the comparative effectiveness of AR versus traditional laboratory settings in fostering cognitive learning is crucial. This research seeks to evaluate and contrast the cognitive learning outcomes in both AR and traditional laboratory environments to determine how they contribute to student learning, engagement, and comprehension. This study addresses the need for evidence-based insights into the educational value of AR, which can help guide the future integration of such technologies into educational curricula (Iriqat & Vatansever, 2025; Müller dkk., 2023).

While the potential of AR to enhance learning is widely recognized, there is limited empirical evidence directly comparing cognitive learning outcomes between AR-based and traditional laboratory learning environments. Most studies on AR in education tend to focus on individual subjects or small-scale applications, with little comparative analysis of AR's effectiveness against traditional teaching methods in a systematic way. Moreover, AR’s impact on cognitive learning outcomes such as memory retention, understanding of complex concepts, and problem-solving skills has not been extensively studied in the context of laboratory-based disciplines where hands-on experience is central to learning (Albawaneh dkk., 2023; Cheng dkk., 2025).

In the context of science education, the challenge lies in determining whether AR can truly replicate the immersive, interactive experience of a physical laboratory or if it offers unique advantages that traditional methods cannot provide. This study seeks to fill this gap by comparing the cognitive learning outcomes of students who engage with content in AR environments versus those who participate in traditional laboratory settings. The research will examine whether AR enhances students’ ability to recall information, understand scientific concepts, and apply knowledge in problem-solving scenarios, compared to traditional methods that rely on direct interaction with physical experiments and materials.

The specific problem addressed by this research is the lack of clear, comparative data on the effectiveness of AR as an alternative to traditional laboratory learning. As educational institutions increasingly consider the integration of AR into their curricula, understanding its impact on cognitive learning outcomes is essential for making informed decisions about its use. The findings of this research will provide valuable insights into the strengths and limitations of AR in comparison to traditional laboratory settings, offering guidance for educators and policymakers looking to adopt or expand the use of AR in educational contexts (Hong dkk., 2024; Wang dkk., 2025).

The primary objective of this study is to compare the cognitive learning outcomes of students who participate in AR-based learning environments with those who engage in traditional laboratory settings. Specifically, the study aims to assess whether AR can enhance students' understanding of complex concepts, improve their ability to apply learned material to real-world scenarios, and increase retention of knowledge compared to traditional learning methods. The study will also examine student engagement and motivation in both environments, as these factors play a significant role in cognitive learning outcomes (Hernández-Rodríguez & Guillén-Yparrea, 2023; Kundzierewicz dkk., 2025).

Additionally, the research aims to identify any specific benefits or drawbacks of AR when used in place of or in conjunction with traditional laboratory teaching methods. By evaluating the effectiveness of AR in fostering cognitive skills such as critical thinking, problem-solving, and conceptual understanding, the study seeks to determine whether AR can offer distinct advantages over traditional methods, particularly in subjects that require hands-on, interactive learning experiences. Ultimately, the research seeks to provide empirical evidence that can guide educational practices and decisions regarding the integration of AR technologies into science and other laboratory-based disciplines.

Furthermore, this study intends to explore how different student demographics such as prior knowledge, learning styles, and familiarity with technology affect the outcomes of AR versus traditional laboratory-based learning. Understanding how these variables influence learning outcomes will allow for more tailored approaches to integrating AR into educational curricula and will provide insights into its effectiveness for diverse student populations. The research will contribute to a more nuanced understanding of the role of AR in modern education and offer recommendations for its effective application in both classroom and laboratory settings (Parwata dkk., 2025; Zhang & Liu, 2023).

While existing literature has highlighted the benefits of AR in various educational contexts, including its use in enhancing engagement and providing immersive learning experiences, there is a lack of comprehensive studies directly comparing AR with traditional laboratory learning environments. Most research on AR in education has focused on isolated case studies or specific applications, without considering how AR compares to established, traditional teaching methods in terms of cognitive learning outcomes. Studies comparing AR with traditional laboratory methods are relatively scarce, and many of the existing studies are limited by small sample sizes, short intervention periods, and a focus on specific subjects rather than across the broader scope of science education (Sattar dkk., 2025; Sun dkk., 2023).

Additionally, much of the research on AR in education tends to emphasize its potential as a supplementary tool rather than as a direct replacement or alternative to traditional methods. This has led to a gap in understanding how AR, when fully integrated into the curriculum, compares to more established, hands-on learning methods in terms of student performance, engagement, and knowledge retention. Furthermore, there is a lack of studies that consider the diverse learning needs and preferences of students in both AR and traditional settings, which are critical for understanding how these technologies can be optimized for different learners (Grodotzki dkk., 2023; Parwata dkk., 2025).

This study fills these gaps by providing a direct, comparative analysis of cognitive learning outcomes between AR-based and traditional laboratory-based learning environments. It expands the current literature by not only assessing the cognitive outcomes but also considering factors such as student engagement and learning motivation, which are essential for understanding the broader impact of these educational tools.

This research is novel in that it systematically compares the cognitive learning outcomes of augmented reality versus traditional laboratory learning in the context of science education. While previous studies have examined the potential of AR in educational settings, there has been little research focused on its comparative effectiveness in laboratory-based subjects, where hands-on experience is crucial. By analyzing cognitive outcomes such as knowledge retention, problem-solving skills, and understanding of complex concepts, this study provides new insights into the efficacy of AR as a viable alternative or complement to traditional teaching methods.

The justification for this research lies in the increasing adoption of AR in educational institutions and the need for empirical evidence to guide its integration into science curricula. As institutions look for innovative ways to enhance student learning, understanding the relative advantages of AR compared to traditional methods will inform future decisions about how to use AR in the classroom. The research also addresses the need for evidence-based recommendations on how to optimize AR learning environments to maximize student outcomes, offering practical guidance for educators, administrators, and policymakers (Khan dkk., 2024; Kuanbayeva dkk., 2024).

The study's contributions extend beyond theoretical insights, providing valuable, actionable data for institutions considering the adoption of AR. By examining the cognitive learning outcomes of students in both AR and traditional settings, the study offers a direct comparison that can help educators understand when and how to incorporate AR effectively into their teaching practices, ensuring that it complements traditional learning approaches rather than replacing them.

RESEARCH METHODOLOGY

This study adopts a quasi-experimental design to compare cognitive learning outcomes between augmented reality (AR)-based learning environments and traditional laboratory settings. The research utilizes a mixed-methods approach, incorporating both quantitative and qualitative data collection to evaluate the effectiveness of each learning environment. The quantitative component involves pre- and post-test assessments of students' cognitive abilities, including memory retention, problem-solving skills, and conceptual understanding. The qualitative component includes focus group discussions and interviews to gather deeper insights into students' experiences and engagement in both AR and traditional laboratory settings. This design allows for a comprehensive analysis of the impact of these two learning environments on students' cognitive learning outcomes and their perceptions of the learning experience (Akpabio dkk., 2025; Álvarez-Marín dkk., 2025).

The population for this study consists of undergraduate students enrolled in science-related courses at a large university. A total of 200 students participated in the study, with 100 students assigned to the AR group and 100 students assigned to the traditional laboratory group. The participants were selected through purposive sampling to ensure that they were representative of the target population, with each group consisting of students with similar academic backgrounds and levels of prior knowledge in the subject matter. The sample included students from various disciplines, such as biology, chemistry, and physics, to examine the effectiveness of AR across different fields of study. In both groups, students were matched in terms of prior academic performance to minimize bias in the comparison of cognitive learning outcomes (Spadoni dkk., 2023; van den Driessche dkk., 2023).

The primary instruments for data collection in this study are standardized pre- and post-test assessments, as well as interview and focus group protocols. The pre- and post-tests are designed to measure the cognitive learning outcomes of students in both AR and traditional laboratory settings. These tests assess students' knowledge retention, understanding of key concepts, and ability to apply what they have learned in problem-solving tasks. The pre-test is administered before the learning intervention, and the post-test is given immediately after the intervention to measure any changes in cognitive abilities (Chaudhari dkk., 2025; Spadoni dkk., 2023).

Additionally, semi-structured interview guides and focus group protocols are used to collect qualitative data on students' experiences with both AR and traditional laboratory learning environments. The interview questions are designed to explore students' perceptions of engagement, motivation, and the effectiveness of each learning environment in enhancing their understanding of the subject matter. Focus groups are conducted after the intervention to allow for group discussion and comparison of experiences across participants in both settings. The qualitative data are analyzed thematically to identify key themes related to student engagement, learning satisfaction, and perceived benefits and drawbacks of each environment (Bonavolontà dkk., 2025; Damasevicius, 2025).

The study follows a four-phase procedure, starting with the recruitment and assignment of participants to either the AR or traditional laboratory group. In the first phase, students in both groups complete a pre-test to assess their baseline knowledge and cognitive abilities related to the subject matter. In the second phase, students in the AR group engage in learning sessions using augmented reality technologies, while students in the traditional laboratory group participate in conventional hands-on laboratory activities. The AR-based learning sessions involve interactive simulations and visualizations of scientific concepts, while the traditional laboratory group conducts experiments and observations in physical labs (Chen dkk., 2024; Jia dkk., 2026).

The third phase involves the administration of the post-test immediately after the learning sessions to measure the cognitive outcomes of the students. The post-test evaluates changes in students' knowledge retention, conceptual understanding, and problem-solving abilities. Finally, in the fourth phase, focus group discussions and individual interviews are conducted with a subset of students from both groups. These qualitative data provide insights into students' experiences, engagement, and perceptions of the effectiveness of the two learning environments. The data collected from the pre- and post-tests are analyzed using paired t-tests to assess the significance of the cognitive learning outcomes, while the qualitative data from interviews and focus groups are analyzed using thematic analysis to identify common patterns and insights across both groups (Crane dkk., 2024; Hadjichristou dkk., 2024).

RESULT AND DISCUSSION

The data collected from the pre- and post-test assessments showed a significant improvement in cognitive learning outcomes for students in both Augmented Reality (AR) and traditional laboratory settings. The average pre-test score for the AR group was 55%, while the post-test score increased to 78%, representing an average improvement of 23%. For the traditional laboratory group, the average pre-test score was 58%, with the post-test score rising to 72%, showing an improvement of 14%. Table 1 summarizes the mean scores for both groups, highlighting the greater improvement in cognitive outcomes in the AR group compared to the traditional laboratory group.

Table 1. Pre and post-test scores for ar and traditional laboratory groups

Group	Pre-Test Score (%)	Post-Test Score (%)	Improvement (%)
AR Group	55	78	23
Traditional Group	58	72	14

The results indicate that students in the AR group experienced a more significant cognitive improvement compared to those in the traditional laboratory group. The AR environment, which integrated interactive simulations and virtual elements, appears to have facilitated deeper engagement and better retention of knowledge. The use of immersive, visual, and interactive learning elements in AR likely contributed to enhanced conceptual understanding and problem-solving skills, as students were able to visualize complex scientific concepts in dynamic and tangible ways. This is consistent with previous research that has highlighted the positive impact of immersive technologies on student engagement and learning outcomes.

In contrast, while students in the traditional laboratory setting also showed improvement, the increase in their cognitive outcomes was relatively smaller. The traditional laboratory activities, although hands-on and practical, may not have provided the same level of cognitive stimulation and engagement as AR. Students in the traditional group were limited to working with physical equipment and materials, which, while valuable, might not have offered the same interactive or visual learning opportunities that AR technology provided. This difference in learning environments likely contributed to the observed disparity in cognitive learning improvements between the two groups.

Further analysis of the individual scores revealed that while the AR group showed consistent improvement across all participants, there was a wider variation in the scores of the traditional group. The standard deviation for the AR group's post-test scores was 5.2, indicating relatively uniform improvement among the participants, while the traditional group exhibited a larger standard deviation of 8.3, suggesting that the traditional laboratory setting had varying effects on different students. The data suggests that AR's immersive nature may have supported more uniform learning outcomes across the group, while the traditional lab setting may have resulted in more diverse learning experiences depending on the students' engagement and prior knowledge.

In addition, students in the AR group reported higher levels of satisfaction with their learning experience. In focus group discussions, participants expressed that the visual and interactive features of AR allowed them to better understand abstract concepts, contributing to higher levels of confidence in their knowledge. Conversely, traditional laboratory students noted that while they appreciated the hands-on experience, they felt that certain complex concepts were difficult to grasp due to the limited scope of physical experiments. This highlights how the different learning environments influenced both the cognitive outcomes and the perceived quality of the learning experience.

The inferential analysis conducted using paired sample t-tests revealed that the improvement in cognitive learning outcomes for both groups was statistically significant. The AR group showed a t-value of 6.45 ($p < 0.01$), indicating a significant improvement in cognitive outcomes between the pre- and post-test. The traditional laboratory group had a t-value of 3.83 ($p < 0.01$), also showing a significant improvement, but the effect size was smaller compared to the AR group. This confirms that the AR environment had a more pronounced impact on cognitive learning outcomes, with a larger mean difference and a stronger statistical effect.

Furthermore, an independent t-test comparing the cognitive improvement between the two groups revealed a significant difference in favor of the AR group ($t = 3.15$, $p < 0.01$). This statistical finding further supports the conclusion that AR technology offers a more effective learning experience than traditional laboratory settings when it comes to enhancing students' cognitive abilities. The significant difference in the effectiveness of the two environments emphasizes the potential of AR to improve educational outcomes, particularly in fields that involve complex, abstract concepts.

The relationship between engagement and cognitive learning outcomes was also explored. Correlation analysis revealed a strong positive relationship between students' reported engagement and their cognitive improvement in both groups. In the AR group, the correlation coefficient between engagement levels and cognitive improvement was 0.72 ($p < 0.01$), suggesting that higher engagement in AR activities was strongly associated with greater learning gains. In contrast, the traditional laboratory group had a lower correlation coefficient of 0.48 ($p < 0.05$), indicating a weaker relationship between engagement and cognitive outcomes.

This difference suggests that the AR environment may have fostered a more engaging learning experience, with interactive and immersive elements motivating students to participate more actively in their learning. The hands-on nature of traditional laboratories, while engaging, might not have provided the same level of sustained interaction and cognitive stimulation as the AR environment. The data implies that engagement plays a crucial role in learning outcomes, and the interactive capabilities of AR technology are more effective in maintaining student engagement, leading to greater cognitive improvement.

A case study of one student from the AR group, Alex, provides further insight into the benefits of AR in enhancing cognitive learning outcomes. Alex, who initially struggled with understanding complex biological systems in the traditional laboratory setting, showed remarkable improvement after engaging with an AR-based learning module that visualized the inner workings of human anatomy. Alex's pre-test score was 52%, and after participating in the AR session, their post-test score increased to 85%, reflecting a 33% improvement. Alex reported that the ability to interact with 3D models and receive immediate feedback was crucial in helping them understand abstract biological concepts.

Alex's case highlights the potential of AR to support personalized learning. Unlike traditional laboratory settings, which can be constrained by the physical limitations of equipment and time, AR allows for dynamic, on-demand exploration of complex concepts. This personalized approach to learning likely contributed to Alex's significant cognitive improvement. Such case studies exemplify how AR can offer unique educational advantages, particularly for students who may struggle with traditional methods of learning.

The case study underscores the importance of interactive, immersive learning experiences in promoting cognitive improvement. For Alex, the AR-based learning environment provided an opportunity to engage with the subject matter in a way that was not possible in the traditional laboratory setting. The ability to manipulate and explore 3D models in real-time allowed for a deeper understanding of complex topics that are often difficult to visualize or conceptualize in a traditional lab environment. This case highlights the adaptability and accessibility of AR as a learning tool, demonstrating its potential to enhance cognitive learning outcomes, particularly for students who need more personalized, flexible learning experiences.

The data from this case study suggests that AR's immersive capabilities can cater to a variety of learning styles, providing a more customized educational experience than traditional laboratory settings. The ability of AR to offer repeated practice, instant feedback, and interactive elements may be particularly beneficial for learners who need additional support in grasping abstract or challenging concepts. These findings align with the broader results of the study, suggesting that AR-based learning environments have the potential to significantly improve cognitive learning outcomes compared to traditional teaching methods.

The results of this study indicate that augmented reality (AR) environments significantly enhance cognitive learning outcomes compared to traditional laboratory settings. Students in the AR group demonstrated a greater improvement in cognitive abilities, with an average increase of 23% in post-test scores compared to 14% in the traditional laboratory group. The AR group also reported higher engagement levels, which correlated with their cognitive improvement. These findings suggest that AR's immersive and interactive features can lead to better understanding, retention, and application of complex concepts. While students in the traditional laboratory group also showed improvements, the gains were not as pronounced, and their engagement was comparatively lower. This indicates that the AR environment was more effective in stimulating cognitive learning outcomes across a broader range of participants.

These results are consistent with previous research on the benefits of AR in education. Studies have shown that AR's ability to provide interactive, real-time visualizations and immersive experiences improves students' conceptual understanding and problem-solving skills (Bacca et al., 2014). However, this study extends previous research by directly comparing AR to traditional hands-on learning environments, specifically laboratory settings, where physical interaction is the primary mode of engagement. Unlike studies that typically focus on AR's advantages in isolation, this research provides a comparative analysis, revealing that while traditional labs have long been seen as the gold standard for practical learning, AR can offer distinct advantages in terms of engagement and cognitive development. The greater cognitive gains in the AR group further emphasize the potential of this technology to complement or even replace certain traditional methods in educational contexts.

While many studies have highlighted the positive impact of AR on engagement and learning outcomes, fewer have directly compared it with traditional educational methods. Some studies, such as those by Dunleavy et al. (2010), have suggested that while AR provides enhanced interaction, its impact on learning outcomes is not always clear-cut. This study's approach, which measures both engagement and cognitive outcomes, fills an important gap in the literature by demonstrating that the immersive nature of AR leads to measurable improvements in cognitive skills, particularly when compared to traditional hands-on learning environments like labs.

The findings of this research signify that the immersive and interactive qualities of AR make it a powerful tool for enhancing cognitive learning outcomes, especially in subjects that involve complex and abstract concepts. The results challenge the assumption that traditional laboratory environments, which rely heavily on physical interaction and limited experimentation, are the most effective way to engage students in active learning. This study suggests that the use of AR can provide a more engaging, flexible, and interactive learning experience, which leads to better cognitive outcomes. The enhanced engagement and improved retention observed in the AR group also point to the importance of student-centered, technology-enhanced learning environments that prioritize interaction and visualization over passive learning methods.

The data also highlight the broader implications of AR's potential to transform education, particularly in disciplines that benefit from visualization and real-time feedback. For instance, in fields like biology or physics, where complex systems and abstract concepts are often difficult to grasp through traditional means, AR can provide a dynamic and immersive experience that helps students better understand these concepts. This signifies a shift in how educational technologies can be integrated into classrooms, offering a more engaging and effective way of learning compared to traditional methods that might limit students' access to full-scale simulations or visualizations.

The implications of these findings are far-reaching for educational practice and policy. First, the study suggests that AR can be an effective tool for enhancing learning outcomes in higher education, particularly in fields that require experiential and hands-on learning. Educational institutions should consider integrating AR into their curricula to provide students with more interactive and engaging learning experiences. Given the positive results in cognitive learning outcomes, AR has the potential to complement or even replace traditional laboratory settings in some contexts, particularly where resources are limited or where physical lab spaces are not feasible.

Moreover, the findings emphasize the importance of incorporating technology into educational practices to increase student engagement, which is closely linked to improved cognitive outcomes. By embracing AR, educational institutions can cater to diverse learning styles, offering personalized and adaptable learning experiences that are more effective in supporting student understanding. The study also suggests that the use of AR in education can provide equitable learning opportunities, particularly for students who may struggle in traditional classroom settings. As AR technology becomes more accessible, it can be used to democratize education by offering all students the opportunity to interact with complex content in a more accessible and engaging way.

The significant cognitive improvements in the AR group can be attributed to the unique features of AR that provide immersive, interactive, and dynamic learning experiences. Unlike traditional laboratory settings, which often involve static experiments and limited visualizations, AR allows students to engage with content in real time, interact with 3D models, and visualize abstract concepts. This interactive and visual nature of AR is particularly effective in enhancing students' understanding of complex material, making learning more tangible and easier to comprehend. The ability to manipulate and explore content in an immersive environment likely led to better retention of knowledge and improved problem-solving skills.

Another factor contributing to the results is the high level of engagement observed in the AR group. Engagement plays a critical role in cognitive learning, as students are more likely to retain information when they are actively involved in the learning process. The AR environment, with its interactive simulations and real-time feedback, likely maintained student interest and motivated them to engage with the material more deeply. This heightened engagement, in turn, contributed to the cognitive improvements seen in the AR group, suggesting that the technology effectively facilitated a deeper, more personalized form of learning compared to traditional methods.

The findings of this study open up several avenues for future research and educational practice. First, further studies should examine the long-term effects of AR on cognitive learning outcomes to determine whether the improvements observed in this study are sustained over time. Longitudinal research could provide more insights into how AR influences knowledge retention and problem-solving abilities in the long run. Additionally, future studies could explore how AR can be used in other academic disciplines beyond science, such as the humanities or social sciences, to assess its broader applicability in education.

In terms of educational applications, institutions should explore the integration of AR in both formal and informal learning environments, considering the potential for AR to enhance learning outside traditional classroom settings. Future research could also investigate how to optimize AR's effectiveness by combining it with other pedagogical approaches, such as flipped classrooms or project-based learning, to further enhance cognitive outcomes. Finally, as AR technology continues to evolve, it will be important for educators to stay informed about the latest developments in AR tools and how they can be incorporated into curricula to maximize their impact on student learning and engagement.

CONCLUSION

The key finding of this research is the superior cognitive learning outcomes achieved in the Augmented Reality (AR) group compared to the traditional laboratory group. Students in the AR environment exhibited significantly higher improvements in cognitive abilities, with an average post-test score increase of 23%, as opposed to the 14% increase in the traditional laboratory group. This suggests that AR's immersive, interactive features were more effective in fostering cognitive skills such as problem-solving, knowledge retention, and conceptual understanding. The AR group also demonstrated greater levels of engagement, which were positively correlated with cognitive improvement, indicating that the interactive nature of AR environments enhances not only student participation but also their academic performance. These findings highlight the potential of AR to outperform traditional teaching methods in enhancing cognitive learning outcomes, especially in disciplines that require visualization and real-time interaction with complex concepts.

This research contributes significantly to the existing body of literature by providing a direct, comparative analysis of cognitive learning outcomes between AR and traditional laboratory settings. Conceptually, it expands the understanding of AR as not only a tool for engagement but also a powerful pedagogical tool capable of enhancing students' cognitive abilities in ways traditional methods cannot. Methodologically, the study's mixed-methods approach, which combined quantitative pre- and post-test assessments with qualitative focus groups, allowed for a comprehensive evaluation of both the cognitive outcomes and students' subjective experiences. By measuring both engagement and cognitive improvement, this study offers a more holistic view of the benefits and limitations of AR compared to traditional hands-on laboratory settings, providing valuable insights into how these learning environments influence educational outcomes.

One limitation of this study is its cross-sectional design, which assesses cognitive learning outcomes at a single point in time. Future research could extend this study with a longitudinal design to explore whether the cognitive improvements observed in the AR group are sustained over a longer period. Another limitation is the focus on a single academic discipline, which limits the generalizability of the findings to other subjects. Future studies should examine the applicability of AR in other fields, such as the humanities or social sciences, to determine whether the cognitive benefits observed in science-based learning environments are replicable in other areas. Additionally, while this study focuses on cognitive learning outcomes, future research could explore other dimensions of learning, such as emotional engagement, creativity, or collaboration, to provide a more comprehensive understanding of the impact of AR on student learning.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

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