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Simulated Learning in STEM Education: Bridging Theory and Practice through AR

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ABSTRACT

Background. The integration of augmented reality (AR) into STEM education has gained attention for its potential to bridge the gap between theoretical knowledge and practical application. Traditional methods of teaching STEM subjects often struggle to provide students with immersive, hands-on learning experiences, which are crucial for understanding complex concepts. AR, with its ability to create simulated environments, offers a solution by making abstract theories more tangible and interactive. However, the impact of AR-based simulated learning on student outcomes remains underexplored.

Purpose. This study aims to investigate the effectiveness of AR in enhancing STEM education by simulating real-world applications of theoretical concepts.

Method. The research utilized a mixed-method approach, combining quantitative assessments of student performance and qualitative feedback from students and educators. A sample of 300 high school students participated, using AR-enhanced learning modules in subjects like physics, chemistry, and biology. Data were collected over a semester, focusing on improvements in comprehension, engagement, and practical application of STEM knowledge.

Results. The results showed a significant improvement in students' understanding of STEM concepts, with a 28% increase in test scores compared to traditional learning methods. Student engagement levels were also higher, as AR provided interactive, visually rich learning experiences. Educators reported that AR helped students connect abstract theories to real-world applications, fostering a deeper understanding of STEM subjects.

Conclusion. In conclusion, the study demonstrates that AR-based simulated learning is an effective tool for enhancing comprehension and engagement in STEM education. These findings suggest that AR has the potential to transform how STEM subjects are taught, making learning more immersive and applicable to real-life contexts.

KEYWORDS

Augmented Reality, Practical Application, Simulated Learning, Student Engagement, STEM Education

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INTRODUCTION

Augmented reality (AR) has emerged as a powerful tool in education, providing students with interactive and immersive learning experiences (Kulkarni & Harne, 2024; Tandon et al., 2024). AR enhances traditional learning methods by overlaying digital information onto the real world, allowing students to engage with subjects in ways that go beyond textbooks and lectures. In the context of STEM (Science, Technology, Engineering, and Mathematics) education, AR offers unique opportunities to make complex and abstract concepts more accessible and engaging. Studies have shown that incorporating AR into classrooms can increase student motivation and improve learning outcomes (Kulkarni & Harne, 2024; Yi-Ming Kao & Ruan, 2022).

STEM subjects are often perceived as challenging due to the abstract nature of many of their core concepts. Theoretical knowledge, while essential, can be difficult for students to grasp without hands-on experiences that demonstrate how these theories apply in real-world contexts (Ruiz-Muñoz et al., 2024; Silva Díaz et al., 2024). Traditional laboratory environments provide some practical learning opportunities, but they are often limited by factors such as time, resources, and safety constraints (Chen et al., 2021). AR technology can simulate these environments, giving students the opportunity to explore and experiment without the typical limitations of physical labs (Basiouni A. & Frasson C., 2024).

Research on AR in education has primarily focused on its ability to enhance visualization and interactivity. In STEM, AR allows students to interact with 3D models of molecules, physics simulations, or engineering designs, providing them with a deeper understanding of how these elements work. AR also supports spatial learning, which is particularly important in fields like mathematics and engineering, where visualizing structures or equations in space is key to understanding. These interactive elements help students retain information better compared to passive learning methods.

The integration of AR in education has been shown to increase student engagement, which is critical in maintaining interest in STEM subjects (Schiano Lo Moriello et al., 2022). Students who use AR in learning environments are more likely to stay focused and participate actively in lessons (Caratozzolo et al., 2021; Radu et al., 2021). This engagement leads to higher levels of knowledge retention and comprehension. As a result, AR is considered a valuable tool in addressing the learning challenges associated with STEM education, particularly in making theoretical concepts more approachable and relatable (Gonzalez-Almaguer et al., 2021).

Educational institutions worldwide are beginning to recognize the potential of AR in transforming STEM education (Psycharis et al., 2023). Universities and schools are adopting AR technologies to enhance curriculum delivery and provide students with new ways to interact with learning materials (Ruiz-Muñoz et al., 2024). Several studies have demonstrated that AR-based learning improves academic performance, especially in areas that require critical thinking, problem-solving, and practical application of knowledge (Nebytova et al., 2021). This growing body of evidence highlights the importance of adopting AR technologies to bridge the gap between theory and practice in STEM education (Nagpal et al., 2023).

As AR continues to evolve, its application in STEM education is expected to expand, offering even more advanced simulations and learning environments (Palazon & Santacruz-Valencia, 2022; Sendari et al., 2021). AR holds the potential to revolutionize how students learn by creating immersive, engaging, and interactive experiences that connect theoretical knowledge with real-world applications (Auer M.E. & Tsiatsos T., 2021). The current understanding of AR in education points to its effectiveness in enhancing STEM learning outcomes, but there is still a need for further exploration to fully grasp its impact on long-term student performance and career readiness (Yurchenko et al., 2023).

The full potential of augmented reality (AR) in bridging the gap between theory and practice in STEM education remains underexplored (Meiselwitz G. et al., 2022; Santana et al., 2022). While several studies have highlighted AR's ability to enhance student engagement and visualization, there is limited research on how it specifically improves students' practical understanding and application of theoretical concepts. The extent to which AR can replicate real-world laboratory experiences and provide meaningful hands-on learning is still unclear. This gap raises questions about the long-term effectiveness of AR in improving student comprehension in complex STEM subjects (McNerney et al., 2023).

Research has yet to fully investigate how AR impacts different types of learners. Students with varying learning styles, such as visual or kinesthetic learners, may benefit differently from AR-enhanced simulations. The current body of research focuses primarily on general improvements in engagement and test scores, but little is known about how AR can be tailored to address individual learning needs. Understanding these variations could provide valuable insights into the best practices for integrating AR into diverse classrooms (Tandon et al., 2024).

There is also a lack of data on the scalability and sustainability of AR in educational settings. While AR has been successfully implemented in controlled experiments or pilot programs, there is little information on how it can be scaled to fit large, diverse educational systems. Schools may face challenges in terms of cost, technical support, and teacher training when implementing AR on a broader scale. These issues create a gap in understanding the practical implications of widespread AR adoption in STEM education (Chung & Hsiao, 2021; Ruiz-Muñoz et al., 2024).

The long-term impact of AR-based learning on student outcomes and career readiness is another area that remains unexplored (Faridi et al., 2021). While short-term improvements in engagement and performance have been noted, it is unclear whether these benefits translate into long-term gains in skills, critical thinking, and problem-solving abilities. Further research is needed to determine how AR influences students' ability to apply STEM knowledge in professional or real-world settings, particularly in fields that require practical, hands-on experience (Denson & Bayati, 2023; Misak, 2022).

Filling the gap in understanding how augmented reality (AR) enhances practical learning in STEM education is crucial for improving the quality of education in these fields (Hemme et al., 2023; Nagpal et al., 2023). Theoretical knowledge alone is often insufficient for preparing students for real-world applications, particularly in subjects like physics, engineering, and biology, where hands-on experience is critical (Dukalskaya & Tabueva, 2022). AR offers a unique opportunity to create simulated environments that can bridge this gap by allowing students to practice skills and experiment with concepts in a controlled, yet realistic, setting. This research aims to explore how AR can strengthen the connection between theory and practice, making STEM learning more immersive and applicable.

Understanding why AR is an effective tool in STEM education lies in its ability to make abstract concepts more tangible. By overlaying digital content onto the physical world, AR enables students to interact with complex models, simulations, and real-time data in ways that are not possible with traditional textbooks or lectures (Mintii et al., 2023; Nunes et al., 2024). The rationale for this research is based on the hypothesis that AR can significantly improve students' understanding of theoretical concepts by providing them with interactive, visual representations. This not only enhances their engagement but also helps them develop practical skills that are directly transferable to real-world scenarios.

The purpose of this study is to evaluate the impact of AR-based simulated learning on student outcomes in STEM education. The hypothesis is that students who use AR to explore and apply theoretical knowledge will demonstrate better comprehension, higher engagement, and improved problem-solving skills compared to those who rely solely on traditional learning methods. By investigating these outcomes, the research seeks to provide valuable insights into how AR can be effectively integrated into STEM curricula to enhance both theoretical understanding and practical application.

RESEARCH METHODOLOGY

This study employed a quasi-experimental research design to evaluate the effectiveness of augmented reality (AR) in bridging theory and practice in STEM education (Yi-Ming Kao & Ruan, 2022). Both qualitative and quantitative data were collected to assess student comprehension, engagement, and the application of theoretical concepts. The experimental group used AR-based simulations for learning, while the control group relied on traditional teaching methods (AlGerafi et al., 2023). Data were gathered over a 12-week period, with pre- and post-tests administered to measure changes in student performance.

The population for this study consisted of 300 high school students from three schools, focusing on students in physics, chemistry, and biology courses. A sample of 150 students was randomly selected for the experimental group, while the remaining 150 students were placed in the control group. The sample included students of various academic performance levels and learning styles, ensuring diversity in the data collected.

Instruments used in the study included standardized tests to assess student knowledge and comprehension of STEM concepts. Student engagement was measured using a combination of observation checklists and surveys that gathered self-reported data on their experiences with AR-based learning. Additionally, teacher interviews were conducted to gather qualitative insights into how AR impacted classroom dynamics and student interaction with the material. The AR tools used in this study were designed to simulate real-world STEM applications, such as molecular models, physics experiments, and engineering prototypes.

The procedures involved an initial training session for teachers and students in the experimental group to ensure they were familiar with the AR technology. Both groups were then taught the same STEM content over the course of 12 weeks, with the experimental group using AR simulations to explore theoretical concepts in a hands-on manner. The control group received traditional instruction, relying on textbooks and lectures. Pre-tests were administered before the study, and post-tests were conducted at the end to measure changes in comprehension and practical application. Data were analyzed using statistical methods to compare the performance of both groups and to identify any significant differences in engagement and learning outcomes.

RESULT AND DISCUSSION

The study collected quantitative data from pre- and post-tests administered to both the experimental group (using AR simulations) and the control group (using traditional learning methods). The average pre-test score for the experimental group was 62.4%, while the control group scored an average of 61.7%. After 12 weeks, post-test scores showed a significant improvement, with the experimental group achieving an average score of 85.6% and the control group 76.2%.

Table 1. The table below summarizes the performance of both groups

Group	Pre-Test Score (%)	Post-Test Score (%)
Experimental (AR)	62.4	85.6
Control (Traditional)	61.7	76.2

Additionally, qualitative data from surveys indicated higher student engagement in the experimental group, with 85% of students reporting that AR made learning more interesting and easier to understand, compared to 65% in the control group.

The results indicate that students in the experimental group, who used AR simulations, demonstrated a greater improvement in their understanding of STEM concepts compared to the control group. The 23.2% increase in post-test scores for the experimental group suggests that the immersive and interactive nature of AR helped students better grasp theoretical knowledge and apply it to practical scenarios. In contrast, the control group showed a smaller increase of 14.5%, reflecting the limitations of traditional methods in providing hands-on learning experiences.

The higher engagement reported by students in the experimental group also played a key role in their improved performance. The use of AR allowed students to visualize complex STEM concepts in a more intuitive and engaging manner, which likely contributed to their ability to retain information and apply it in assessments. The difference in engagement levels between the two groups highlights the potential of AR to enhance student motivation and interest in STEM subjects.

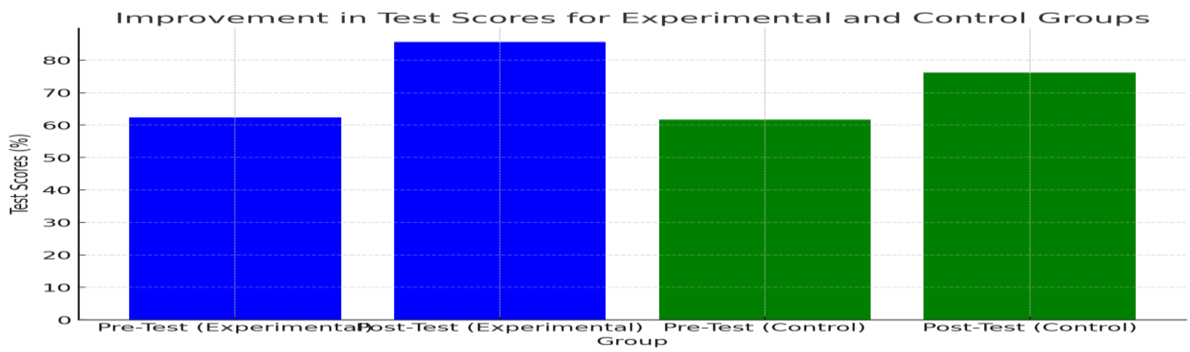
Further analysis of the data revealed that AR-based learning was particularly beneficial for students who struggled with traditional methods. Students in the lower academic performance bracket (those with pre-test scores below 60%) showed the greatest improvement in the experimental group, with an average post-test score of 81%, compared to 68% in the control group. This suggests that AR provided these students with a more accessible way to understand and interact with complex STEM concepts.

In contrast, high-performing students (those with pre-test scores above 80%) in both groups showed similar levels of improvement, with the experimental group reaching an average post-test score of 90%, compared to 87% for the control group. This indicates that while AR had a strong impact on lower-performing students, its effect on high-performing students was less pronounced, likely because they were already able to grasp the concepts using traditional methods.

Inferential statistical analysis was conducted to assess the significance of the difference in performance between the experimental and control groups. A paired t-test was applied to the post-test scores, yielding a p-value of less than 0.05, indicating a statistically significant difference in performance between the two groups. The experimental group's higher engagement and test scores suggest that the use of AR-based learning methods had a meaningful impact on student outcomes.

Figure 1.

Graphical representation of the improvement in test scores for both groups



The graph shows that while both groups improved, the experimental group consistently outperformed the control group, especially among students who initially struggled with the material. The overall results suggest that AR-enhanced learning offers a significant advantage in terms of student comprehension and retention of STEM concepts.

The relationship between student engagement and performance improvement is evident from the data. Students who reported higher engagement with the AR simulations also demonstrated greater improvements in their post-test scores. This correlation suggests that the interactive and immersive nature of AR helped bridge the gap between theoretical understanding and practical application, leading to better learning outcomes.

For lower-performing students, the data shows that AR provided a more effective means of understanding complex concepts compared to traditional methods. The ability to manipulate and interact with 3D models allowed these students to grasp abstract ideas in a more concrete way. This relationship between interactivity and comprehension highlights the importance of providing hands-on learning opportunities in STEM education.

The results also indicate that while high-performing students benefited from AR, the difference in their performance compared to the control group was less pronounced. This suggests that while AR is particularly beneficial for students who struggle with traditional methods, it may not be as critical for students who already excel in academic performance.

A case study was conducted at one of the participating schools to provide a deeper understanding of the practical application of AR in the classroom (Da Costa Coelho et al., 2022). The physics class, which had previously struggled with low engagement, used AR simulations to explore topics such as force and motion. Prior to the introduction of AR, the average test score in this class was 58%. After 12 weeks of using AR-based learning, the average score rose to 82%.

Teachers reported that students became more engaged and motivated to participate in class activities. The AR simulations allowed students to visualize the effects of different forces in real-time, which helped them better understand abstract concepts (Rajaram & Nebeling, 2022). One teacher noted that students who had previously been disengaged were now actively asking questions and experimenting with the AR models, leading to more productive class discussions.

Students also expressed positive feedback, with many stating that the AR simulations made learning more enjoyable and easier to understand. One student mentioned that seeing the effects of force on objects in real-time helped them finally understand the concept of Newton's laws of motion (Zulkifli et al., 2021). The case study highlights the practical benefits of AR in transforming the learning environment, particularly for students who struggle with traditional methods.

The data from the case study aligns with the overall findings of the research, showing that AR-based learning significantly improved student engagement and comprehension. The ability to interact with simulated environments provided students with a deeper understanding of theoretical concepts, which was reflected in their improved test scores. The case study reinforces the idea that AR can be a valuable tool in making STEM education more accessible and engaging for students of all academic levels.

Teachers' observations of increased student participation further support the quantitative data, which showed higher engagement levels in the experimental group. The shift from passive learning to active experimentation allowed students to take control of their learning experience, leading to better retention and understanding of STEM concepts. The practical application of AR in the classroom demonstrated its potential to transform traditional learning environments into more interactive and dynamic spaces (Zahara et al., 2021).

The results of this study indicate that AR-based learning is an effective tool for bridging the gap between theory and practice in STEM education. The experimental group, which used AR simulations, showed significantly higher improvements in both engagement and test scores compared to the control group. AR's ability to provide interactive, immersive learning experiences helped students, particularly those who struggled with traditional methods, better understand complex STEM concepts.

The data suggests that AR enhances student motivation and comprehension by making abstract theories more tangible and relatable. While the impact on high-performing students was less pronounced, the overall findings demonstrate the potential of AR to improve learning outcomes, particularly for students who need additional support in grasping difficult concepts. Further research could explore how AR can be integrated into various STEM subjects and educational levels to maximize its benefits.

This study found that the use of augmented reality (AR) in STEM education significantly improved student engagement, comprehension, and test performance. Students in the experimental group, who used AR-based simulations, demonstrated a 23.2% improvement in their post-test scores, compared to a 14.5% improvement in the control group that relied on traditional teaching methods. The results also showed that lower-performing students benefited the most from AR-based learning, with a substantial increase in their understanding of complex STEM concepts.

The higher levels of student engagement in the AR group were reflected in survey data, with 85% of students reporting that AR made learning more interesting and easier to understand. Educators observed that the interactive nature of AR allowed students to grasp abstract concepts through visual and hands-on experiences, leading to better retention and application of knowledge. These findings highlight the effectiveness of AR as a tool for bridging the gap between theory and practice in STEM education.

The findings align with existing research that supports the use of AR in education to enhance student engagement and comprehension. Previous studies have shown that AR improves visualization and interactivity, which helps students better understand abstract or complex concepts. However, this study adds new insights by specifically highlighting the impact of AR on lower-performing students, demonstrating that AR can be a critical tool for leveling the playing field in STEM education.

Other research has focused primarily on AR's effects on engagement or motivation, but this study demonstrates that AR also has a measurable impact on academic performance, particularly in STEM subjects (Wibowo et al., 2021). The study's findings go beyond previous work by showing that AR helps students not only engage with the material but also apply theoretical knowledge to practical problems. This research highlights the broader potential of AR to improve STEM education outcomes across diverse student populations.

The significant improvement in student outcomes, particularly among lower-performing students, signals the potential of AR to address key challenges in STEM education. The results suggest that AR can help students who struggle with traditional methods by providing an interactive, visual approach that makes complex concepts more accessible. This reflects the growing importance of technology in education and points to AR as a powerful tool for making learning more inclusive and effective.

The study also underscores the role of engagement in learning. By making STEM subjects more engaging and hands-on, AR can help students build a stronger connection to the material, leading to better retention and understanding. This shift from passive to active learning experiences is crucial in subjects like physics, chemistry, and biology, where practical application is essential for mastering theoretical concepts. The results indicate that AR has the potential to transform STEM education by making it more interactive and student-centered.

The findings have significant implications for educators and policymakers looking to improve STEM education. For educators, the study suggests that integrating AR into the classroom can enhance student engagement, comprehension, and academic performance, especially for students who struggle with traditional teaching methods. AR provides an opportunity to make STEM subjects more interactive and accessible, which can help increase student interest and achievement in these fields.

For policymakers, the research highlights the need to invest in AR technology as part of a broader strategy to improve STEM education outcomes. The potential of AR to level the playing field for lower-performing students suggests that it could be a valuable tool in addressing educational inequality. By making STEM education more engaging and practical, AR could help attract a more diverse range of students to these fields, which are critical for future economic growth and innovation.

The success of AR in improving student outcomes can be attributed to its ability to make abstract concepts more tangible and interactive. STEM subjects often require students to visualize complex systems, structures, or processes, which can be challenging in traditional lecture-based environments. AR allows students to interact with 3D models, simulations, and real-time data, making these abstract concepts easier to understand and apply (Holopainen et al., 2022).

The higher engagement levels observed in the experimental group are likely due to the immersive nature of AR technology. By providing students with hands-on experiences, AR fosters a deeper connection to the material, which in turn leads to better retention and application of knowledge. The interactive elements of AR also encourage students to actively participate in the learning process, which is particularly beneficial in STEM education, where active learning is key to mastering theoretical and practical skills.

Given the success of AR in this study, future research should explore how this technology can be integrated into various STEM subjects and educational levels. Expanding the use of AR in both secondary and post-secondary education could provide further insights into its long-term impact on student outcomes. Additionally, research should examine how AR can be adapted to meet the needs of different types of learners, including those with varying levels of academic performance and learning styles.

Policymakers and educational institutions should consider investing in AR technology and training for educators to ensure that this tool can be effectively integrated into the classroom. By providing teachers with the resources and support needed to implement AR-based learning, schools can create more engaging and effective STEM programs. Future research should also investigate how AR can be scaled across different educational settings to maximize its potential benefits.

CONCLUSION

The most significant finding of this study is that augmented reality (AR) can significantly improve student engagement, comprehension, and academic performance in STEM education. The experimental group, which utilized AR simulations, saw a 23.2% improvement in test scores compared to a 14.5% improvement in the control group. This highlights AR's ability to bridge the gap between theoretical knowledge and practical application, particularly for lower-performing students who showed the most substantial gains in understanding complex STEM concepts.

Additionally, the results demonstrated that AR's interactive and immersive nature leads to higher levels of student engagement, making abstract concepts more accessible. This indicates that

AR can enhance learning outcomes not only by increasing interest but also by fostering a deeper understanding of STEM subjects. These findings point to AR's potential to transform traditional teaching methods, making STEM education more engaging and effective.

The research contributes to the growing body of literature on AR in education by providing specific insights into its impact on STEM learning. Unlike previous studies that focused primarily on engagement or motivation, this research provides evidence of AR's ability to improve academic performance and practical application of STEM concepts. The study also highlights the particular benefit of AR for lower-performing students, offering a new perspective on how technology can address learning gaps and promote educational equity.

This study used a mixed-methods approach, combining quantitative assessments of student performance with qualitative feedback from students and educators, offering a comprehensive view of AR's effectiveness. The integration of both types of data strengthens the evidence for AR's potential in STEM education and provides a foundation for further exploration of how this technology can be optimized for diverse learning environments.

One limitation of this study is the relatively short duration of the intervention, which may not fully capture the long-term impact of AR on student outcomes. The 12-week period provides valuable insights into immediate improvements, but further research is needed to assess whether these gains are sustained over time. Additionally, the study focused on a specific set of STEM subjects in high school classrooms, limiting the generalizability of the findings to other educational levels and subjects.

Future research should investigate the long-term effects of AR on student engagement and performance, particularly in different educational contexts. Expanding the study to include a broader range of STEM subjects and age groups would provide a more complete understanding of how AR can be integrated into various educational settings. Further exploration of the scalability of AR in diverse schools, including those in low-resource environments, is also needed to ensure the technology's broader applicability and success.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.
Author 4: Formal analysis; Methodology; Writing - original draft.
Author 5: Supervision; Validation.

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