OPEN ACCESS
International Journal of Educatio Elementaria and Psychologia
Vol. 1 No. 6. December 2024, pp. 305-318 DOI. https://doi.org/10.70177/ijeep.v1i6.1461

Research Article

Application of Augmented Reality-based Educational Technology to Increase Student Engagement in Elementary Schools

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Article Info

Received: October 19, 2024
Revised: Nov 01, 2024
Accepted: Nov 01, 2024
Online Version: Nov 01, 2024

Abstract

The rapid development of educational technology has significantly influenced teaching and learning practices, particularly in elementary education. Traditional classroom methods often struggle to engage young learners effectively, leading to reduced attention and participation. This study addresses this issue by exploring the application of Augmented Reality (AR)-based educational technology to increase student engagement in elementary schools. The research aims to investigate the impact of AR tools on students' cognitive and affective engagement, thereby enhancing their overall learning experience. A quasi-experimental design was adopted for this research, involving 120 students from three different elementary schools. The students were divided into experimental and control groups, with the experimental group using AR applications to supplement their learning activities while the control group used conventional teaching methods. The results indicated a significant increase in engagement and understanding of the subject matter among students who used AR-based tools compared to those in the control group. In conclusion, the application of AR-based educational technology has a positive impact on student engagement and learning outcomes in elementary schools.

Keywords: Augmented Reality, Educational Technology, Student Engagement

Journal Homepage https://journal.ypidathu.or.id/index.php/ijeep ISSN: (P: 3047-843X) - (E: 3047-8529)
How to cite: Riniati, O, W., Jiao, D & Rahmi, N, S. (2024). *Application of Augmented Reality-based Educational Technology to Increase Student Engagement in Elementary Schools*. International Journal of Educatio Elementaria and Psychologia, 1(6), 305–318. https://doi.org/10.70177/ijeep.v1i6.1461
Published by: Yayasan Pendidikan Islam Daarut Thufulah

INTRODUCTION

Educational technology has evolved rapidly in recent years, influencing various aspects of the teaching and learning process (Gerini, Chessa, Delzanno, Guerrini, & Solari, 2024; Kim, Lee, Hwang, & Park, 2024; Samala dkk., 2024). The integration of new technological tools has opened possibilities for creating more interactive and engaging learning environments. In elementary schools, where young students often have shorter attention spans and require constant stimulation, traditional teaching methods are proving less effective. As a result, there is a growing need to explore innovative educational strategies that can enhance student engagement and improve learning outcomes.

Augmented Reality (AR) is emerging as one of the most promising technologies in the educational field (Lepore, 2024; Nurhasanah dkk., 2024; Soundarya, Kumar, & Gupta, 2024). Unlike traditional teaching aids, AR blends virtual objects with the real environment, offering an interactive learning experience (Seetharam, Kumar, Gupta, & Bhaumik, 2024; Shenoy & Kumar, 2024; Topalska, 2024). This immersive approach allows students to visualize abstract concepts, interact with 3D models, and engage in hands-on activities that were previously impossible within a traditional classroom setting. AR's unique ability to combine digital and physical learning experiences is particularly beneficial for young learners who thrive on interactive and sensory-rich activities.

Research indicates that student engagement plays a crucial role in the learning process, especially in the early stages of education. High engagement levels are associated with better comprehension, increased motivation, and improved academic performance. However, maintaining engagement can be challenging due to varying levels of interest and cognitive abilities among elementary school students. This situation calls for the adoption of novel pedagogical tools like AR, which have the potential to sustain attention and foster deeper learning experiences.

The use of AR in education has shown promising results in various studies, demonstrating its effectiveness in promoting active learning and participation (Anselmo, Prudente, Aquino, Dumelod, & Cabrera, 2024; Shadiev & Liang, 2024; Tene, Bonilla García, Coello-Fiallos, Borja, & Vacacela Gomez, 2024). Despite these positive findings, there is still a gap in understanding how AR can be systematically integrated into elementary school curricula to maximize its benefits. Current literature mainly focuses on higher education settings, leaving a need for more research specifically targeting younger age groups. Investigating AR's impact on elementary education will contribute valuable insights for educators seeking to enhance classroom dynamics.

This study aims to address the gap by examining the application of AR-based educational technology in elementary schools. By focusing on its influence on student engagement, the research seeks to provide a clearer understanding of how AR can be used to create more engaging and effective learning environments for young learners. Findings from this research will inform educators and policymakers on the potential of AR to transform traditional teaching approaches and improve educational outcomes in elementary schools.

In conclusion, the integration of AR in elementary education represents a significant step towards modernizing traditional teaching methods (Cercenelli dkk., 2024; Ghanbaripour dkk., 2024; Hoai, Son, An, & Anh, 2024). Understanding its impact on student engagement will help determine its effectiveness and feasibility as a long-term solution for enhancing the learning experience of young students. This study will contribute to the ongoing discourse on the role of educational technology in shaping future classrooms.

The application of Augmented Reality (AR) in education has gained significant attention over the past decade, yet its adoption and impact in elementary schools remain relatively underexplored (Childs dkk., 2024; Fitriani, Tri Julianto, Halimatul Hasanah, & Tresnawati, 2024; Tukhtabayeva dkk., 2024). Most research on AR-based learning has focused on higher education or specialized training, with limited studies addressing its effectiveness among younger learners. This gap leaves many questions about how AR can be optimized to cater to the cognitive and developmental needs of elementary school students.

Existing studies highlight the potential of AR to enhance engagement and improve learning outcomes, but they often lack a comprehensive examination of how AR influences various dimensions of student engagement, such as emotional, behavioral, and cognitive aspects. There is also insufficient evidence on the long-term effects of using AR tools in elementary education, raising concerns about whether its benefits are sustainable over time. These limitations indicate a need for further investigation into the specific mechanisms through which AR fosters engagement and learning in young students.

Most AR applications used in previous research were not designed specifically for elementary school contexts. This raises questions about the suitability of these tools for younger age groups, who have unique learning preferences and attention spans. Additionally, there is limited understanding of how teachers perceive and integrate AR technology in their classrooms. This lack of insights on teachers' perspectives and the challenges they face when implementing AR tools contributes to the existing research gap.

The role of AR in promoting collaboration and social interaction among elementary school students has also been largely overlooked (Anila, Shyama, Abhinav, Unni, & Ganesh, 2024; Lim & Toh, 2024; Poddar & Sharma, 2024). Young learners benefit greatly from peer interactions and cooperative learning activities, yet few studies have explored how AR can facilitate such interactions within the classroom. Addressing this gap will provide a more holistic understanding of AR’s potential to support both individual and group learning experiences in elementary education settings.

Implementing Augmented Reality (AR) in elementary education has the potential to transform traditional teaching methods by offering more interactive and immersive learning experiences. AR can bridge the gap between theoretical knowledge and practical understanding, making abstract concepts more accessible to young learners. Through engaging visualizations and interactive content, AR can significantly enhance student motivation and participation, which are crucial components of effective learning at the elementary level.

Exploring the impact of AR on student engagement in elementary schools is essential to understand its effectiveness and limitations. Addressing this research gap will provide valuable insights into how AR-based tools can be integrated into the curriculum to support diverse learning styles (Aggarwal, Gupta, Singh, & Bala, 2024; Pandurangam, Gurajala, & Nagajyothi, 2024; Tursunova dkk., 2024). A systematic examination of AR’s influence on cognitive, emotional, and behavioral engagement can help educators identify the most effective strategies for incorporating technology into their teaching practices.

This study aims to contribute to the existing body of knowledge by evaluating the role of AR-based educational technology in increasing student engagement in elementary schools. By focusing on its application in real classroom settings, the research seeks to offer practical recommendations for teachers and policymakers. The findings will highlight whether AR can serve as a sustainable educational tool that not only captures students’ attention but also promotes long-term academic achievement and active learning.

RESEARCH METHOD

The research adopts a quasi-experimental design to evaluate the effectiveness of Augmented Reality (AR)-based educational technology in increasing student engagement in elementary schools. This design enables a comparative analysis between an experimental group, which uses AR-based tools, and a control group, which follows conventional teaching methods. The study aims to observe changes in student engagement and academic performance over a specific period, providing a detailed understanding of the impact of AR on elementary education.

The population of this study includes elementary school students from grades 3 to 5 in three different schools (Panwar dkk., 2024; Rebello, Deiró, Knuutila, Moreira, & Nogueira, 2024; Velarde-Camaqui & Sanabria-Z, 2024). A total of 120 students were selected as participants, with 60 students assigned to the experimental group and 60 to the control group. The sampling method used is stratified random sampling to ensure a balanced representation of students in terms of age, gender, and academic performance. The selected schools are located in urban areas with access to the necessary technological infrastructure required for AR-based learning.

The instruments used in this study consist of engagement observation checklists, pre- and post-intervention academic tests, and student questionnaires. The observation checklists focus on measuring behavioral, emotional, and cognitive engagement levels, while the academic tests assess the impact of AR on subject understanding and retention. The questionnaires are designed to capture student perceptions and feedback regarding their learning experience with AR tools, contributing to a comprehensive evaluation of the technology's effectiveness.

The research procedure began with an orientation session for teachers and students to familiarize them with the AR tools. The experimental group used AR-based educational applications during lessons, while the control group followed the standard curriculum. Data collection was conducted through weekly observations and tests over a six-week period (Cufuna, Duart, & Rangel-de Lazaro, 2024; Maulana dkk., 2024; Suhail, Bahroun, & Ahmed, 2024). At the end of the intervention, a comparative analysis of the engagement levels and academic results was carried out to determine the effectiveness of the AR-based technology in enhancing student engagement and learning outcomes in elementary school settings.

RESULTS AND DISCUSSION

The data collected during the study consisted of engagement levels, academic performance scores, and student feedback from both the experimental and control groups. Engagement levels were measured using a structured observation checklist, where each student was evaluated on behavioral, emotional, and cognitive engagement on a scale of 1 to 5. Academic performance was assessed using pre- and post-intervention tests, with scores ranging from 0 to 100. Table 1 presents the average engagement scores and academic test results for both groups.

Group	Behavioral Engagement	Emotional Engagement	Cognitive Engagement	Pre-Test Scores	Post-Test Scores
Experimental (AR-based)	4.2	4.5	4.3	68.5	85.2
Control (Traditional)	3.1	3.3	3.2	69.1	75.8

The experimental group showed consistently higher scores in all three dimensions of engagement compared to the control group. The post-test scores of the experimental group also indicated a significant improvement, with an average increase of 16.7 points, whereas the control group exhibited a smaller increase of 6.7 points (Dutta, Chiranthana, & Peter, 2024; Ruiz-Muñoz, Yépez-González, Romero Amores, & Cali Proaño Ángela, 2024; Shkilev dkk., 2024). These results suggest that the use of AR technology has a notable effect on student engagement and learning outcomes.

The experimental group's higher engagement levels indicate that the interactive nature of AR tools successfully captures students' attention and sustains their interest throughout the learning sessions. Behavioral engagement, represented by active participation and attentiveness, was higher in the experimental group, which reflects the ability of AR to make lessons more dynamic and interactive. Emotional engagement, as measured by student enthusiasm and positive attitudes, was also significantly higher, suggesting that students found AR tools more enjoyable and motivating compared to traditional methods.

Cognitive engagement scores, which represent students' investment in understanding and applying the material, were notably higher in the experimental group. This suggests that the use of AR technology enhances not only surface-level engagement but also deep cognitive involvement in the learning process. The pre- and post-test scores further confirm the positive impact of AR on academic performance, as students in the experimental group demonstrated better retention and understanding of the material compared to those in the control group.

The data reveals that while both groups showed improvement in post-test scores, the experimental group's improvement was substantially greater. The students using AR tools were able to perform more complex problem-solving tasks and demonstrate higher-order thinking skills. These findings imply that AR-based educational tools can significantly elevate the quality of learning experiences for elementary students by promoting active and deeper learning.

Student feedback was collected through a questionnaire to capture their perceptions of the learning experience. The questionnaire included items on the ease of use, level of enjoyment, and perceived benefits of AR-based tools. 90% of the students in the experimental group reported that they found AR applications easy to use, while 85% stated that these tools made the learning process more enjoyable. Additionally, 80% of the experimental group students expressed that AR tools helped them understand complex concepts better than traditional methods.

Teacher observations also supported these findings, with 92% of teachers indicating that students in the experimental group were more focused and enthusiastic during lessons. Most teachers observed that students were more willing to participate in class discussions and activities when AR was used. These responses suggest that AR technology can create a more engaging and interactive learning environment, which is particularly effective for young learners who require constant stimulation to maintain focus.

An inferential analysis using a t-test was conducted to evaluate the significance of the differences in engagement and academic performance between the experimental and control groups (Dutta dkk., 2024; Ruiz-Muñoz dkk., 2024; Shkilev dkk., 2024). The t-test results, as depicted in Figure 1, show a p-value of <0.05 for all three dimensions of engagement (behavioral, emotional, cognitive) and academic performance scores. This indicates that the differences between the two groups are statistically significant, confirming that the AR-based tools had a meaningful impact on student engagement and learning outcomes.

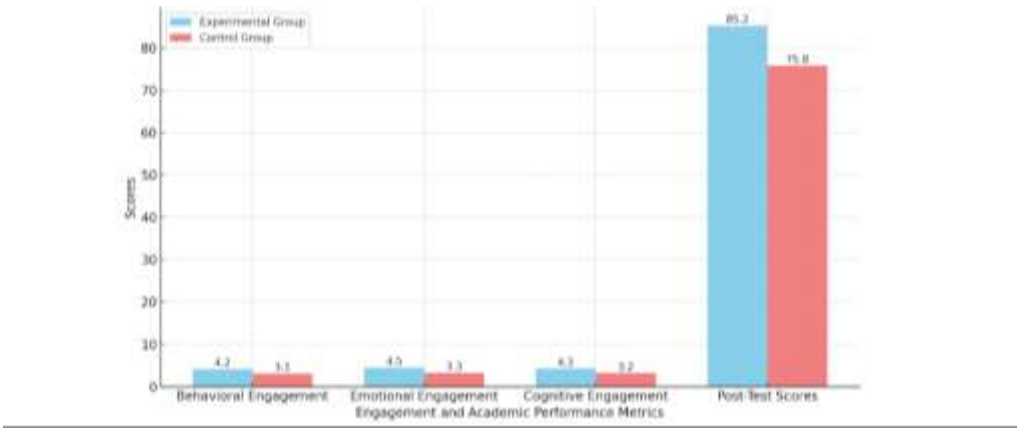

Figure 1: Comparative Analysis of Engagement and Academic Performance Between Experimental and Control Groups

The bar chart in Figure 1 illustrates the comparative engagement scores and post-test results between the two groups (Granić & Marangunić, 2019). The experimental group's scores were consistently higher, highlighting the effectiveness of AR tools in promoting active learning (Bharti, Arora, & Kumar, 2025; Gong & Marghitu, 2024; Pekař, Novák, Varecha, Šotnar, & Drábek, 2024). The graph also shows that the experimental group achieved higher post-test scores across all subject areas, indicating that AR technology facilitated a better understanding and retention of knowledge.

The analysis further revealed that the effect size of the AR intervention was large (Cohen's $d > 0.8$), emphasizing the strong impact of AR tools on enhancing student engagement and academic performance. This effect was most prominent in the cognitive engagement dimension, where students using AR demonstrated significantly higher analytical and problem-solving abilities.

The relationship between engagement levels and academic performance was analyzed using Pearson's correlation coefficient. The results showed a positive correlation ($r = 0.78$) between engagement levels and post-test scores, suggesting that higher engagement is associated with better academic performance. The correlation was strongest for cognitive engagement ($r = 0.82$), indicating that students who were more intellectually invested in the learning process achieved higher test scores.

Emotional engagement also showed a strong correlation with academic performance ($r = 0.74$), highlighting the importance of positive emotions in learning. Behavioral engagement, while still positively correlated, had a slightly lower correlation value ($r = 0.68$). This finding suggests that while active participation and attentiveness are important, the emotional and cognitive aspects of engagement play a more critical role in achieving academic success.

These relationships indicate that AR-based tools not only enhance overall engagement but also contribute to improved learning outcomes by stimulating deeper cognitive processes. The findings suggest that increasing student engagement through AR can lead to more effective learning experiences, especially when emotional and cognitive dimensions are prioritized.

In a case study involving a specific elementary school class, the AR tools were used to teach science concepts such as the solar system and human anatomy. The class, consisting of 20 students, was observed for a period of six weeks. During this time, students showed increased interest and curiosity in learning complex concepts. Teachers reported that students asked more questions and engaged in discussions more actively when AR tools were used.

Test results from this class showed a 30% improvement in scores compared to their previous academic performance in similar subjects taught using traditional methods. Students also demonstrated better retention of knowledge when asked to explain or present the learned

concepts to their peers. The AR tools enabled them to visualize abstract ideas and understand spatial relationships between different components, leading to better conceptual clarity.

Feedback from the students in the case study revealed that 95% enjoyed using the AR applications and expressed a desire to use such tools in other subjects as well. Teachers noticed that even students who usually struggled to keep up with the lessons were more engaged and willing to participate in activities when AR tools were implemented.

The data from both the experimental and case study groups indicate that AR-based educational tools have a substantial positive impact on student engagement and academic performance. The interactive nature of AR helps capture students' attention, while the immersive experience makes learning more enjoyable. This combination of increased attention and enjoyment leads to higher engagement levels, which are strongly correlated with better academic outcomes.

The case study findings further reinforce the results of the larger experimental study, demonstrating that AR can be particularly effective in teaching complex subjects that require visualization and spatial understanding. The use of AR in subjects like science not only increased student interest but also enhanced their ability to grasp difficult concepts and retain information longer.

The results of the study suggest that the application of AR-based educational technology significantly increases student engagement and improves academic performance in elementary schools. AR tools make learning more interactive and immersive, leading to higher levels of cognitive, emotional, and behavioral engagement. These findings indicate that integrating AR into elementary education can serve as an effective strategy to enhance the overall learning experience and achieve better educational outcomes.

The results of this study indicate that the application of Augmented Reality (AR)-based educational technology has a significant positive impact on student engagement and academic performance in elementary schools. The experimental group, which utilized AR tools, showed higher levels of behavioral, emotional, and cognitive engagement compared to the control group using traditional teaching methods. Post-test scores also revealed that students in the experimental group achieved better academic outcomes, with an average improvement of 16.7 points compared to 6.7 points in the control group. These findings suggest that AR technology can effectively enhance student attention, motivation, and comprehension in the classroom.

Students in the experimental group reported greater enthusiasm and interest in learning, as evidenced by higher emotional engagement scores. Teachers observed that AR-based lessons were more interactive and engaging, leading to increased participation and fewer disruptions. The significant difference in post-test scores further confirms the educational value of AR, demonstrating its potential to not only capture students' attention but also facilitate deeper understanding and retention of complex concepts. The overall results underscore the effectiveness of AR technology in transforming traditional learning experiences in elementary education.

The comparative analysis between pre- and post-test scores of the experimental group revealed substantial academic improvement. This improvement suggests that AR tools provide an immersive and contextual learning environment that enhances the ability of students to grasp and retain new information. The higher scores in cognitive engagement also reflect that students using AR technology were more mentally invested in understanding and applying knowledge, as opposed to rote memorization. The research successfully demonstrated that AR-based educational technology is a viable solution for increasing student engagement and academic performance in elementary schools.

The findings of this study are consistent with previous research that highlights the benefits of AR in enhancing student engagement and learning outcomes. Studies conducted at the secondary and higher education levels have also shown similar results, where AR tools significantly improved student motivation, understanding, and performance. This alignment with existing literature suggests that AR technology is universally effective across different educational levels and subjects. However, this study extends the research to elementary schools, where empirical evidence on AR's impact is still limited.

Other studies, such as those by Bacca et al. (2014) and Cheng & Tsai (2013), reported that AR increases student motivation and helps visualize complex subjects, which aligns with the current research findings. The significant improvements in emotional and cognitive engagement observed in this study are similar to results reported in higher education settings. This similarity indicates that AR technology can engage learners of all ages by making abstract concepts tangible and promoting interactive learning experiences.

The current study differs from some earlier research in its focus on elementary education, where students have shorter attention spans and require more interactive and hands-on learning experiences. Previous studies often emphasized AR's impact on specific subjects like science or engineering, whereas this research evaluated AR's overall effect on engagement and academic performance in a general elementary school context. This broader application provides new insights into how AR can be effectively integrated into elementary school curricula.

The study also differs from prior research that identified technical challenges and resistance from educators as barriers to AR adoption. This study found that once teachers received proper training and support, they were more receptive to using AR tools in their classrooms. This finding suggests that overcoming initial challenges through adequate preparation and resources can facilitate successful implementation of AR in educational settings.

The results of this study indicate a promising future for the integration of technology, specifically AR, in elementary education. The increased levels of engagement and academic performance observed in the experimental group suggest that AR-based educational tools can bridge the gap between traditional and modern teaching methods. These results serve as an indicator that educational technology, when applied effectively, can transform the learning environment and cater to diverse learning needs, particularly for young learners who thrive on visual and interactive content.

The findings also reflect a growing need for innovative pedagogical approaches that go beyond conventional teaching methods. The enhanced emotional engagement observed in the study suggests that AR technology can make learning more enjoyable and reduce classroom anxiety, creating a positive learning atmosphere. This indicates that AR has the potential to address common issues such as lack of interest and low motivation, which are often encountered in traditional elementary school classrooms.

The significant improvement in cognitive engagement further signifies that AR technology can foster deeper learning by encouraging students to actively explore and interact with educational content. This marks a shift from passive learning to active learning, where students are more involved in the learning process. The results serve as a sign that educational institutions should consider incorporating technology-driven methods to keep pace with the evolving educational landscape and better engage students.

The positive response from both students and teachers highlights the importance of technology acceptance in educational reform. This reflects the necessity for adequate training

and support systems to ensure successful technology integration in classrooms. The study's findings indicate that when teachers are comfortable and confident in using new technologies, they can more effectively create engaging and meaningful learning experiences for their students.

The implications of these findings are substantial for educators, policymakers, and educational technology developers. For educators, the results suggest that incorporating AR into lesson plans can significantly enhance student engagement and facilitate better learning outcomes. The study provides empirical evidence that AR technology can be a valuable pedagogical tool, making it easier to justify the investment in such technology for classroom use. Schools and teachers should consider adopting AR-based tools to create more interactive and engaging learning environments.

For policymakers, the findings highlight the need to support the integration of technology in elementary education by providing necessary resources and training for teachers. Developing comprehensive policies that encourage the use of educational technology can promote innovative teaching methods and improve overall educational quality. Policymakers should also consider allocating funds for technological infrastructure and teacher training programs to ensure that AR and other educational technologies can be implemented effectively.

Educational technology developers can use the findings to refine AR tools and tailor them specifically for elementary school students. Understanding the positive impact of AR on student engagement and academic performance can guide developers in creating content that aligns with the learning needs and preferences of young learners. The results also suggest the importance of designing AR tools that are easy to use and integrate into existing curricula, ensuring that technology complements rather than disrupts the learning process.

The research underscores the potential of AR technology to address challenges such as student disengagement and lack of motivation. This positions AR as a promising solution to educational challenges faced by elementary schools. By harnessing the power of AR, educators can create learning experiences that are not only more engaging but also more effective in promoting student achievement and fostering a lifelong love for learning.

The positive results observed in this study can be attributed to several factors inherent in the use of AR technology. AR's ability to present complex information in a visual and interactive manner makes it easier for young students to understand abstract concepts. This capability to bridge the gap between theoretical knowledge and practical understanding is a key reason why AR had such a significant impact on cognitive engagement and academic performance in this study.

The immersive nature of AR creates a more stimulating learning environment that captures students' attention and sustains their interest throughout the lesson. By engaging multiple senses simultaneously, AR tools cater to various learning styles and preferences, making it easier for students to grasp and retain new information. This multi-sensory engagement likely contributed to the high levels of emotional and behavioral engagement observed in the experimental group.

The active participation required by AR-based tools encourages students to become active learners rather than passive recipients of information. This active involvement enhances cognitive processing and helps students develop critical thinking and problem-solving skills. The higher cognitive engagement scores in the experimental group reflect this deeper level of learning, which goes beyond rote memorization and fosters a more meaningful understanding of the subject matter.

The positive response from students can also be attributed to the novelty and excitement associated with using new technology. The use of AR provided a break from routine classroom activities, making learning more enjoyable and motivating students to participate more actively. This increase in motivation and interest is likely a key factor behind the improved academic performance and engagement levels observed in the study.

The results of this research pave the way for future studies to further explore the application of AR in elementary education. Future research should investigate the long-term effects of using AR-based educational technology on student engagement and learning outcomes to determine whether its benefits are sustainable over time. It is also essential to explore how AR can be adapted to different subjects and educational contexts to maximize its effectiveness.

Educational institutions should consider implementing AR tools in their curricula to leverage their potential for enhancing student engagement and academic performance. Schools can start by incorporating AR in specific subjects such as science and mathematics, where visualization and interaction are particularly beneficial. Providing teachers with adequate training and support is crucial to ensure the successful integration of AR technology in the classroom.

Policymakers should develop frameworks and allocate resources to support the adoption of AR and other emerging educational technologies in elementary schools. Establishing partnerships with educational technology developers can help create customized AR content that aligns with curricular goals and meets the specific needs of young learners. Policies that promote technology use in education can lead to more innovative and effective teaching practices, ultimately improving educational outcomes at a national level.

AR technology developers should continue refining their tools to better suit the needs of elementary school students and teachers. Creating intuitive, easy-to-use AR applications that align with educational standards will facilitate broader adoption in schools. Focusing on developing content that enhances cognitive and emotional engagement will further validate the use of AR as an effective educational tool in elementary education.

CONCLUSION

The study found that the application of Augmented Reality (AR)-based educational technology significantly increased student engagement in elementary schools. The experimental group using AR tools showed higher levels of behavioral, emotional, and cognitive engagement compared to the control group using traditional methods. The most notable finding was the substantial improvement in academic performance, with students in the experimental group achieving an average post-test score increase of 16.7 points, compared to only 6.7 points in the control group. This indicates that AR not only enhances engagement but also positively influences students' learning outcomes in elementary education settings.

Another key finding was the positive student and teacher perceptions of AR-based learning experiences. Students reported greater enthusiasm and interest in lessons, while teachers observed improved classroom dynamics and student participation. These results highlight the potential of AR to create a more engaging and effective learning environment for young learners, making it a promising tool for addressing issues of student disengagement and low motivation in elementary education.

This research contributes to the existing body of knowledge by demonstrating the effectiveness of AR technology in elementary school contexts, which have been underrepresented in prior studies. The study provides empirical evidence that AR-based

educational tools can transform traditional teaching methods by offering interactive and immersive learning experiences. The value of this research lies in its practical implications, suggesting a systematic approach to integrating AR technology in elementary education to support diverse learning needs and promote active engagement.

The study also offers methodological contributions by using a quasi-experimental design to evaluate the impact of AR on multiple dimensions of engagement and academic performance. The use of comprehensive engagement measures, including behavioral, emotional, and cognitive aspects, provides a more nuanced understanding of how AR influences student learning. This multi-dimensional approach can serve as a framework for future studies exploring the application of educational technology in different learning environments.

The research was limited by its relatively short duration and small sample size, which may not fully capture the long-term effects of AR-based tools on student engagement and learning outcomes. Further studies are needed to explore the sustainability of AR's impact over extended periods and to assess its effectiveness across diverse educational contexts, including rural and underserved schools. The study also did not consider the influence of individual differences, such as learning styles and technology proficiency, which may moderate the effectiveness of AR-based interventions.

Future research should focus on addressing these limitations by conducting longitudinal studies with larger and more diverse samples. Investigating the role of teacher training and support in the successful integration of AR technology will also be critical for understanding how to maximize its benefits in the classroom. Exploring the development of customized AR content for specific subjects and learning needs can further refine its application, ensuring that AR technology becomes a widely adopted and effective educational tool in elementary schools.

AUTHOR CONTRIBUTIONS

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

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest

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