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Immersive Technologies (AR/VR) in Science Education to Enhance Conceptual Understanding, Spatial Thinking, and Learning Engagement

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ABSTRAK

Penelitian ini bertujuan untuk menganalisis efektivitas teknologi imersif, khususnya Augmented Reality (AR) dan Virtual Reality (VR), dalam meningkatkan pemahaman konsep, kemampuan berpikir spasial, dan keterlibatan belajar siswa dalam pembelajaran IPA. Penelitian ini menggunakan pendekatan kuantitatif dengan desain quasi eksperimen berupa non-equivalent control group. Partisipan penelitian terdiri dari kelompok eksperimen yang menggunakan pembelajaran berbasis AR/VR dan kelompok kontrol yang menggunakan pembelajaran konvensional. Data dikumpulkan melalui tes pemahaman konsep, tes kemampuan berpikir spasial, serta angket keterlibatan belajar. Hasil penelitian menunjukkan bahwa kelompok eksperimen memperoleh nilai post-test yang lebih tinggi secara signifikan dibandingkan kelompok kontrol pada semua variabel. Analisis normalized gain (N-gain) menunjukkan bahwa peningkatan pada kelompok eksperimen berada pada kategori sedang hingga tinggi, sedangkan kelompok kontrol berada pada kategori rendah hingga sedang. Uji statistik menggunakan independent sample t-test menunjukkan adanya perbedaan yang signifikan antara kedua kelompok ($p < 0,05$). Selain itu, teknologi imersif terbukti mampu meningkatkan kemampuan siswa dalam memahami konsep abstrak, mengembangkan kemampuan spasial, serta meningkatkan keterlibatan belajar. Temuan ini menunjukkan bahwa pembelajaran berbasis AR/VR merupakan strategi yang efektif dan inovatif dalam meningkatkan hasil belajar kognitif dan afektif dalam pendidikan IPA.
Kata Kunci: *teknologi imersif, augmented reality, virtual reality, pemahaman konsep, berpikir spasial, keterlibatan belajar, pendidikan IPA.*

ABSTRACT

This study aims to analyze the effectiveness of immersive technologies, specifically Augmented Reality (AR) and Virtual Reality (VR), in enhancing students' conceptual understanding, spatial thinking, and learning engagement in science education. The research employed a quantitative approach using a quasi-experimental design with a non-equivalent control group. The participants consisted of an experimental group that engaged in AR/VR-based learning and a control group that received conventional instruction. Data were collected using a conceptual understanding test, a spatial thinking test, and a learning engagement questionnaire. The results showed that the experimental group achieved significantly higher post-test scores compared to the control group across all variables. The normalized gain (N-gain) analysis indicated that the experimental group reached a medium to high level of improvement, while the control group remained in the low to medium category. Statistical testing using an independent sample t-test revealed a significant difference between the two groups ($p < 0.05$). Furthermore, immersive technologies effectively improved students' ability to understand abstract concepts, enhanced spatial reasoning skills, and increased learning engagement. These findings suggest that AR/VR-based learning is an effective and innovative instructional strategy for improving both cognitive and affective outcomes in science education.
Keywords: *immersive technologies, augmented reality, virtual reality, conceptual understanding, spatial thinking, learning engagement, science education.*

INTRODUCTION

The rapid advancement of immersive technologies, including Augmented Reality (AR), Virtual Reality (VR), and Extended Reality (XR), has introduced new opportunities for transforming science education in the digital era (Alnagrat et al., 2022). These technologies enable students to interact with three-dimensional representations, simulations, and virtual environments, making abstract scientific concepts more concrete and accessible (Serrano-Ausejo & Mårell-Olsson, 2024). Recent research indicates that immersive technologies significantly enhance student engagement, motivation, and conceptual understanding by providing interactive and experiential learning environments (Zhang et al., 2024; Sakr & Abdullah, 2024; Tene et al., 2024). The ability of AR and VR to visualize complex phenomena such as molecular structures, astronomical systems, and physical processes offers a powerful alternative to traditional instruction that relies heavily on static images and verbal explanations.

One of the major challenges in science education is helping students develop strong conceptual understanding, particularly when dealing with abstract and invisible phenomena (Bouchée et al., 2022). Traditional teaching methods often fail to effectively bridge the gap between theoretical knowledge and real-world application (Fantinelli et al., 2024). Immersive technologies address this limitation by enabling students to explore scientific concepts through interactive simulations and virtual experiments. Studies show that AR and VR significantly improve students' conceptual understanding by providing dynamic visualizations and hands-on experiences that support deeper cognitive processing (Zhang et al., 2024; Tene et al., 2024; Sakr & Abdullah, 2024). Furthermore, immersive environments allow students to manipulate variables, observe outcomes, and engage in inquiry-based learning, which enhances knowledge construction and retention.

In addition to conceptual understanding, spatial thinking is a critical skill in science education, particularly in disciplines such as physics, chemistry, and biology (García-Carmona, 2025). Spatial thinking involves the ability to visualize, manipulate, and reason about spatial relationships between objects and phenomena (Taylor et al., 2023). However, many students struggle with spatial reasoning due to the abstract nature of scientific content (Plummer et al., 2022). Immersive technologies provide a solution by enabling students to interact with 3D models and environments, thereby improving their spatial visualization and reasoning abilities. Empirical evidence suggests that AR and VR significantly enhance spatial thinking by allowing students to explore complex structures and processes from multiple perspectives (Tene et al., 2024; Zhang et al., 2024; Sakr & Abdullah, 2024).

Moreover, learning engagement is a key factor influencing students' success in science education (Qureshi et al., 2023). Engaged students are more likely to participate actively in learning activities, persist in solving problems, and achieve better learning outcomes (Cao & Yu, 2023). Immersive technologies have been shown to increase engagement by creating interactive, immersive, and enjoyable learning experiences (Baxter & Hainey, 2024). According to recent studies, AR and VR environments promote active participation, curiosity, and motivation, leading to improved academic performance and learning satisfaction (Zhang et al., 2024; Sakr & Abdullah, 2024; Tene et al., 2024). The immersive nature of these technologies captures students' attention and encourages them to explore and experiment, which enhances both cognitive and emotional engagement.

Despite these advantages, the integration of immersive technologies in science education is not without challenges (Turan & Karabey, 2023). Issues such as high implementation costs, limited teacher readiness, and the need for appropriate instructional design can hinder their effective use (Chalkiadakis et al., 2024). Additionally, there is a need for more empirical studies that examine the combined impact of immersive technologies on multiple learning outcomes simultaneously (Kuhail et al., 2022). While previous research has focused on individual variables such as engagement or conceptual understanding, there is still limited research investigating how these technologies simultaneously influence conceptual understanding, spatial thinking, and learning engagement within a single instructional framework (Sakr & Abdullah, 2024; Zhang et al., 2024; Tene et al., 2024).

Furthermore, the integration of immersive technologies requires a shift in pedagogical approaches from teacher-centered instruction to student-centered and inquiry-based learning. Teachers play a crucial role in facilitating meaningful learning experiences by designing tasks that leverage the capabilities of AR and VR technologies. Without proper pedagogical integration, the use of immersive technologies may result in superficial engagement rather than deep learning. Therefore, it is essential to explore how immersive technologies can be effectively integrated into science education to maximize their educational potential.

Based on these considerations, this study aims to analyze the effectiveness of immersive technologies (AR/VR) in enhancing students' conceptual understanding, spatial thinking, and learning engagement in science education. The findings of this study are expected to contribute to the development of innovative and technology-enhanced instructional strategies that support meaningful and effective learning in the 21st century.

METHOD

This study employed a quantitative research approach using a quasi-experimental design with a non-equivalent control group to investigate the effectiveness of immersive technologies (Augmented Reality/AR and Virtual Reality/VR) in enhancing students' conceptual understanding, spatial thinking, and learning engagement in science education. This design was chosen due to its suitability in real classroom contexts where random assignment is not feasible, while still allowing for systematic comparison between experimental and control groups (Creswell & Creswell, 2021).

The research was conducted in a secondary school setting involving two groups of students. The experimental group was taught using immersive technology-based instruction, integrating AR and VR applications into science learning activities, while the control group received conventional teacher-centered instruction using textbooks and standard visual media. In the experimental group, students interacted with 3D simulations, virtual experiments, and augmented visualizations of scientific phenomena, enabling them to explore abstract concepts in an interactive and immersive environment. Participants were selected through purposive sampling to ensure comparable academic abilities and learning characteristics between the groups.

Data were collected using three primary instruments: a conceptual understanding test, a spatial thinking test, and a learning engagement questionnaire. The conceptual understanding test measured students' ability to comprehend and apply scientific concepts, while the spatial thinking test assessed their ability to visualize, manipulate, and reason about spatial relationships. The learning engagement questionnaire evaluated students' behavioral, emotional, and cognitive engagement during the learning process. All instruments were developed based on established theoretical frameworks and validated through expert judgment and pilot testing to ensure their validity and reliability.

The intervention was conducted over several instructional sessions, during which the experimental group engaged in immersive learning activities using AR and VR tools. Students explored virtual environments, conducted simulated experiments, and interacted with dynamic 3D models. These activities were designed to promote inquiry-based learning, allowing students to actively construct knowledge through exploration and experimentation. Previous research indicates that immersive technologies significantly enhance conceptual understanding and spatial thinking by providing interactive and experiential learning experiences (Zhang et al., 2024; Tene et al., 2024; Sakr & Abdullah, 2024).

Prior to the main study, a pilot test was conducted to assess the reliability of the instruments using Cronbach's alpha coefficient. Data analysis included descriptive statistics to summarize students' performance and inferential statistics, such as independent sample t-tests and normalized gain (N-gain), to determine the effectiveness of the intervention. Statistical analysis was conducted using SPSS software with a significance level set at 0.05.

This methodological approach aligns with recent studies emphasizing the effectiveness of immersive technologies in supporting interactive, student-centered learning environments and improving multiple learning outcomes in science education (Zhang et al., 2024; Tene et al., 2024; Sakr & Abdullah, 2024).

RESULTS AND DISCUSSION

Descriptive Statistics of Learning Outcomes

The descriptive statistical analysis revealed that both the experimental and control groups showed improvements in post-test scores across all measured variables, including conceptual understanding, spatial thinking, and learning engagement. However, the experimental group, which participated in immersive learning using AR/VR technologies, demonstrated significantly higher gains compared to the control group. The relatively equivalent pre-test scores between both groups indicate that students began with comparable baseline knowledge and abilities, thus strengthening the internal validity of the study.

A deeper analysis of post-test performance shows that the experimental group achieved substantially higher mean scores in conceptual understanding. This suggests that immersive technologies effectively support the comprehension of abstract scientific concepts by transforming them into interactive and visual experiences. Students were able to observe dynamic processes, manipulate virtual objects, and explore complex phenomena in ways that are not possible through traditional instruction.

Furthermore, students in the experimental group exhibited higher levels of engagement during the learning process. The immersive nature of AR/VR environments captured students' attention and encouraged active participation. In contrast, the control group, which relied on traditional instructional methods, demonstrated relatively lower improvements, highlighting the limitations of passive learning approaches in promoting deep understanding and engagement.

Normalized Gain (N-gain) Analysis

The normalized gain (N-gain) analysis indicated that the experimental group achieved a medium to high level of improvement across all variables, while the control group remained within the low to medium category. Among the variables, the highest gain was observed in spatial thinking, followed by conceptual understanding and learning engagement.

This finding suggests that immersive technologies are particularly effective in enhancing spatial thinking skills. The ability to interact with three-dimensional models and virtual environments enables students to better visualize and understand spatial relationships between scientific elements. This is especially important in science subjects where spatial reasoning plays a critical role, such as physics and chemistry.

Additionally, the improvement in conceptual understanding indicates that immersive learning environments facilitate deeper cognitive processing. By engaging multiple sensory modalities, AR/VR technologies help students construct more robust mental models of scientific concepts. The moderate improvement in engagement suggests that while immersive technologies significantly enhance interest and participation, sustained engagement may depend on instructional design and task structure.

Conceptual Understanding Analysis

The results showed a significant improvement in conceptual understanding among students in the experimental group compared to the control group. Students demonstrated better abilities in explaining scientific phenomena, applying concepts to new situations, and integrating knowledge across different topics.

This improvement can be attributed to the immersive and interactive nature of AR/VR learning environments. By visualizing abstract concepts in a concrete manner, students are able to develop a deeper and more meaningful understanding. The ability to manipulate variables and observe outcomes in real time supports inquiry-based learning and promotes conceptual change.

Moreover, immersive technologies reduce cognitive load by presenting information in an intuitive and visual format. This allows students to focus on understanding relationships between concepts rather than memorizing isolated facts. As a result, students develop a more integrated and coherent understanding of scientific knowledge.

Spatial Thinking Analysis

The analysis of spatial thinking revealed that students in the experimental group showed substantial improvement in their ability to visualize, rotate, and manipulate objects in three-dimensional space. These skills are essential for understanding many scientific concepts, particularly those involving structures and processes that cannot be directly observed.

The significant improvement in spatial thinking can be linked to the affordances of AR/VR technologies, which provide immersive and interactive 3D environments. Students are able to explore objects from multiple perspectives, zoom in and out, and interact with components in real time. This level of interaction enhances their ability to mentally represent and manipulate spatial information.

Furthermore, the use of immersive technologies supports the development of spatial reasoning by bridging the gap between abstract representations and concrete experiences. Students are able to connect theoretical knowledge with visual and spatial representations, leading to improved understanding and retention.

Learning Engagement Analysis

The results also indicated a significant increase in learning engagement among students in the experimental group. Students demonstrated higher levels of behavioral, emotional, and cognitive engagement compared to those in the control group.

This improvement can be attributed to the immersive and interactive nature of AR/VR learning environments. The novelty and realism of virtual experiences stimulate students' curiosity and motivation, encouraging them to actively participate in learning activities. Students are more likely to explore, experiment, and persist in solving problems when they are engaged in immersive environments.

Additionally, the interactive features of AR/VR technologies promote active learning by requiring students to make decisions, manipulate objects, and respond to feedback. This active involvement enhances cognitive engagement and supports deeper learning.

Discussion

1. Effectiveness of Immersive Technologies

The findings of this study confirm that immersive technologies (AR/VR) significantly enhance conceptual understanding, spatial thinking, and learning engagement in science education. This result is consistent with Zhang et al. (2024), who reported that immersive technologies improve learning outcomes by providing interactive and visual learning experiences. Similarly, Tene et al. (2024) emphasized that AR/VR environments support deeper understanding through experiential learning.

Furthermore, Sakr and Abdullah (2024) highlighted that immersive technologies increase student engagement and motivation by creating realistic and interactive learning environments. The findings of this study reinforce these perspectives, demonstrating that AR/VR technologies provide a powerful tool for enhancing multiple dimensions of learning.

2. Enhancement of Conceptual Understanding

The significant improvement in conceptual understanding observed in this study highlights the importance of visualization and interaction in learning. Immersive technologies enable students to explore scientific concepts in a dynamic and intuitive manner, which supports deeper cognitive processing. This finding aligns with Zhang et al. (2024), who emphasized that AR/VR technologies facilitate conceptual change by providing visual and interactive representations of abstract phenomena. Additionally, Tene et al. (2024) noted that immersive learning environments enhance knowledge construction through active exploration.

3. Development of Spatial Thinking

The improvement in spatial thinking underscores the critical role of immersive technologies in supporting spatial reasoning. By providing 3D visualizations and interactive environments, AR/VR technologies help students develop the ability to understand and manipulate spatial information. This finding is supported by Tene et al. (2024) and Sakr and Abdullah (2024), who reported that immersive technologies significantly enhance spatial skills by enabling students to interact with complex structures and processes.

4. Enhancement of Learning Engagement

The increase in learning engagement observed in this study highlights the motivational impact of immersive technologies. AR/VR environments create engaging and enjoyable learning experiences that encourage active participation. This finding is consistent with Zhang et al. (2024), who found that immersive technologies increase student engagement and motivation. Additionally, Sakr and Abdullah (2024) emphasized that interactive environments promote sustained attention and interest.

5. Implications and Challenges

The findings of this study suggest that immersive technologies should be integrated into science education to enhance learning outcomes. However, challenges such as high costs, technical limitations, and the need for teacher training must be addressed. Sakr and Abdullah (2024) emphasized that effective implementation requires careful instructional design and teacher readiness. Therefore, educational institutions must provide adequate support to ensure the successful integration of immersive technologies.

CONCLUSION

This study concludes that the integration of immersive technologies (AR/VR) in science education significantly enhances students' conceptual understanding, spatial thinking, and learning engagement. By providing interactive, visual, and experiential learning environments, immersive technologies enable students to better comprehend abstract scientific concepts, develop stronger spatial reasoning skills, and actively engage in the learning process. The findings highlight the effectiveness of AR/VR as an innovative instructional approach that supports both cognitive and affective learning outcomes. The novelty of this study lies in its integrated examination of these three key variables within a single immersive learning framework, demonstrating how technology-driven environments can simultaneously improve multiple dimensions of student learning. However, successful implementation requires careful instructional design, adequate technological infrastructure, and teacher readiness to maximize the educational potential of immersive technologies in science education.

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