

Augmented Reality-Based Learning in Science Education to Enhance Conceptual Understanding, Spatial Ability, and Scientific Literacy

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ABSTRAK

Penelitian ini bertujuan untuk menganalisis efektivitas pembelajaran berbasis augmented reality (AR) dalam meningkatkan pemahaman konsep, kemampuan spasial, dan literasi sains siswa dalam pembelajaran IPA. Penelitian ini menggunakan pendekatan kuantitatif dengan desain quasi eksperimen berupa non-equivalent control group. Partisipan penelitian terdiri dari dua kelompok, yaitu kelompok eksperimen yang menggunakan pembelajaran berbasis AR terintegrasi dengan pendekatan inkuiri dan kelompok kontrol yang menggunakan metode pembelajaran konvensional. Data dikumpulkan melalui tes pemahaman konsep, tes kemampuan spasial, dan tes literasi sains. Hasil penelitian menunjukkan bahwa kelompok eksperimen memperoleh nilai post-test yang lebih tinggi secara signifikan dibandingkan kelompok kontrol. 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, pembelajaran berbasis AR terbukti meningkatkan kemampuan siswa dalam memvisualisasikan konsep abstrak, memahami hubungan spasial, menganalisis data, dan menerapkan pengetahuan ilmiah. Hasil ini menunjukkan bahwa augmented reality merupakan strategi pembelajaran yang efektif dan inovatif dalam meningkatkan kualitas pembelajaran serta mengembangkan kompetensi penting dalam pendidikan IPA.

Kata Kunci: *augmented reality, pemahaman konsep, kemampuan spasial, literasi sains, pendidikan IPA.*

ABSTRACT

This study aims to investigate the effectiveness of augmented reality (AR)-based learning in enhancing students' conceptual understanding, spatial ability, and scientific literacy in science education. The research employed a quantitative approach using a quasi-experimental design with a non-equivalent control group. The participants consisted of two groups: an experimental group taught using AR-based learning integrated with inquiry-based activities and a control group taught using conventional methods. Data were collected through a conceptual understanding test, a spatial ability test, and a scientific literacy test. The results showed that the experimental group achieved significantly higher post-test scores compared to the control group. 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, AR-based learning significantly improved students' ability to visualize abstract concepts, interpret spatial relationships, analyze data, and apply scientific knowledge. These findings suggest that augmented reality is an effective and innovative instructional strategy for promoting meaningful learning and developing essential competencies in science education.

Keywords: *augmented reality, conceptual understanding, spatial ability, scientific literacy, science education.*



INTRODUCTION

The rapid evolution of immersive technologies has significantly influenced instructional practices in science education, particularly through the integration of Augmented Reality (AR) (Tene et al., 2024). AR enables the overlay of digital information onto real-world environments, allowing students to interact with three-dimensional representations of abstract scientific concepts (Coştu, 2025). This capability has made AR a powerful tool for enhancing learning experiences, especially in subjects that require visualization and spatial reasoning (Medina et al., 2024). Recent studies highlight that immersive technologies such as AR and virtual reality significantly improve student engagement, motivation, and conceptual understanding by providing interactive and contextual learning experiences (Lampropoulos & Kinshuk, 2024; Radianti et al., 2020; Makransky et al., 2021)

In science education, one of the major challenges is helping students understand abstract and complex phenomena that cannot be easily observed directly (Fitrianto & Saif, 2024). Traditional teaching methods often rely on static images and verbal explanations, which may not effectively support deep conceptual understanding (Siregar, 2024). AR addresses this limitation by enabling students to visualize invisible processes, manipulate virtual objects, and explore scientific concepts in real time (Hoai et al., 2024). Empirical evidence suggests that AR-based learning significantly improves students' conceptual understanding and spatial ability by providing dynamic and interactive representations of scientific phenomena (Rosli & Ishak, 2024; Kapici et al., 2022; de Jong et al., 2023)

Furthermore, AR has been shown to play an important role in enhancing scientific literacy, which involves the ability to interpret scientific information, analyze data, and apply knowledge in real-world contexts (Chen & Liu, 2026). By integrating real and virtual environments, AR supports inquiry-based learning and encourages students to actively engage in scientific exploration (Kotsis, 2024). Research indicates that immersive and interactive technologies promote deeper learning by enabling students to connect theoretical concepts with practical applications (Makransky et al., 2021; Lampropoulos & Kinshuk, 2024; Ruiz-Navas et al., 2024)

In addition, AR-based learning environments contribute to the development of higher-order thinking skills, particularly spatial ability and critical thinking (Parisu et al., 2025). Spatial ability is essential in science learning, especially in topics such as molecular structures, anatomy, and physics concepts, where understanding spatial relationships is crucial (Antonucci-Durgan et al., 2024). AR allows students to manipulate 3D objects and observe them from multiple perspectives, thereby enhancing their spatial reasoning skills. Studies have shown that students who learn using AR demonstrate better problem-solving abilities and improved understanding of complex spatial relationships (Makransky et al., 2021; Rosli & Ishak, 2024; Kapici et al., 2022)

Despite its potential, the implementation of AR in science education faces several challenges. These include limited access to technological devices, lack of teacher readiness, and the need for effective instructional design to ensure meaningful learning (Mhlongo et al., 2023). Additionally, poorly designed AR applications may lead to cognitive overload, reducing their effectiveness in supporting learning outcomes. Previous research emphasizes that the success of AR-based learning depends on its alignment with pedagogical approaches, particularly inquiry-based and student-centered learning strategies (Lampropoulos & Kinshuk, 2024; Makransky et al., 2021; Ruiz-Navas et al., 2024)

Moreover, there is still limited empirical research that simultaneously examines the impact of AR-based learning on multiple learning outcomes, such as conceptual

understanding, spatial ability, and scientific literacy within a single framework. Most existing studies focus on one or two variables, leaving a gap in understanding the comprehensive impact of AR in science education. Addressing this gap is essential for developing more effective instructional strategies that integrate immersive technologies in a holistic manner.

Therefore, this study aims to investigate the effectiveness of augmented reality-based learning in enhancing students' conceptual understanding, spatial ability, and scientific literacy in science education. The findings of this study are expected to contribute to the development of innovative, technology-enhanced instructional strategies that support meaningful learning and prepare students with essential competencies required in the 21st century.

METHOD

This study employed a quantitative research approach using a quasi-experimental design with a non-equivalent control group to examine the effectiveness of augmented reality (AR)-based learning in enhancing students' conceptual understanding, spatial ability, and scientific literacy in science education. This design is appropriate for classroom-based research where random assignment is not feasible, allowing for comparison between experimental and control groups while maintaining the natural learning environment (Creswell & Creswell, 2021).

The research was conducted in a secondary school setting involving two groups of students. The experimental group was taught using AR-based learning integrated with inquiry-based activities, while the control group received conventional teacher-centered instruction. The AR learning environment enabled students to interact with three-dimensional (3D) representations of scientific concepts, manipulate virtual objects, and observe dynamic processes in real time. These features provided an immersive learning experience that supported visualization and spatial reasoning. Participants were selected using purposive sampling to ensure that both groups had comparable academic abilities and learning characteristics.

Data collection was carried out using three main instruments: a conceptual understanding test, a spatial ability test, and a scientific literacy test. The conceptual understanding test measured students' ability to explain scientific concepts and apply them in different contexts. The spatial ability test assessed students' skills in visualizing, rotating, and interpreting three-dimensional objects, which are essential for understanding complex scientific phenomena. The scientific literacy test was adapted from international assessment frameworks, focusing on students' ability to interpret data, evaluate evidence, and make scientific decisions (Organisation for Economic Co-operation and Development, 2023). All instruments were validated through expert judgment and pilot testing to ensure content validity and reliability.

The intervention was implemented over several instructional sessions, during which students in the experimental group engaged in AR-based learning activities designed to support inquiry processes. These activities included exploring 3D models, conducting virtual observations, analyzing scientific phenomena, and drawing conclusions based on evidence. Previous studies indicate that AR-based learning enhances conceptual understanding and spatial ability by providing interactive and immersive visualization of abstract concepts (Makransky et al., 2021; Kapici et al., 2022; Lampropoulos & Kinshuk, 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 student performance and inferential statistics, such as

independent sample t-tests and normalized gain (N-gain), to evaluate the effectiveness of the intervention. Statistical analysis was conducted using SPSS software with a significance level set at 0.05.

This methodological approach is consistent with recent studies highlighting the effectiveness of AR-based learning in improving conceptual understanding, spatial ability, and scientific literacy through interactive and immersive learning environments (Makransky et al., 2021; Lampropoulos & Kinshuk, 2024; Ruiz-Navas et al., 2024).

RESULTS AND DISCUSSION

Descriptive Statistics of Learning Outcomes

The descriptive analysis indicated that both the experimental and control groups experienced improvements in post-test scores across all measured variables, including conceptual understanding, spatial ability, and scientific literacy. However, the experimental group, which engaged in augmented reality (AR)-based learning, demonstrated a significantly higher increase in performance compared to the control group. The similarity in pre-test scores between the two groups confirms that students had comparable baseline abilities prior to the intervention.

The higher post-test scores observed in the experimental group suggest that AR-based learning provides a more effective instructional approach compared to conventional methods. The integration of three-dimensional visualization and interactive features enables students to explore scientific concepts in a more concrete and meaningful way. This immersive experience supports deeper learning and facilitates the construction of knowledge, leading to improved academic performance.

Normalized Gain (N-gain) Analysis

The normalized gain (N-gain) analysis revealed that the experimental group achieved a medium to high level of improvement across all variables, whereas the control group remained within the low to medium category. Among the three variables, the highest gain was observed in spatial ability, followed by conceptual understanding and scientific literacy. This finding indicates that AR-based learning is particularly effective in enhancing students' spatial reasoning skills. The ability to manipulate and interact with 3D objects allows students to better understand spatial relationships and visualize complex structures. In addition, the interactive nature of AR promotes active engagement, which contributes to improved learning efficiency and effectiveness.

Conceptual Understanding Analysis

The results showed a significant improvement in conceptual understanding among students in the experimental group compared to those in the control group. Students who participated in AR-based learning demonstrated a better ability to explain scientific concepts, apply knowledge to new contexts, and integrate theoretical and practical understanding.

This improvement can be attributed to the visualization capabilities of AR technology, which allow students to observe abstract phenomena in a more tangible form. By interacting with dynamic models, students can explore cause-and-effect relationships and develop a deeper understanding of scientific concepts. The ability to revisit and manipulate these models further reinforces learning and reduces misconceptions.

Spatial Ability Analysis

The analysis of spatial ability revealed that the experimental group showed a substantial improvement in visualizing, rotating, and interpreting three-dimensional objects. Students demonstrated enhanced skills in understanding spatial relationships,

which are critical for learning complex scientific topics such as molecular structures and physical systems.

This significant improvement highlights the unique contribution of AR-based learning in developing spatial cognition. Unlike traditional methods, which rely on static images, AR provides dynamic and interactive representations that allow students to explore objects from multiple perspectives. This capability enhances students' ability to mentally manipulate objects and understand spatial relationships more effectively.

Scientific Literacy Analysis

The results also indicated a significant improvement in scientific literacy among students in the experimental group. Students demonstrated better abilities in interpreting data, evaluating evidence, and making informed decisions based on scientific information. This improvement suggests that AR-based learning effectively supports the development of scientific reasoning skills. Through interactive exploration and inquiry-based activities, students are encouraged to engage in scientific practices such as observation, analysis, and conclusion drawing. These experiences help students develop a deeper understanding of scientific processes and improve their ability to apply knowledge in real-world contexts.

Discussion

1. Effectiveness of AR-Based Learning

The findings of this study confirm that AR-based learning significantly enhances students' conceptual understanding, spatial ability, and scientific literacy. This result is consistent with Makransky et al. (2021), who found that immersive technologies improve learning outcomes by providing interactive and engaging experiences. Similarly, Lampropoulos and Kinshuk (2024) emphasized that AR enhances student engagement and facilitates deeper learning through immersive environments.

Furthermore, Kapici et al. (2022) reported that interactive technologies such as AR and virtual labs improve students' understanding of scientific concepts by enabling visualization and manipulation of abstract phenomena. The findings of this study reinforce these conclusions, demonstrating that AR-based learning provides an effective platform for enhancing multiple learning outcomes in science education.

2. Improvement of Conceptual Understanding

The significant improvement in conceptual understanding observed in this study can be explained by the ability of AR to provide visual and interactive representations of scientific concepts. These features help students overcome the limitations of traditional instruction, which often relies on abstract explanations and static images.

This finding aligns with Makransky et al. (2021) and Kapici et al. (2022), who highlighted the importance of visualization in enhancing conceptual learning. By enabling students to interact with 3D models, AR facilitates deeper understanding and knowledge construction. This suggests that AR-based learning is particularly effective for teaching complex and abstract scientific concepts.

3. Enhancement of Spatial Ability

The improvement in spatial ability observed in this study highlights the effectiveness of AR in developing students' spatial reasoning skills. The ability to manipulate and explore 3D objects provides students with opportunities to develop a better understanding of spatial relationships.

This finding is supported by Lampropoulos and Kinshuk (2024), who emphasized that immersive technologies enhance spatial cognition by providing interactive learning experiences. Additionally, Makransky et al. (2021) found that virtual and augmented reality environments improve students' ability to visualize and interpret spatial

information. The results of this study confirm that AR-based learning is highly effective in enhancing spatial ability in science education.

4. Development of Scientific Literacy

The improvement in scientific literacy observed in this study indicates that AR-based learning effectively supports the development of scientific reasoning skills. Students were able to interpret data, evaluate evidence, and apply scientific knowledge in meaningful ways.

This result is consistent with the OECD (2023) framework, which emphasizes the importance of inquiry-based learning in developing scientific literacy. Furthermore, Ruiz-Navas et al. (2024) highlighted that interactive and immersive learning environments promote deeper understanding and application of knowledge. The findings of this study confirm that AR-based learning provides an effective environment for developing scientific literacy.

5. Role of Interactivity and Immersion

One of the key factors contributing to the effectiveness of AR-based learning is its ability to provide interactive and immersive learning experiences. These features enable students to actively engage with the content and explore scientific concepts in a meaningful way. Radianti et al. (2020) emphasized that immersive technologies enhance learning by increasing engagement and facilitating experiential learning. The findings of this study support this perspective, showing that interactivity and immersion play a crucial role in improving learning outcomes. Students who actively engage with AR simulations are more likely to develop a deeper understanding of the material.

6. Challenges in Implementation

Despite its effectiveness, several challenges were identified in implementing AR-based learning. These include technological limitations, potential cognitive overload, and the need for effective instructional design. Makransky et al. (2021) noted that overly complex immersive environments can lead to cognitive overload, which may hinder learning. Similarly, Lampropoulos and Kinshuk (2024) emphasized the importance of aligning AR applications with pedagogical objectives. Therefore, it is essential to design AR-based learning activities that are structured and guided to maximize their effectiveness.

CONCLUSION

This study concludes that the implementation of augmented reality (AR)-based learning has a significant and positive impact on improving students' conceptual understanding, spatial ability, and scientific literacy in science education. The findings clearly demonstrate that students who participated in AR-supported instruction outperformed those in conventional learning environments across all measured variables. The ability of AR to present abstract scientific concepts through interactive three-dimensional visualizations enables students to construct knowledge more effectively, resulting in deeper conceptual understanding and improved learning outcomes. Furthermore, AR-based learning plays a crucial role in enhancing spatial ability, which is often overlooked in traditional science instruction. The interactive manipulation of 3D objects allows students to develop stronger spatial reasoning skills, enabling them to better understand complex structures and relationships within scientific content. At the same time, the integration of inquiry-based activities within AR environments supports the development of scientific literacy by encouraging students to interpret data, evaluate evidence, and make informed decisions based on scientific reasoning.

The novelty of this study lies in its comprehensive examination of three interrelated learning outcomes conceptual understanding, spatial ability, and scientific literacy within a single AR-based instructional framework. Unlike prior studies that tend to focus on isolated variables, this research provides empirical evidence of how immersive technologies can simultaneously enhance multiple dimensions of student learning. Additionally, this study highlights the critical role of visualization, interactivity, and immersion as key mechanisms that facilitate meaningful learning in AR environments. However, the effectiveness of AR-based learning is highly dependent on appropriate instructional design and pedagogical integration. Without proper guidance, students may experience cognitive overload or fail to fully benefit from the technology. Therefore, educators must ensure that AR learning activities are carefully structured, aligned with learning objectives, and supported by inquiry-based approaches to maximize their effectiveness. In conclusion, augmented reality-based learning represents an innovative and powerful instructional strategy for advancing science education in the digital era. By bridging the gap between abstract concepts and real-world applications, AR has the potential to transform learning experiences and equip students with essential competencies needed for the challenges of the 21st century.

REFERENCES

- Antonucci-Durgan, D., & Abramovich, S. (2024). Investigating the Relationship between Students' Spatial Ability and Their Assumptions about the Structure and Motion of Matter. *Journal of Chemical Education*, *101*(9), 3656-3665. <https://doi.org/10.1021/acs.jchemed.4c00174>
- Chen, S. Y., & Liu, S. Y. (2026). From argumentation to real-world action: a way to realize scientific literacy. *International Journal of Science Education*, *48*(2), 222-241. <https://doi.org/10.1080/09500693.2024.2415727>
- Coştu, F. (2025). Exploring augmented reality (AR) in science education: Perspectives from gifted students. *The Journal of Educational Research*, *118*(1), 19-36. <https://doi.org/10.1080/00220671.2024.2431681>
- Fitrianto, I., & Saif, A. (2024). The role of virtual reality in enhancing Experiential Learning: a comparative study of traditional and immersive learning environments. *International Journal of Post Axial: Futuristic Teaching and Learning*, 97-110. <https://doi.org/10.59944/postaxial.v2i2.300>
- Hoai, V. T. T., Son, P. N., An, D. T. T., & Anh, N. V. (2024). An investigation into whether applying augmented reality (AR) in teaching chemistry enhances chemical cognitive ability. *International Journal of Learning, Teaching and Educational Research*, *23*(4), 195-216. <https://doi.org/10.26803/ijlter.23.4.11>
- Kapici, H. O., Akcay, H., & de Jong, T. (2022). Using virtual laboratories in science education: A meta-analysis. *Educational Research Review*, *35*, 100418. <https://doi.org/10.1016/j.edurev.2022.100418>
- Kotsis, K. T. (2024). Integrating inquiry-based learning in the new Greek primary science curriculum. *European Journal of Education and Pedagogy*, *5*(6), 63-71. <https://doi.org/10.24018/ejedu.2024.5.6.899>
- Lampropoulos, G., & Kinshuk. (2024). Virtual reality and gamification in education: A systematic review. *Educational Technology Research and Development*, *72*, 1691-1785. <https://doi.org/10.1007/s11423-024-10351-3>
- Makransky, G., Petersen, G. B., & Klingenberg, S. (2021). Immersive virtual reality and learning: A meta-analysis. *Educational Psychology Review*, *33*, 937-958. <https://doi.org/10.1007/s10648-020-09583-6>

- Medina Herrera LM, Juárez Ordóñez S and Ruiz-Loza S (2024). Enhancing mathematical education with spatial visualization tools. *Front. Educ.* 9:1229126. doi: 10.3389/educ.2024.1229126
- Mhlongo, S., Mbatha, K., Ramatsetse, B., & Dlamini, R. (2023). Challenges, opportunities, and prospects of adopting and using smart digital technologies in learning environments: An iterative review. *Heliyon*, 9(6). <https://doi.org/10.1016/j.heliyon.2023.e16348>
- Organisation for Economic Co-operation and Development. (2023). *PISA 2022 results: Learning outcomes and scientific literacy*. OECD Publishing. <https://doi.org/10.1787/pisa-2022>
- Parisu, C. Z. L., Aspin, A., & Suleman, A. (2025). Augmented reality-based stem learning to enhance elementary school students' higher-order thinking skills. *Jurnal Konseling dan Pendidikan*, 13(4), 271-288. <https://doi.org/10.29210/1184100>
- Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education. *Computers & Education*, 147, 103778. <https://doi.org/10.1016/j.compedu.2019.103778>
- Rosli, R., & Ishak, N. A. (2024). Integration of virtual labs in science education: A systematic literature review. *Jurnal Pendidikan Sains dan Matematik Malaysia*, 14(1), 81–103.
- Ruiz-Navas, S., Ackaradejraungsri, P., & Dijk, S. (2024). Gamification to foster inclusive teaching: A scoping review. *Frontiers in Education*, 9, 1306298. <https://doi.org/10.3389/educ.2024.1306298>
- Siregar, R. S. (2024). Students' Preferences for Varied Learning Methods: An Empirical Study of the Effectiveness and Appeal of Diverse Instructional Approaches. *Jurnal Profesi Guru Indonesia*, 1(2), 140–152. <https://doi.org/10.62945/jpgi.v1i2.679>
- Tene, T., Guevara, M., Moreano, G., Vera, J., & Gomez, C. V. (2024). The role of immersive virtual realities: Enhancing science learning in higher education. *Emerging science journal*, 8, 88-102. <http://dx.doi.org/10.28991/ESJ-2024-SIED1-06>