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The Role of Augmented Reality (AR) in Enhancing Conceptual Understanding of Geometry in Mathematics Education: Systematic Review

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Abstract

Geometry, a fundamental branch of mathematics, often challenges students due to its abstract nature and the demands it places on spatial reasoning and visualization, and traditional teaching methods frequently fail to convey complex geometric concepts effectively, leading to low engagement and poor understanding. This systematic review investigates the impact of Augmented Reality (AR) on enhancing students' conceptual understanding of geometry in mathematics education by synthesizing existing empirical studies on AR-based geometry instruction. AR technology provides interactive, immersive learning environments that enable learners to manipulate three-dimensional geometric shapes and transformations in real time, thereby supporting deeper cognitive engagement with abstract content. The reviewed studies consistently report that AR interventions enhance spatial reasoning, improve visualization abilities, and foster deeper conceptual understanding of geometric ideas, while also increasing student motivation, engagement, and retention and supporting the development of critical problem-solving skills. At the same time, the review identifies key implementation challenges, including the high cost and limited availability of AR tools, as well as the need for targeted teacher training to design and facilitate AR-enhanced lessons. The review concludes that AR holds strong potential as a pedagogical innovation for geometry education, provided that infrastructural, financial, and professional development barriers are addressed, and recommends future research focusing on longitudinal designs, more affordable AR solutions, and the integration of AR into advanced geometric topics and diverse educational contexts.

Keywords: Augmented Reality; Geometry Education; Spatial Reasoning; Student Engagement; Mathematics Education.

Introduction

Geometry is a foundational subject in mathematics education, often serving as a key indicator of a student's overall mathematical ability and success in higher-level mathematical concepts. Despite its importance, many students struggle with grasping the abstract and spatial nature of geometry. Challenges such as visualizing complex geometric shapes, understanding spatial relationships, and applying geometric principles to real-world problems are common obstacles faced by learners at various levels. These difficulties are particularly pronounced in topics like solid geometry, transformations, and the intricacies of plane geometry. Traditional methods of teaching geometry, which often rely on two-dimensional diagrams, static textbooks, and passive learning environments, tend to exacerbate these challenges, leaving students with inadequate conceptual understanding and limited spatial reasoning skills (Nadzri et al., 2023; Ruslau et al., 2025). Consequently, students may experience disengagement and low motivation, ultimately leading to poor academic performance in geometry (Herrera et al., 2024).

In recent years, Augmented Reality (AR) has emerged as a potential solution to these challenges, offering an interactive and immersive approach to mathematics instruction. AR involves overlaying digital information—such as three-dimensional models, animations, or data—onto the real world through the use of devices like smartphones, tablets, or AR glasses (Ye & Xu, 2023). This integration of digital content into the physical environment allows students to engage directly with geometric objects and concepts, providing a dynamic and engaging learning experience that traditional methods cannot match. The ability to manipulate and visualize geometric shapes in real-time through AR has the potential to significantly improve students' understanding of geometric concepts, spatial reasoning abilities, and problem-solving skills (Herrera et al., 2024; Hanggara et al., 2024).

Numerous studies have highlighted the benefits of AR in educational settings, particularly in mathematics and geometry. Research suggests that AR enhances students' ability to visualize abstract geometric shapes and relationships, which are often difficult to comprehend through traditional, static representations (Celayir et al., 2025; Pujiastuti et al., 2024). Furthermore, AR has been shown to increase student engagement and motivation by offering an interactive, "game-like" environment where students can actively manipulate geometric objects and experiment with different configurations (Angraini et al., 2022; Bertrand et al., 2024a). These interactive learning experiences are not only more engaging but also promote deeper conceptual understanding, as they allow students to experiment, explore, and solve problems in real-world contexts (Zekeik et al., 2025).

However, despite the promising results from previous studies, there remains a notable research gap regarding the specific ways in which AR enhances students' conceptual understanding of geometry, particularly across a range of geometric topics. Most existing studies focus on narrow topics such as basic shape recognition or specific geometric transformations, with limited attention given to broader concepts like solid geometry, spatial reasoning, and geometric problem-solving (Naeem & Hanif, 2025; Hanggara et al., 2024). Additionally, there is a lack of studies that synthesize the various ways in which AR can be applied across different geometry topics, making it difficult to draw comprehensive conclusions about its overall effectiveness in improving geometry education.

The current study aims to fill this gap by examining the role of AR in enhancing the conceptual understanding of a wide range of geometric concepts, including both plane and solid geometry, as well as geometric transformations. By exploring the impact of AR on students' spatial reasoning, visualization abilities, and engagement, this research seeks to provide a more comprehensive understanding of how AR can transform geometry education. Given the increasing integration of AR into educational settings, this study is both timely and necessary to inform educators about the potential benefits and challenges of using AR to teach geometry, and to provide insights into the future of mathematics instruction.

Objectives

1. To examine how AR-based interventions influence secondary-school students' conceptual mastery of key geometry topics.

2. To evaluate the effect of AR on students' spatial reasoning, visualization ability, and geometric problem-solving skills.

3. To assess how AR impacts student engagement, motivation, and retention in geometry learning.

Research Questions

1. In what ways does AR use affect students' understanding of geometric concepts compared to traditional methods?

2. Does AR improve spatial reasoning and problem-solving performance in geometry?

3. How does AR influence students' interest, motivation, and sustained engagement when learning geometry?

Conceptual Foundations of Geometry Education and Spatial Reasoning

Geometry is one of the most critical branches of mathematics, laying the groundwork for understanding spatial relationships, shapes, and structures that form the foundation of many fields such as engineering, architecture, and computer graphics. Conceptual understanding in geometry refers to the ability to grasp abstract ideas, recognize patterns, and apply geometric principles to real-world situations. In particular, geometry requires the development of spatial reasoning skills, which involve the ability to visualize, manipulate, and reason about geometric shapes and their relationships in space. However, these skills can be difficult to develop through traditional teaching methods, especially when students are faced with complex three-dimensional shapes and transformations (Nadzri et al., 2023).

Traditional methods of teaching geometry often rely on two-dimensional diagrams, static representations, and verbal descriptions to convey complex geometric concepts. These methods can be limiting, particularly when it comes to teaching more advanced topics, such as solid geometry and geometric transformations, where spatial visualization is essential (Herrera et al., 2024). Without interactive, dynamic tools, students may struggle to mentally manipulate geometric objects, which leads to gaps in their conceptual understanding

(Bertrand et al., 2024b). Consequently, many students struggle with abstract mathematical concepts, particularly in topics that require a solid understanding of spatial relationships, such as transformations, surface area, volume, and three-dimensional geometry (Ye & Xu, 2023).

Studies have consistently shown that spatial reasoning skills are crucial for success in geometry and other areas of mathematics. These skills are necessary for visualizing the relationships between shapes, understanding geometric properties, and solving problems that involve transformations, symmetry, and measurement (Celayir et al., 2025). Spatial reasoning has also been shown to correlate strongly with overall mathematics performance, making it a critical area of focus in geometry education (Koparan et al., 2025). Unfortunately, many students fail to develop these skills due to the limitations of traditional teaching approaches, which often do not provide sufficient opportunities for hands-on interaction or visualization.

Given these challenges, there is a growing interest in using Augmented Reality (AR) as a tool to enhance spatial reasoning and conceptual understanding in geometry education. AR offers an immersive learning environment where students can interact with three-dimensional models of geometric shapes, manipulate these objects, and observe their transformations in real time. By superimposing digital content onto the physical world, AR allows students to visualize and explore geometric concepts that are otherwise difficult to grasp through static diagrams (Tursynkulova & Madiyarov, 2023). The dynamic nature of AR provides students with a tangible experience of abstract geometric concepts, making them more accessible and easier to understand (Pujiastuti et al., 2024). Studies suggest that AR has the potential to enhance students' spatial reasoning by providing a hands-on, interactive approach to learning geometry that traditional methods cannot replicate (Hanggara et al., 2024).

By allowing students to engage with geometric objects in a more interactive and dynamic way, AR helps them visualize complex shapes, transformations, and spatial relationships, which are critical to understanding geometry. AR-based learning tools enable students to manipulate objects in a virtual environment, rotate them, and observe how changes affect their properties, such as area, volume, and angles (Angraini et al., 2022). This interactive learning environment promotes the development of spatial skills, such as mental rotation, which are essential for mastering geometry (Herrera et al., 2024). Furthermore, AR can provide immediate feedback, allowing students to correct mistakes and refine their understanding of geometric concepts in real time (Zekeik et al., 2025).

The integration of AR in geometry education has been shown to improve not only students' spatial reasoning and visualization abilities but also their motivation and engagement. Studies have indicated that students who use AR-based tools report higher levels of interest and enjoyment in learning geometry compared to those who learn through traditional methods (Alkhabra et al., 2023). The interactive nature of AR transforms geometry lessons from passive activities into active learning experiences, which can increase students' investment in the material and make the learning process more engaging and enjoyable (Yazdi, 2025). This increased engagement is crucial, as motivated students are more likely to persist through challenges and develop a deeper understanding of the subject matter (Hidajat, 2023).

In summary, the limitations of traditional geometry instruction highlight the need for more interactive and engaging approaches to teaching spatial reasoning and geometric concepts. AR has the potential to address these challenges by providing students with hands-on, immersive learning experiences that enhance spatial visualization and conceptual understanding. As more research is conducted on AR in education, the technology shows promise for transforming how geometry is taught, making it more accessible, engaging, and effective for students across a range of learning levels.

Augmented Reality in Geometry Education: Enhancing Spatial Reasoning and Visualization

In the context of geometry education, one of the most significant challenges students face is the development of spatial reasoning skills. Spatial reasoning involves the ability to visualize and mentally manipulate objects in three-dimensional space, which is crucial for understanding geometric principles such as transformations, symmetry, and three-dimensional shapes. Traditional methods of teaching geometry, which rely primarily on two-dimensional representations and static diagrams, often fail to provide students with a concrete understanding of spatial relationships. As a result, students may struggle to visualize complex geometric objects and transformations, leading to a shallow conceptual understanding (Hanggara et al., 2024).

The integration of Augmented Reality (AR) into geometry education addresses this challenge by offering interactive, three-dimensional visualizations that allow students to manipulate geometric shapes in real-time. AR technology enables students to view and interact with virtual 3D objects overlaid onto their physical environment, creating a more immersive and engaging learning experience (Angraini et al., 2022). By manipulating geometric shapes in this dynamic, interactive environment, students are able to develop a deeper understanding of spatial relationships, which is essential for mastering geometry (Pujiastuti et al., 2024).

Several studies have highlighted the effectiveness of AR in improving spatial reasoning skills in geometry. For example, studies by Tursynkulova and Madiyarov (2023) found that AR applications designed for teaching geometry enhanced students' ability to visualize and mentally manipulate 3D geometric objects, leading to better performance in spatial reasoning tasks. Similarly, a study by Zekeik et al. (2025) demonstrated that AR-based interventions significantly improved students' understanding of three-dimensional shapes and their transformations, as students could directly interact with virtual representations of these objects.

In addition to improving spatial reasoning, AR has been shown to enhance students' visualization abilities. Visualization is a key component of geometric understanding, particularly when it comes to complex concepts like geometric transformations, symmetry, and the relationships between different geometric objects. AR allows students to visualize geometric transformations, such as rotations, translations, and reflections, by providing dynamic, real-time representations of these transformations (Bertrand et al., 2024b). This interactive experience makes abstract geometric concepts more tangible and easier to grasp, improving students' conceptual understanding and their ability to apply these concepts in problem-solving scenarios (Hidajat, 2023).

Also, the interactive nature of AR promotes active learning, which is crucial for the development of spatial reasoning and visualization skills. In traditional geometry instruction, students often passively observe geometric concepts through static diagrams or verbal explanations. However, AR encourages students to actively engage with geometric objects by manipulating them, exploring their properties, and observing the effects of transformations. This hands-on learning approach fosters a deeper understanding of geometry and provides students with the opportunity to experiment and solve problems in a real-world context (Zekeik et al., 2025). Studies by Hanggara et al. (2024) have shown that when students are actively involved in the learning process, they are more likely to retain information and apply their knowledge effectively.

AR also facilitates the development of higher-order thinking skills, such as critical thinking and problem-solving. By interacting with 3D models of geometric objects and transformations, students are encouraged to analyze geometric problems from different perspectives and consider multiple solutions. This type of active engagement promotes critical thinking, as students are required to evaluate their observations, make inferences, and test their hypotheses (Koparan et al., 2025). Furthermore, the ability to experiment with geometric concepts in a virtual environment allows students to approach problems in creative ways, fostering innovative thinking and problem-solving skills (Angraini et al., 2022).

The benefits of AR in geometry education extend beyond spatial reasoning and visualization to include improvements in student engagement and motivation. Traditional geometry lessons, which often involve rote memorization of formulas and theorems, can be disengaging for students, especially when they struggle to see the real-world applications of the concepts they are learning (Yazdi, 2025). In contrast, AR-based learning tools create a more interactive and enjoyable learning environment, making geometry more accessible and interesting. Research has shown that students who use AR in their geometry lessons report higher levels of motivation, engagement, and interest in the subject (Alkhabra et al., 2023). The gamification elements of many AR applications, such as challenges, rewards, and real-time feedback, make learning geometry more engaging and help students develop a positive attitude toward the subject (Zekeik et al., 2025).

As well, AR-based learning tools provide opportunities for personalized learning. By interacting with AR applications, students can learn at their own pace, revisit concepts they find challenging, and receive immediate feedback on their performance. This adaptability is particularly beneficial in diverse classrooms, where students may have varying levels of prior knowledge and different learning preferences (Ye & Xu, 2023). Personalized learning experiences have been shown to improve students' confidence in their ability to succeed in mathematics, which is crucial for fostering a growth mindset and promoting long-term success (Herrera et al., 2024).

To sum up, the integration of AR into geometry education has the potential to revolutionize how spatial reasoning and geometric concepts are taught. AR provides students with an interactive, hands-on learning experience that enhances their spatial reasoning, visualization abilities, and problem-solving skills. Furthermore, AR improves student engagement and motivation, making geometry more accessible and enjoyable for learners.

As the use of AR continues to expand in educational settings, it is likely that its impact on geometry education will only grow, providing students with the tools they need to develop a deeper understanding of geometric concepts and succeed in mathematics.

Challenges, Limitations, and Future Directions in the Use of AR in Geometry Education

While the integration of Augmented Reality (AR) into geometry education holds immense promise, it is not without its challenges and limitations. The existing literature highlights both the advantages of AR-based learning tools and the difficulties associated with their implementation in the classroom. Understanding these challenges is crucial for educators and researchers to optimize the use of AR in geometry education and ensure its effectiveness in improving student learning outcomes.

One of the primary challenges in implementing AR in geometry education is the cost and accessibility of AR technology. Despite the increasing availability of mobile devices and AR applications, the adoption of AR in classrooms can be costly, especially for schools with limited budgets. High-quality AR tools, such as AR headsets and advanced software, are often expensive and may not be feasible for widespread use in all educational settings (Yazdi, 2025). This cost barrier limits the ability of many schools, particularly those in low-income areas, to take advantage of AR's potential benefits. Additionally, there are disparities in access to technology, with some students lacking the necessary devices (smartphones, tablets) to engage with AR applications effectively (Zekeik et al., 2025).

Beside that, the technical expertise required to integrate AR into the classroom presents another obstacle. Although many AR applications are user-friendly, teachers still need adequate training to use these tools effectively. The successful integration of AR requires teachers to be proficient not only in the technology itself but also in how to align AR activities with curriculum objectives and classroom practices (Hanggara et al., 2024). Without proper training and support, teachers may struggle to use AR effectively, potentially hindering the learning experience. This issue is particularly prevalent in schools where teachers are not well-versed in using digital tools or AR applications in mathematics instruction (Tursynkulova & Madiyarov, 2023).

In addition to these challenges, there are concerns about the long-term effectiveness of AR in geometry education. While short-term studies have shown positive outcomes, such as improved spatial reasoning and motivation, there is a lack of longitudinal research that examines the sustained impact of AR on students' learning over time (Herrera et al., 2024). Most studies focus on immediate post-intervention assessments, which may not capture the lasting effects of AR on students' understanding and retention of geometric concepts. Long-term studies are necessary to determine whether AR leads to durable improvements in spatial reasoning, problem-solving abilities, and overall academic performance in geometry (Bertrand et al., 2024a).

Another limitation of AR-based geometry education is the narrow focus of many AR tools. While AR can be highly effective for visualizing basic geometric concepts such as shapes, angles, and transformations, it may not adequately address more complex topics, such as the relationships between multiple geometric objects or the application of geometry to real-world problems (Zekeik et al., 2025). Some AR applications are limited to visualizing static geometric objects or basic transformations, which can restrict students' ability to engage with more advanced topics, such as 3D geometry, geometric proofs, and higher-order problem-solving tasks. Future AR tools should aim to cover a broader range of geometric topics and provide more complex, interactive learning experiences that challenge students to apply geometric concepts in varied contexts (Pujiastuti et al., 2024).

Not to mention, classroom integration of AR requires careful consideration of pedagogical practices. While AR offers a dynamic, interactive learning environment, it must be integrated thoughtfully into the curriculum to maximize its educational potential. Research has shown that simply introducing AR tools into the classroom is not enough to guarantee improved learning outcomes. Instead, AR must be used as part of a well-designed instructional strategy that aligns with students' learning goals, provides opportunities for collaboration, and encourages active problem-solving (Hidajat, 2023). Additionally, AR should be complemented by other teaching methods and tools to create a balanced, multifaceted learning environment that supports various learning styles and abilities (Hanggara et al., 2024).

also, pedagogical concerns regarding AR's role in geometry education must be addressed. Some educators argue that the overuse of AR in the classroom may lead to a reliance on technology, potentially diminishing students' ability to solve problems independently or develop mental models of geometric concepts without external assistance (Alkhabra et al., 2023). There is also the concern that AR-based learning could exacerbate existing inequalities in education, as students who do not have access to AR devices or applications may be left behind. Ensuring equitable access to AR technology and integrating AR into a diverse range of learning contexts are crucial considerations for its effective implementation (Angraini et al., 2022).

Despite these challenges, the future of AR in geometry education remains promising. As AR technology continues to evolve, it is expected that new tools and applications will address many of the current limitations. For example, the development of more affordable AR devices, greater integration with existing educational platforms, and the introduction of more sophisticated AR applications could make AR more accessible and effective for all students. Additionally, ongoing research is likely to provide valuable insights into the long-term effects of AR on learning outcomes and will help refine pedagogical practices to better integrate AR into geometry instruction (Yazdi, 2025).

Tosum up, while AR has shown significant promise in enhancing spatial reasoning, visualization, and student engagement in geometry education, several challenges remain. These challenges include the cost and accessibility of AR tools, the need for teacher training, limited longitudinal research, and the narrow focus of many AR applications. Addressing these issues will be crucial for maximizing the potential of AR in geometry education and ensuring that it is integrated effectively into classrooms worldwide. Moving forward, it is important for researchers, educators, and policymakers to collaborate to overcome these challenges and continue to explore the transformative potential of AR in geometry education.

Objective 1: To examine how AR-based interventions influence secondary-school students' conceptual mastery of key geometry topics.

(RQ1): *How does AR impact students' understanding of geometric concepts in comparison to traditional teaching methods?*

Table 1: ***Key Benefits of Augmented Reality (AR) in Geometry Education***

Author(s)	Year	Benefits Identified	Geometric Topics Focused	Methodology
Celayir et al.	2025	Improved spatial reasoning, better visualization of 3D shapes	Spatial reasoning, 3D geometry	Literature Review, Model Evaluation
Pujiastuti et al.	2024	Enhanced conceptual understanding, interactive learning	Geometry transformations	AR-based intervention

Author(s)	Year	Benefits Identified	Geometric Topics Focused	Methodology
Celayir et al.	2025	Improved spatial reasoning, better visualization of 3D shapes	Spatial reasoning, 3D geometry	Literature Review, Model Evaluation
Hanggara et al.	2024	Increased student engagement and motivation, better problem-solving skills	3D geometry, transformations	Experimental Study

Interpretation:

This table summarizes the key benefits of AR in geometry education. The studies presented highlight the positive impact of AR on spatial reasoning, visualization, and student engagement. The findings support the claim that AR tools enhance conceptual understanding by providing interactive learning experiences that make abstract concepts more tangible. Celayir et al. (2025) and Pujiastuti et al. (2024) note that AR enables students to better visualize complex 3D shapes and understand geometric transformations. Moreover, Hanggara et al. (2024) highlight that AR fosters increased motivation and problem-solving skills, which are critical in geometry learning. These benefits directly address the first research question (RQ1), exploring how AR improves students' understanding of geometric concepts.

Objective 2: To evaluate the effect of AR on students' spatial reasoning, visualization ability, and geometric problem-solving skills.

(RQ2): *In what ways does AR improve spatial reasoning, mental rotation, and geometric problem-solving in students?*

Table 2: ***Challenges in Implementing AR in Geometry Education***

Author(s)	Year	Challenges Identified	Geometric Topics Affected	Impact on Teaching
Tursynkulova & Madiyarov	2023	High costs of AR technology, limited access in low-income schools	Solid geometry, transformations	Limited classroom integration
Yazdi	2025	Lack of long-term studies, narrow focus of AR tools	3D transformations, problem-solving	Limited sustained impact
Hanggara et al.	2024	Technical expertise needed for effective integration	General geometry, spatial visualization	Need for teacher training

Interpretation:

Table 2 outlines several challenges in the implementation of AR in geometry education. Tursynkulova & Madiyarov (2023) identify high costs and limited access as significant barriers, which can restrict the widespread use of AR tools, particularly in schools with fewer resources. Yazdi (2025) emphasizes the lack of long-term research and the narrow focus of most AR tools, which may not address the full spectrum of geometry topics. This limitation is significant for sustained impact, as AR's benefits may diminish without long-term engagement. Hanggara et al. (2024) underscore the need for teacher training to effectively integrate AR into the classroom. These challenges directly relate to RQ2, exploring the effectiveness of AR in improving spatial reasoning and problem-solving in geometry, as well as how AR tools can be better integrated into teaching practices.

Objective 2: To evaluate the effect of AR on students' spatial reasoning, visualization ability, and geometric problem-solving skills.

(RQ2): *In what ways does AR improve spatial reasoning, mental rotation, and geometric problem-solving in students?*

Table 3*: Effectiveness of AR in Enhancing Spatial Reasoning and Visualization Skills*

Author(s)	Year	Spatial Reasoning Skills Enhanced	Methodology Used	Results
Zekeik et al.	2025	Mental rotation, shape manipulation	Mobile AR app evaluation	Significant improvement in mental rotation and problem-solving skills
Herrera et al.	2024	Visualization of transformations, geometric properties	AR-based interactive tools	Positive impact on spatial visualization and conceptual understanding
Angraini et al.	2022	Critical thinking, creative problem-solving	AR-based learning games	Enhanced problem-solving through active learning

Interpretation:

This table provides strong evidence on the effectiveness of AR in enhancing spatial reasoning and visualization skills, which are critical in geometry education. Zekeik et al. (2025) found that using AR apps significantly improved students' mental rotation skills and their ability to manipulate geometric shapes, essential for visualizing 3D geometry. Similarly, Herrera et al.

(2024) report that AR-based interactive tools have a positive impact on students' spatial visualization abilities, helping them better understand transformations and geometric properties. Angraini et al. (2022) further highlight that AR supports the development of critical thinking and problem-solving skills through active learning. These findings directly address RQ2, demonstrating how AR improves spatial reasoning and problem-solving in geometry learning.

Objective 3: To assess how AR impacts student engagement, motivation, and retention in geometry learning.

(RQ3): *How does the use of AR technology in geometry classrooms affect student motivation, engagement, and retention of learned concepts?*

Table 4*: Pedagogical Implications of AR in Geometry Education*

Author(s)	Year	Pedagogical Strategies Suggested	Geometric Topics	Implications for Instruction
Alkhabra et al.	2023	Active learning, integration of AR with traditional methods	Geometry transformations, surface area	Encourage collaborative learning alongside AR tools
Hanggara et al.	2024	Align AR tools with curriculum goals, promote problem-solving	3D geometry, transformations	AR should complement traditional methods, not replace them
Bertrand et al.	2024	Gamification of learning experiences	All geometry topics	AR can create a more engaging, game-like learning environment

Interpretation:

This table addresses the pedagogical implications of using AR in geometry classrooms. Alkhabra et al. (2023) suggest integrating AR with traditional teaching methods to encourage collaborative learning and deepen students' understanding of geometry. Hanggara et al. (2024) emphasize that AR tools should be aligned with curriculum goals and should complement traditional methods rather than replace them, ensuring a balanced approach to geometry instruction. Bertrand et al. (2024) argue that gamification of AR learning experiences can make geometry more engaging, thus improving students' overall interest and performance. These findings provide guidance on how AR can be used effectively in the classroom, directly contributing to RQ3, which investigates the impact of AR on student motivation and engagement.

Discussion

The integration of Augmented Reality (AR) in geometry education offers a transformative approach to addressing the challenges students face in understanding abstract geometric concepts. This study, based on a comprehensive literature review, found consistent evidence across various studies supporting the effectiveness of AR in improving spatial reasoning, visualization skills, and student engagement in geometry learning. AR's ability to enhance spatial reasoning through interactive visualizations was a recurring theme in the literature. For example, Pujiastuti et al. (2024) and Hanggara et al. (2024) noted that AR allowed students to manipulate three-dimensional shapes and observe transformations in real-time, fostering a deeper understanding of geometric principles. This hands-on interaction is critical in geometry, where traditional methods often fail to engage students with the dynamic and abstract nature of geometric relationships. The findings confirm that AR tools can help bridge the gap between abstract geometric concepts and students' understanding by making these concepts more tangible and interactive.

Beside that, the study emphasized the positive impact of AR on student engagement and motivation. As highlighted by Zekeik et al. (2025) and Celayir et al. (2025), students who used AR-based learning tools reported greater interest in the subject and were more likely to persist through challenges compared to those who relied solely on traditional teaching methods. Gamified learning experiences, facilitated by AR, seem to significantly boost students' enthusiasm for learning, transforming geometry from a traditionally dry and challenging subject into an engaging and dynamic learning experience. This engagement is crucial for fostering a positive attitude towards mathematics and building the confidence needed to tackle complex geometric problems.

However, the study also uncovered several challenges and barriers to the widespread implementation of AR in geometry education. One of the most significant obstacles identified in the literature is the cost of AR tools and devices. As noted by Tursynkulova & Madiyarov (2023) and Yazdi (2025), high-quality AR applications and devices can be expensive, limiting access in schools with limited resources. This technological divide could exacerbate existing inequities in education, particularly in low-income areas where AR tools may not be readily available. Additionally, the technical expertise required for effective integration of AR in classrooms was highlighted by Hanggara et al. (2024), who pointed out that without proper training, teachers may struggle to utilize AR effectively, thereby reducing its impact on student learning. This finding aligns with the notion that teacher preparedness is critical in ensuring that AR is used effectively to enhance geometric learning.

Another critical limitation identified in the literature is the narrow scope of many AR tools. While AR has been shown to be highly effective in visualizing basic geometric concepts, such as 3D shapes and transformations, there is a lack of AR tools designed for more complex geometric topics such as geometric proofs and advanced problem-solving. Yazdi (2025) argued that AR's focus on elementary geometric tasks may limit its utility in helping students understand higher-order mathematical thinking, which is essential for advanced learners and university-bound students. This suggests the need for more comprehensive AR applications that can support a wider range of geometry topics.

Despite these challenges, the findings from this study indicate a significant potential for AR in enhancing geometry education. The literature reveals that when AR tools are integrated effectively into the classroom, they can significantly improve students' spatial reasoning, visualization abilities, and problem-solving skills. This is particularly important because geometry is often seen as one of the most challenging areas of mathematics, requiring abstract thinking and spatial visualization, both of which can be difficult to develop through traditional teaching methods.

What is more, AR's ability to offer real-time feedback and allow students to manipulate geometric shapes as part of a dynamic learning experience presents an exciting opportunity to foster active learning. Active learning, where students engage directly with the material through hands-on experiences, is shown to deepen conceptual understanding and long-term retention of geometric principles. The interactive nature of AR, as highlighted in the studies reviewed, encourages problem-solving and critical thinking, skills that are crucial for students not only in geometry but in many other areas of mathematics and beyond.

Conclusion

This study underscores the transformative potential of Augmented Reality in geometry education. AR provides a dynamic and interactive platform for improving students' spatial reasoning, problem-solving skills, and motivation. However, the implementation challenges, such as cost and teacher preparedness, must be addressed for its successful integration into geometry classrooms. Further research, especially longitudinal studies, is needed to explore the long-term impact of AR on students' learning outcomes and to develop more inclusive, affordable solutions for schools. The findings of this study offer valuable insights for educators, researchers, and policymakers seeking to enhance geometry education through technology.

Recommendations for Future Research

1. Longitudinal Studies: Future research should focus on long-term studies that track students' progress in geometry over an extended period. This will provide a clearer picture of how AR influences learning outcomes over time and its sustained impact on spatial reasoning and conceptual understanding.

2. Wider Range of Geometric Topics: Current AR tools focus on basic geometry concepts, such as 3D shapes and transformations. Future research should explore how AR can be applied to more advanced geometry topics, such as geometric proofs, higher-dimensional spaces, and geometric modeling.

3. Teacher Training and Professional Development: As highlighted in this study, effective teacher training is essential for successful AR implementation. Future research should explore best practices for training teachers to effectively use AR in the classroom and integrate it with the existing curriculum.

4. Cost-Effective Solutions: Given the cost barriers identified, future research should investigate ways to make AR tools more affordable and accessible to schools with limited budgets, perhaps through low-cost AR apps or web-based platforms.

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