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Review Article

From Chalkboards to Cyberspace: The Role of Augmented and Virtual Reality in Transforming Mathematics Education

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Abstract
The integration of immersive technologies, such as Augmented Reality (AR) and Virtual Reality (VR), is reshaping educational landscapes, particularly in mathematics instruction. These tools provide dynamic visualizations and interactive simulations that bridge the gap between abstract theories and experiential learning. This narrative review explores the evolving role of AR and VR in mathematics education, emphasizing their application in understanding three-dimensional (3D) geometric concepts. The review seeks to address two main questions: (a) How are AR and VR technologies applied in the teaching of mathematics? (b) To what extent do immersive learning environments enhance students' understanding and achievement in 3D geometry? Recent research indicates that AR and VR contribute to improved conceptual understanding, increased engagement, and enhanced spatial visualization by enabling learners to interact with mathematical objects in realistic and immersive settings. These technologies promote active learning and the development of higher-order thinking skills, while motivating students through experiential engagement. The review finds that AR and VR possess significant transformative potential for mathematics education, offering innovative pathways for conceptual growth and cognitive involvement. To fully realize this potential, future research should prioritize scalable implementation strategies, comprehensive teacher training, and an assessment of the long-term pedagogical impact of immersive technologies within classroom settings.

Keywords: Augmented Reality, Virtual Reality, Mathematics Education, Immersive Learning, Spatial Visualization, 3D Geometry

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1. INTRODUCTION

Education in the 21st century is shifting from traditional instruction to immersive, technology-driven environments. Augmented Reality (AR) and Virtual Reality (VR) are key innovations that enhance learning by blending physical and digital dimensions. These technologies particularly benefit mathematics education, making abstract concepts like geometry more tangible and intuitive. Students often struggle to visualize three-dimensional (3D) structures from two-dimensional (2D) textbooks, leading to misconceptions and poor retention (Chen & Yang, 2019). AR allows real-time interaction with 3D objects in real-world settings, while VR immerses students in simulated environments to explore and manipulate mathematical concepts (Medina Herrera et al., 2019).

Both AR and VR extend beyond simple visualization; they encourage exploration, creativity, and multisensory engagement. These technologies align with constructivist principles by promoting active meaning-making through interactive experiences rather than passive observation. This narrative review explores how AR and VR technologies are transforming the teaching and learning of mathematics, particularly in the visualization and comprehension of three-dimensional geometric solids such as cubes, cones, cylinders, pyramids, and spheres. The landscape of education in the 21st century is rapidly evolving from traditional text-based instruction to immersive, technology-driven learning environments. Among the most revolutionary innovations are AR and VR, which blend the physical and digital realms to create interactive, experiential learning experiences. Mathematics, often perceived as abstract and challenging, stands to gain immensely from these immersive technologies. With AR and VR, mathematical concepts, especially those related to geometry and spatial reasoning, become tangible, manipulable, and visually intuitive (del Cerro Velázquez & Morales Méndez, 2021).

Mathematics education has long emphasized spatial reasoning and geometric understanding as core components of cognitive development. However, many learners struggle to visualise 3D structures presented in 2D textbooks (Chen & Yang, 2019). This cognitive gap often leads to misconceptions and limited retention of knowledge. AR overlays digital information onto real-world settings, allowing learners to interact with 3D objects in real time. In contrast, VR immerses students entirely within a simulated environment, enabling them to manipulate and explore mathematical entities in a virtual space (Arvanitis et al., 2009). Both AR and VR extend beyond visualisation, fostering exploration, creativity, and multisensory engagement. They align with constructivist principles by encouraging students to actively construct meaning through interactions rather than passive observation. Therefore, this narrative review explores how AR and VR technologies transform the teaching and learning of mathematics, particularly in visualizing and comprehending 3D geometric solids such as cubes, cones, cylinders, pyramids, and spheres.

1.1. Research Questions

This review addresses the following research questions:

RQ1. How are Augmented Reality and Virtual Reality applied in the teaching and learning of mathematics?
RQ2. To what extent do immersive AR and VR learning environments enhance students' achievement and understanding of 3D geometric shapes?

1.2. Review of Literature

1.2.1 Immersive Technologies in Education

Immersive technologies such as AR and VR effectively connect digital and real-world experiences, transforming passive learning into active exploration. AR adds virtual elements to the physical environment, while VR completely immerses users in a simulated world (Asif et al., 2024). Both technologies share three key features: interactivity, 3D visualization, and real-time engagement, which make them powerful tools for education. Recent research has highlighted their benefits across various fields, including science (Altmeyer et al., 2020; Akçayır & Akçayır, 2017), biology (Chang et al., 2016), mathematics education (Ahmad & Junaini, 2020; Hidajat, 2024), and engineering (Fidan & Tuncel, 2019). These studies suggest that immersive learning environments significantly enhance student motivation, comprehension, and retention compared to traditional teaching methods (Di Serio et al., 2013; Zhang et al., 2022). While VR completely submerges students in computer-generated simulations, AR incorporates virtual elements into the physical world. Key features that improve student involvement and conceptual understanding are shared by both technologies, including interaction, three-dimensional visualization, and real-time engagement (Reilly & Dede, 2019; Makransky & Petersen, 2021). Recent systematic reviews and meta-analyses further confirm that immersive learning environments promote learning experience, autonomy of learning, and higher-order thinking skills when supported by sound pedagogical design (López-Belmonte et al., 2023; Parong & Mayer, 2021; Radianti et al., 2020).

1.2.2. Augmented and Virtual Reality in Mathematics Education

Mathematics, often considered abstract, can be learned through Augmented Reality and Virtual Reality technologies. AR enables learners to visualise equations, graphs, and shapes overlaid on real-world contexts, while VR offers fully manipulable 3D environments for problem solving and exploration (Radu, 2014; Ibáñez & Delgado-Kloos, 2018; Wu et al., 2013). Salinas et al. (2013) demonstrated that interventions utilizing AR make abstract mathematical relationships more visible and accessible to young learners. Bujak et al. (2013) further observed that integrating immersive 3D visualizations with cognitive learning principles enhances both conceptual understanding and retention. In VR-based classrooms, students can "enter" geometric models, manipulate solids, measure volumes, and experiment with dimensions within a simulated environment (Sommerauer & Müller, 2014). These interactive experiences transform traditional problem-solving into inquiry-based learning (Chen & Tsai, 2012; Chen, 2020; Yu et al., 2019). According to a meta-analysis by Garzón et al. (2023), AR and VR have a moderate to substantial favorable impact on students' arithmetic achievement, especially in subjects that call on spatial thinking and visualization. These results imply that interactive, learner-centered experiences can be achieved through the use of immersive technologies in place of traditional, procedure-oriented mathematics training.

1.2.3. Immersive Learning in Geometry and Spatial Visualization

Geometry education greatly benefits from the use of AR and virtual reality VR, which enhance spatial reasoning skills (Walkington et al., 2025). Cahyono et al. (2018) demonstrated that AR significantly improves students' ability to visualize and interpret geometric structures. Meanwhile, Yixuan and Qiang (2021) highlighted the role of VR in deepening spatial understanding through immersive 3D experiences. In elementary education, tools like Gem AR (Husniah et al., 2020) and VR Geometry Labs (Rossano et al., 2020) have been shown to increase motivation and academic achievement. Sun and Chen (2019) noted that AR-assisted geometry instruction improved students' understanding of volumetric measurements in compound shapes. Collectively, these findings confirm that immersive technologies promote both engagement and cognitive development in mathematics education (Bertrand et al., 2024; Yang et al., 2025). AR-assisted geometry tools have been shown to improve student motivation, engagement, and academic performance in educational settings (Klingenberg et al., 2020; Wu & Chiang, 2023). When immersive technologies were incorporated into geometry training, Sun and Chen (2019) and Bower et al. (2020) also noted enhanced comprehension of volumetric measurement and three-dimensional thinking.

2. METHODOLOGY

This study adopted a narrative review methodology to examine and synthesise scholarly literature on the use of AR and VR in mathematics education. Narrative reviews are particularly appropriate for emerging and interdisciplinary research areas, as they allow flexibility in integrating diverse theoretical perspectives, empirical findings, and educational practices while identifying conceptual trends and research gaps. The review focused on studies published between 2010 and 2024. The year 2010 was selected as the starting point because it marks a period when AR and VR technologies became increasingly viable for educational use, driven by advancements in mobile devices, graphics processing, and affordable immersive hardware. Furthermore, systematic and classroom-based research on AR and VR in mathematics education began to emerge more consistently after 2010. The selected time frame, therefore, captures both early adoption and recent pedagogical developments in immersive technologies in mathematics teaching.

2.1. Search Strategy

The literature search was conducted between January 2024 and June 2024 using multiple academic databases to ensure comprehensive coverage. The databases included ERIC, IEEE Xplore, and Google Scholar. These databases were selected for their relevance to education, technology-enhanced learning, and immersive technologies. The search employed keywords, including: ("augmented reality" OR "virtual reality" OR "immersive technology") AND ("mathematics education" OR "geometry learning" OR "spatial visualisation").

2.2. Inclusion and Exclusion Criteria

To ensure relevance and quality, clear inclusion and exclusion criteria were applied. Studies were included if they:

2.2.1. Inclusion Criteria

Studies were included in the review if they:

- Consisted of peer-reviewed journal articles or selected conference proceedings
- Published in the English language
- Focused on AR and/ or VR applications within mathematics education
- Presented empirical evidence (quantitative, qualitative, or mixed-methods) or provided comprehensive reviews related to immersive learning technologies

2.2.2. Exclusion Criteria

Studies were excluded from the review if they:

- Included opinion pieces, editorials, conceptual papers, or non-academic reports
- Addressed subject areas other than mathematics
- Lacked a focus on immersive AR or VR technologies
- Did not provide full-text access or sufficient methodological detail for critical evaluation

2.3. Study Selection and Data Analysis

The initial database search yielded a substantial number of records, which were first screened by title and abstract to remove duplicates and irrelevant studies. The remaining articles underwent full-text screening to ensure alignment with the inclusion criteria. The final set of studies underwent thematic synthesis, focusing on recurring themes related to educational benefits, learning outcomes, challenges, and best practices in integrating AR and VR into mathematics education. Rather than aiming for exhaustive coverage, the narrative synthesis emphasized conceptual patterns, pedagogical implications, and emerging trends, enabling a holistic understanding of how immersive technologies contribute to the teaching and learning of mathematics, particularly in the context of three-dimensional geometry.

3. RESULTS AND DISCUSSION

3.1. Application of AR and VR in Teaching Mathematics

Immersive technologies are increasingly being used to enhance visualization, interaction, and engagement in mathematics classrooms. AR allows students to explore geometric structures overlaid on physical objects using tablets or smartphones. VR, on the other hand, immerses students in a virtual environment where they can examine mathematical constructs from different angles.

AR and VR have emerged as powerful tools in mathematics education, transforming traditionally abstract concepts into visual, interactive, and meaningful learning experiences. Instead of relying on flat textbook diagrams or merely imagining shapes, students can use AR and VR to manipulate three-dimensional objects, rotate geometric solids, resize shapes, and even dissect them to reveal hidden components. This hands-on, immersive exploration makes complex ideas such as volume, surface area, and spatial relationships much more intuitive and comprehensible. Research by Sommerauer and Müller (2014) and Di Serio et al. (2013) indicates that these immersive technologies significantly enhance student engagement and motivation. They capture attention, stimulate curiosity, and foster excitement about learning tasks. When learners feel "present" in the virtual environment, they tend to be more focused and emotionally invested in their activities. In addition to boosting motivation, AR and VR offer unique opportunities for collaborative learning. Students can enter shared virtual spaces, interact with the same digital models, discuss strategies in real time, and collectively solve problems. This shared immersion promotes communication, teamwork, and peer-supported knowledge building, which are essential for deeper and more meaningful conceptual development. Furthermore, these technologies encourage strong cognitive integration by helping learners connect new information with their existing knowledge base. As emphasized by Bujak et al. (2013), AR and VR align well with cognitive learning theory by presenting information in multiple modalities: visual, spatial, and experiential, allowing students to construct more robust mental models. Overall, AR and VR enhance the learning environment by making abstract ideas concrete, increasing student involvement, supporting peer collaboration, and promoting cognitive processes essential to long-term understanding and knowledge transfer.

3.2. Enhancing Understanding of 3D Geometry

In teaching 3D geometric shapes, AR and VR demonstrate strong potential for improving spatial reasoning and visualization skills. Learners can manipulate solids, explore hidden surfaces, and intuitively understand volumetric relationships.

AR and VR have proven to be highly effective in enhancing students' comprehension of three-dimensional geometric concepts. Research indicates that geometry learning through AR significantly improves spatial reasoning skills; for instance, Cahyono et al. (2018) reported remarkable advancements in students' abilities to visualize and manipulate spatial forms. Additionally, VR environments further enhance understanding by enabling learners to interact with complex shapes, thereby making abstract geometric relationships more tangible and accessible. Practical measurement skills also see improvement, as Sun and Chen (2019) found that AR applications allow students to explore volumetric properties through real-time, hands-on engagement. Furthermore, incorporating immersive technologies into geometry lessons fosters higher academic performance and motivation; Rossano et al. (2020) and Husniah et al. (2020) observed increased engagement and achievement among learners exposed to AR/VR-based instructional methodologies. In summary, AR and VR serve as powerful tools for teaching three-dimensional geometric shapes by facilitating learners' investigations of solids, examinations of hidden surfaces, and intuitive understanding of volumetric relationships.

3.3. Challenges and Limitations

The current findings emphasize that AR and VR technologies offer significant educational benefits for teaching 3D geometry. These technologies enhance learners' spatial reasoning, improve their visualization of abstract relationships, and deepen their understanding of volumetric measurement. Previous research by Cahyono et al. (2018) and Sun and Chen (2019) has shown that immersive environments enable students to manipulate geometric solids, explore multiple viewpoints, and engage with abstract forms in ways that traditional instruction cannot match. This has resulted in increased motivation and academic performance in classrooms that utilize AR/VR technology (Husniah et al., 2020; Rossano et al., 2020)

However, it is important to recognize the implementation challenges that may limit the effectiveness of these technologies. Research indicates that access to technology is not uniform across educational settings. Many schools lack the devices, updated systems, and stable internet connections necessary to support high-quality AR/VR experiences (Rahman & Salam, 2020). The high costs associated with purchasing and maintaining immersive tools also create barriers, particularly in resource-constrained environments (Zhao et al., 2019). Furthermore, the successful integration of AR and VR heavily relies on teachers' competence and confidence; inadequate training can result in either underutilization of the technology or ineffective classroom implementation (Huang & Liaw, 2018). Infrastructure limitations, such as insufficient bandwidth, outdated hardware, or inadequate technical support, can also disrupt the learning process, reducing the positive impact of these technologies (Kamarainen et al., 2020).

Another critical concern is the cognitive load on learners. As Makransky and Petersen (2021) highlight, immersive environments can overwhelm students if the interface is not user-friendly or if there are excessive visual stimuli that distract from core mathematical concepts. Poorly designed AR/VR content may lead students to focus more on navigating the technology than on understanding geometric principles. In conclusion, while the findings illustrate the transformative potential of AR and VR in education, they also stress the need for careful pedagogical integration. Effective implementation demands thoughtful instructional design, simplified user interfaces, continuous teacher training, and sustained investment in technological infrastructure. By addressing these challenges, schools can utilise AR and VR not just as visualisation tools but as meaningful components of geometry education that foster deep conceptual understanding.

4. CONCLUSION AND RECOMMENDATIONS

Immersive technologies, such as AR and VR, are revolutionising mathematics education by merging conceptual learning with experiential exploration. Through interactive 3D simulations, students can visualize mathematical relationships and engage in active inquiry, collaboration, and problem-solving. This narrative review underscores that AR and VR significantly enhance spatial reasoning, conceptual understanding, and motivation in learning 3D geometry. However, successful integration requires systemic support, including teacher training, curriculum alignment, and equitable access to devices. Future research should explore the long-term impacts, scalable implementation models, and pedagogical frameworks for immersive learning. As education transitions "from chalkboards to cyberspace," AR and VR stand at the forefront of creating transformative, inclusive, and deeply engaging mathematical experiences for learners to explore.

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