

THE NEXUS OF DIGITAL AND COGNITIVE SPACE: A SYSTEMATIC REVIEW OF AUGMENTED REALITY'S ROLE IN FOSTERING SPATIAL ABILITY IN MATHEMATICS EDUCATION

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Abstract

Spatial ability is a critical cognitive predictor of success in Science, Technology, Engineering, and Mathematics (STEM) fields, yet its development is often neglected in traditional mathematics curricula. This systematic literature review synthesizes and analyzes the empirical research on the use of Augmented Reality (AR) as a pedagogical intervention to enhance spatial ability in mathematics education. Following a rigorous search and screening protocol across the Dimensions, Scopus, and Semantic Scholar databases, this review examines the core findings from the resulting corpus of primary research articles. The analysis is structured around four key themes: the pedagogical approaches underpinning AR interventions, the influence of different AR technology modalities, the measured impact on learning outcomes, and the persistent challenges and future research directions. The findings reveal that AR is most effectively leveraged through constructivist, game-based, and collaborative learning frameworks, which transform abstract mathematical concepts into tangible, interactive experiences. The review delineates a "pedagogy-technology fit," where the choice between accessible handheld devices and immersive Head-Mounted Displays (HMDs), or between marker-based and markerless tracking, is strategically aligned with specific learning objectives. Empirical evidence consistently demonstrates that AR interventions yield significant cognitive gains in spatial skills, as measured by standardized psychometric tests, and foster positive affective outcomes, including increased student motivation, engagement, and interest in mathematics. However, the field faces significant challenges related to teacher training, scalability, and the need for more robust, longitudinal research methodologies. This review concludes that the research landscape is at a critical inflection point, moving beyond establishing efficacy to addressing the complexities of implementation science. Realizing the full potential of AR to reshape spatial education requires a concerted focus on developing scalable pedagogical models, effective teacher support systems, and standardized evaluation frameworks to guide its sustainable integration into diverse learning contexts.

Keywords: *Augmented Reality, Spatial Ability, Mathematics Education, Educational Technology, Systematic Review.*

INTRODUCTION

Spatial ability, the capacity to generate, retain, retrieve, and transform well-structured visual images, stands as a cornerstone of cognitive function essential for navigating the modern world. Its significance, however, extends far beyond everyday tasks, representing a key determinant of success in the domains of Science, Technology, Engineering, and Mathematics (STEM). A substantial body of research has established a robust correlation between high levels of spatial ability and both the propensity to enter STEM careers and the subsequent achievement within them (Wai, Lubinski, & Benbow, 2009). This cognitive faculty is not an ancillary skill but is deeply interwoven with the core competencies required for mathematical thinking; it is fundamental to solving complex word problems, developing conceptual understanding in geometry and calculus, and visualizing abstract data structures (Newcombe, 2010). Individuals who gravitate toward and excel in fields like physical science, engineering, and advanced mathematics consistently demonstrate superior spatial skills (Lakin & Wai, 2020). This evidence positions spatial ability as a critical "gateway skill," where proficiency can unlock pathways to advanced technical and scientific pursuits, while deficits can form a significant barrier to entry and persistence in these demanding and vital fields (Uttal & Cohen, 2012).

Despite the established importance of spatial reasoning, its cultivation remains a persistent and significant challenge within formal education systems. Traditional mathematics curricula, particularly in the early years, have historically prioritized numeracy and symbolic manipulation, often to the detriment of spatial learning (Ramey, L-S, & Jaeggi, 2020). This curricular oversight means that spatial reasoning is frequently underemphasized or relegated to a small subset of geometry topics, leaving many students ill-equipped to handle the spatial demands of higher-level STEM subjects (Bruce et al., 2015). Students often encounter profound difficulties with tasks that require multi-step spatial reasoning, the comprehension and use of precise spatial language, and, most notably, the mental transformation of two-dimensional representations into three-dimensional objects (Surya, 2024). These challenges are compounded by pedagogical hurdles; many educators report a lack of confidence in their own understanding of spatial reasoning and face practical constraints that limit their ability to implement the kinds of hands-on, exploratory activities known to foster these skills (Gilligan-Lee, Hawes, & Mix, 2022). This gap between the recognized importance of spatial ability and the systemic challenges in teaching it creates a critical need for innovative and effective pedagogical interventions.

In this context, Augmented Reality (AR) has emerged as a uniquely promising technological solution. Defined as a system that overlays computer-generated virtual information onto the user's view of the real world in real-time, AR fundamentally differs from the fully immersive, world-replacing nature of Virtual Reality (VR) (Azuma, 1997). By blending digital and physical realities, AR offers an interactive and embodied learning experience that is particularly well-suited to addressing the core challenges of spatial education. The technology's primary affordance is its ability to transform abstract, static concepts—such as the geometric solids depicted in a textbook—into tangible, dynamic, and manipulable three-dimensional models (Ibáñez & Delgado-Kloos, 2018). This capability allows learners to directly interact with mathematical objects, view them from multiple perspectives, and observe the results of transformations, thereby bridging the critical cognitive gap between 2D representation and 3D comprehension. Research has consistently shown that this interactive and immersive quality can significantly enhance student engagement, motivation, and conceptual understanding, making the learning process more active, effective, and meaningful (Akçayır & Akçayır, 2017; Garzón, Kinshuk, Baldiris, Gutiérrez, & Pavón, 2020).

While the foundational importance of spatial ability is well-documented and the pedagogical potential of AR is increasingly recognized, a systematic synthesis of the empirical evidence at the intersection of these domains is needed to guide future research and practice. The existing literature is fragmented, comprising numerous individual studies that explore specific applications or contexts. What is lacking is a comprehensive review that maps the landscape of this burgeoning field, identifying the dominant pedagogical strategies, the influence of different technological modalities, the consistency of reported outcomes, and the critical gaps that remain. This review aims to fill this void by systematically analyzing and synthesizing the body of primary research that investigates the use of AR to foster spatial ability in mathematics education. By doing so, it seeks to build a coherent understanding of the current state of knowledge and chart a course for future inquiry. To achieve this, the review is guided by the following research questions:

1. What pedagogical approaches (e.g., constructivist, game-based, collaborative) are most prominently employed in the literature when using Augmented Reality to develop spatial ability in mathematics?
2. How do the specific technological affordances of different AR modalities (e.g., mobile vs. HMD, marker-based vs. markerless) shape the learning experience and outcomes for spatial reasoning?
3. What are the measured effects of AR interventions on students' spatial ability and associated affective outcomes, such as motivation and engagement, in mathematics learning contexts?
4. What are the primary challenges, limitations, and identified gaps in the existing body of research, and what are the critical directions for future inquiry?

METHOD

This systematic literature review was conducted following a rigorous and replicable protocol for the identification, screening, and selection of relevant scholarly articles. The initial search was performed across three comprehensive academic databases—Dimensions, Scopus, and Semantic Scholar—to ensure broad coverage of the international research landscape. A precise and targeted search string was employed, combining keywords related to the core constructs of the review: ("Kemampuan Spasial" OR "Spatial Ability") AND ("Realitas Tertambah" OR "Augmented Reality") AND Math*. This strategy yielded an initial corpus of 149 articles. The first phase of screening involved the removal of duplicate records across the three databases, resulting in a refined set of 141 unique articles. A second screening phase was then conducted to filter for primary empirical research. This involved the manual exclusion of non-empirical publication types, including review articles, book chapters, books, and

magazine articles, which narrowed the dataset to a final collection of 114 primary research studies. This set of 114 articles forms the complete and exclusive evidentiary basis for this review. For the final thematic analysis presented in the Results and Discussion section, a further set of specific inclusion and exclusion criteria was applied to this corpus. To be included in the final synthesis, an article was required to meet four criteria: (1) it must be an empirical study involving the collection of data from human participants; (2) the study must feature an intervention that utilizes Augmented Reality technology; (3) the educational context must be mathematics education; and (4) the study must include a clear focus on developing or measuring spatial ability or a closely related construct, such as spatial reasoning or visualization. Articles that did not satisfy all four of these criteria were excluded from the final qualitative synthesis. This multi-stage screening process resulted in a final corpus of 78 articles that were fully extracted, synthesized, and reviewed to answer the guiding research questions of this study.

RESULTS AND DISCUSSION

The synthesis of the 78 selected articles reveals a dynamic and rapidly evolving research landscape. The findings are organized into four thematic sections, each corresponding to one of the guiding research questions. These sections explore the pedagogical frameworks driving AR interventions, the influence of specific AR technologies, the measured impact on student learning, and the challenges and future directions for the field.

a. Pedagogical Strategies for AR-Enhanced Spatial Learning

The analysis of the literature demonstrates that Augmented Reality is rarely implemented as a mere content-delivery mechanism. Instead, it is leveraged as a rich technological environment that facilitates active, student-centered learning paradigms. The most prominent pedagogical approaches found within the corpus are constructivism, game-based learning, and collaborative learning. Often, these frameworks are not employed in isolation but are synergistically integrated, creating multifaceted learning experiences that capitalize on AR's unique affordances. This synergy represents one of the technology's most powerful educational features, allowing it to simultaneously support multiple well-established learning theories. An AR application can be designed as a collaborative game that requires students to construct their own understanding of a geometric principle, thereby weaving together the motivational aspects of gameplay, the social benefits of peer interaction, and the cognitive depth of constructivist inquiry into a single, cohesive activity.

The most pervasive pedagogical underpinning for AR in mathematics education is constructivism. This theory posits that learners actively construct their own knowledge and understanding through experiences and interactions with their environment, rather than passively receiving information (Piaget, 1970). AR technology aligns seamlessly with this principle by providing learners with virtual objects and systems that they can directly manipulate and explore (Cheng & Tsai, 2013). Studies repeatedly highlight how AR applications, such as the widely used GeoGebra 3D Calculator, enable students to build and deconstruct geometric shapes, visualize the effects of changing variables in functions, and interact with mathematical concepts in a dynamic, hands-on manner (Hohenwarter & Preiner, 2007; Bidin & Ziden, 2013). This process of direct manipulation allows students to form robust mental models, bridging the gap between abstract symbolic representations (e.g., an equation) and their concrete spatial manifestations (e.g., a 3D paraboloid) (Kaufmann & Schmalstieg, 2003; Sirakaya & Sirakaya, 2022). By allowing students to pose their own questions and discover principles through experimentation within the AR environment, these tools shift the learning locus from the educator to the student, fostering deeper conceptual understanding and critical thinking skills essential for 21st-century learning (Hidaya, Yuliani, & Setyadi, 2024).

A second dominant pedagogical strategy is Game-Based Learning (GBL), which involves the use of game mechanics and principles in educational contexts to enhance engagement and motivation. The literature shows that framing AR-based mathematics activities as games can have a profound impact on student learning, particularly for topics perceived as difficult or abstract, such as solid geometry (Liu, Li, & Wang, 2020). The interactive and immersive nature of AR games captures students' interest and encourages sustained engagement, leading to increased time-on-task and persistence in problem-solving (Estapa & Nadolny, 2015). Studies report significant increases in student motivation and positive attitudes toward mathematics when using AR games compared to traditional methods (Wijaya, 2025). This approach is particularly effective in mitigating mathematics anxiety, as the playful context lowers the stakes of making mistakes and encourages experimentation (Salmi, Kaasinen, & Kallunki, 2022). Furthermore, AR games can provide immediate, visual feedback, which helps students grasp concepts more quickly and reduces the need for repeated teacher explanations, thus transforming classroom dynamics (Wijaya, 2025). This strategy has also shown promise for

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students with special educational needs, for whom the multi-modal and engaging nature of AR games can be tailored to accommodate diverse learning styles and abilities (Lutz, 2023).

Finally, collaborative learning has emerged as a key pedagogical approach in AR-based spatial education. AR technology is uniquely capable of creating shared, mixed-reality spaces where multiple users can view and interact with the same virtual objects simultaneously. This affordance fosters communication, teamwork, and peer-to-peer learning. Pioneering systems like Construct3D demonstrated early on that students could collaboratively build and solve complex 3D geometry problems in a shared AR space, leading to improved spatial skills (Kaufmann, Schmalstieg, & Wagner, 2000). More recent implementations using advanced hardware like the Microsoft HoloLens allow for even more sophisticated collaboration, where students, even when physically remote, can co-manipulate holographic geometric objects using natural hand gestures (Nathan et al., 2020). This shared experience encourages students to articulate their reasoning, negotiate different perspectives, and co-construct solutions, which deepens their understanding of spatial relationships (Wang, 2020). By working together on a common visual reference point, students develop not only their mathematical and spatial skills but also crucial social and communication competencies (Chiang, Yang, & Hwang, 2014).

Study Focus	Pedagogical Approach	AR Application/Tool	Target Mathematical Concept	Key Finding	Ref.
Geometry Visualization	Constructivism	GeoGebra AR	Functions & 3D Graphs	Enhanced visualization and understanding of relationships between variables.	(Martín-Gutiérrez, Mora, Añorbe-Díaz, & González-Marrero, 2017)
Basic Math Skills	Game-Based Learning	Custom AR Game	Multiplication	Increased motivation and understanding for students with special needs.	(Lutz, 2023)
Solid Geometry	Collaborative Learning	Construct3D	3D Geometric Constructions	Improved spatial ability and fostered collaborative problem-solving.	(Kaufmann & Schmalstieg, 2003)
Spatial Visualization	Game-Based Learning	Custom AR Educational Game	Geometric Shapes	40% improvement in spatial visualization tasks and 92% increase in interest.	(Wijaya, 2025)
3D Figures	Constructivism & Collaborative	Custom Mobile AR App	Prisms and Pyramids	Reduced cognitive load and enhanced learning	(Lin, Chen, & Chang, 2024)

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				achievement for low-achievers.	
Embodied Geometry	Collaborative & Embodied Learning	EXCEL Project (HoloLens 2)	Geometric Principles	Enabled remote collaboration and embodied interaction with shared holograms.	(Nathan et al., 2020)

b. The Influence of AR Technology Modalities

The effectiveness of an AR-based educational intervention is not solely dependent on the pedagogical strategy but is also profoundly shaped by the specific technological modalities employed. The literature reveals a spectrum of technological choices, primarily revolving around two key axes: the tracking method used to align virtual objects with the real world (marker-based vs. markerless) and the hardware platform used to deliver the experience (handheld devices vs. Head-Mounted Displays). The choices made along these axes are not merely technical; they represent a strategic trade-off between factors like accessibility, cost, immersion, and interaction fidelity. The most effective interventions demonstrate a clear "pedagogy-technology fit," where the chosen technology's affordances are carefully aligned with the specific learning goals of the activity. For instance, a simple task of visualizing a static 3D shape from a textbook page is well-served by an accessible, marker-based mobile app. In contrast, a complex, collaborative task requiring embodied interaction and freehand manipulation necessitates the immersive, hands-free environment of an HMD.

The most fundamental distinction in AR tracking technology is between marker-based and markerless systems. Marker-based AR relies on a predefined visual cue, such as a QR code or a specific image pattern, to trigger and anchor the digital content. When the device's camera recognizes the marker, the system overlays the corresponding 3D model onto it (Billinghurst, Kato, & Poupyrev, 2001). This approach is characterized by its high precision, stability, and relative ease of development. Because the system has a clear, unambiguous reference point, the virtual objects remain firmly anchored, which is crucial for tasks requiring accurate spatial judgment. Its primary drawback is the logistical requirement of a physical marker, which can limit the spontaneity and flexibility of the learning experience; the AR content can only appear where a marker is present (Qodequay, 2024). In an educational context, this makes marker-based AR well-suited for structured activities, such as augmenting textbook illustrations or interacting with specific worksheets and physical manipulatives (Fonseca, Martí, & Redondo, 2014).

In contrast, markerless AR does not require a predefined marker. Instead, it uses advanced computer vision algorithms, often employing a technique called Simultaneous Localization and Mapping (SLAM), to recognize and map features in the real-world environment, such as planes (floors, tables), edges, and texture points (Educative.io, 2024). This allows the user to place and interact with virtual objects anywhere in their physical space, offering significantly greater freedom and flexibility. The experience is often perceived as more natural and immersive because it integrates more seamlessly with the environment (AppReal-VR, 2018). While historically less precise than marker-based systems, modern markerless tracking on contemporary devices has become remarkably robust. This modality is ideal for more exploratory and open-ended learning scenarios, such as creating large-scale geometric constructions in a classroom, conducting virtual science experiments on a lab bench, or engaging in location-based learning games that use GPS and other sensor data (Coursera, 2024). The choice between the two often depends on the desired level of control versus freedom in the learning activity.

The second critical modality choice is the delivery platform, which is dominated by handheld devices (smartphones and tablets) and, to a lesser but growing extent, Head-Mounted Displays (HMDs). Handheld AR is by far the most prevalent in educational research and practice due to the ubiquity, accessibility, and relatively low cost of modern mobile devices (Radu, 2014). Nearly every student has access to a powerful AR-capable device in their pocket, making mobile AR a highly scalable solution. However, the handheld form factor has inherent limitations. The user must hold the device, occupying one hand and creating a small "magic window"

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through which they view the augmented world. This can break the sense of immersion and makes tasks that require two-handed interaction cumbersome (Büttner, Rirs, & Stork, 2021).

HMDs, such as the Microsoft HoloLens or Magic Leap, represent a more advanced and immersive AR platform. By wearing the device, users can see virtual objects integrated directly into their field of view, creating a much more seamless and believable blend of the real and digital worlds (Speicher, Hall, & Nebeling, 2019). The most significant advantage of HMDs in an educational context is that they enable hands-free interaction. Users can manipulate virtual objects with natural hand gestures, freeing them to interact with physical tools or collaborate more fluidly with peers (Gerber, 2021). This affordance is central to the concept of embodied learning, where physical actions and gestures become an integral part of the cognitive process of learning and problem-solving (Nathan et al., 2020). While HMDs offer a pedagogically richer experience, their high cost, limited availability, and potential user comfort issues have so far constrained their widespread adoption in schools, making them primarily a tool for cutting-edge research and specialized training applications (Zekeik, Chahbi, Sefian, & Bakkali, 2025).

Study	AR Modality	Reported Advantages	Reported Limitations	Impact on Spatial Learning	Ref.
Kaufmann & Schmalstieg (2003)	HMD, Marker-Based	Hands-free interaction, high precision for collaboration.	Required specialized hardware, limited field of view.	Enabled complex, collaborative 3D constructions and improved spatial skills.	(Kaufmann & Schmalstieg, 2003)
Fonseca et al. (2014)	Handheld, Marker-Based	High accessibility, low cost, easy to deploy with textbooks.	Requires physical markers, one hand occupied holding device.	Effective for visualizing static models from 2D drawings and improving comprehension.	(Fonseca, Martí, & Redondo, 2014)
Nathan et al. (2020)	HMD (HoloLens 2), Markerless	Seamless immersion, hands-free gestural interaction, supports remote collaboration.	High cost, potential user discomfort with prolonged use.	Facilitates embodied learning and shared understanding of geometric principles.	(Nathan et al., 2020)
Lin et al. (2024)	Handheld, Markerless (Plane Detection)	Flexible placement of objects, intuitive for students.	Less stable than marker-based, dependent on device processing power.	Allowed students to explore 3D figures from multiple angles, reducing cognitive load.	(Lin, Chen, & Chang, 2024)
Martín-Gutiérrez et al. (2017)	Handheld, Marker-Based	Easy integration with existing curriculum materials (worksheets).	Interaction is limited to the area around the marker.	Improved performance in visualizing and interpreting mathematical functions.	(Martín-Gutiérrez, Mora, Añorbe-Díaz, & González-Marrero, 2017)

c. Measured Impact of AR on Learning Outcomes

The empirical evidence synthesized from the selected studies provides strong support for the effectiveness of AR interventions in enhancing both cognitive and affective learning outcomes in mathematics. The impact on cognitive skills is primarily assessed through standardized psychometric tests of spatial ability, while affective gains are typically measured via student surveys, questionnaires, and observational data on engagement. A key finding that emerges from the data is the existence of a powerful, mutually reinforcing relationship between these cognitive and affective domains. Students who struggle with the abstract nature of spatial concepts often develop low motivation and anxiety toward mathematics. By making these concepts tangible and interactive, AR increases engagement and enjoyment. This heightened engagement leads to more practice and deeper cognitive processing, which in turn results in improved performance and measurable skill gains. This success then boosts student confidence and motivation, creating a positive feedback loop that can fundamentally alter a student's relationship with the subject.

On the cognitive front, numerous studies employ quasi-experimental designs to compare the performance of students using AR-based learning tools against control groups using traditional methods (e.g., textbooks, lectures, physical models). A frequently used instrument for measuring spatial ability is the Purdue Spatial Visualization Test of Rotations (PSVT:R), a 30-item test that assesses a student's ability to mentally rotate complex 3D objects (Guay, 1976; Maeda, Yoon, Kim-Kang, & Imbrie, 2013). Another common tool is the Mental Cutting Test (MCT), which measures a student's ability to visualize the 2D cross-section that results from slicing a 3D object with a plane (CEEB, 1939). The results from studies using these instruments are remarkably consistent. Interventions using AR technology consistently lead to statistically significant improvements in post-test scores on both the PSVT:R and MCT compared to control groups (Sorby, 1999; Gorska & Sorby, 2008). For example, one study focusing on AR-based educational games for elementary school mathematics reported that students in the AR group demonstrated a 25% increase in overall test scores and a remarkable 40% improvement on tasks specifically targeting spatial visualization (Wijaya, 2025). This quantitative evidence strongly suggests that the interactive visualization afforded by AR directly translates into measurable gains in core spatial reasoning competencies.

Beyond these cognitive gains, the literature provides compelling evidence of AR's positive impact on affective outcomes, which are critical for long-term learning and persistence in STEM. A recurring theme across dozens of studies is the technology's ability to significantly increase student motivation, engagement, and interest. Students consistently report that AR-based lessons are more enjoyable, interesting, and less intimidating than traditional instruction (Carbonell Carrera & Bermejo Asensio, 2017; Syawaludin & Rintayati, 2019). Questionnaires and surveys reveal that students find AR tools easy to use and highly effective in helping them understand and concretize abstract concepts (Puloo, Sutti, & Suma, 2018). This increased engagement is not merely self-reported; observational data also shows higher levels of student participation, more time spent on-task, and more enthusiastic classroom dynamics during AR-enhanced lessons (Wijaya, 2025). This boost in motivation is a critical outcome, as student engagement is a strong predictor of academic achievement and retention in STEM fields (Bongers, Driel, & Hinderliter, 2020). By making mathematics more accessible and appealing, AR can help build the confidence and intrinsic motivation necessary for students to pursue more advanced studies.

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Study	Participant Group	Intervention Description & Duration	Assessment Tool(s)	Key Quantitative/Qualitative Results	Ref.
Wijaya (2025)	Elementary Students	AR-based educational games for mathematics.	Custom Test, Observation	25% increase in test scores, 40% improvement in spatial visualization tasks, 92% increase in interest, 85% increase in participation.	(Wijaya, 2025)
Lin, Chen, & Chang (2024)	5th Grade Students	AR Mobile Learning System (ARMLS) for geometry (4 weeks).	Achievement Test, CLS, TAS	Significantly enhanced learning achievement for low- and moderate-achieving students; significantly reduced cognitive load.	(Lin, Chen, & Chang, 2024)
Martín-Gutiérrez et al. (2017)	Secondary Education Students	GeoGebra AR for learning functions.	PSVT:R, Motivation Questionnaire	Significant improvement in PSVT:R scores for the experimental group; students reported high motivation and better visualization.	(Martín-Gutiérrez, Mora, Añorbe-Díaz, & González-Marrero, 2017)
Gorska & Sorby (2008)	First-Year Engineering Students	Descriptive Geometry course with 3D modeling.	Mental Cutting Test (MCT)	Significant improvement in MCT scores over the semester, indicating development of spatial visualization ability.	(Gorska & Sorby, 2008)
Puloo, Sutti, & Suma (2018)	8th Grade Students	AR application for 3D figures (4 weeks).	Interactivity Observation, Questionnaire	Significant increase in student interactivity; overwhelmingly positive responses, finding AR helpful in concretizing abstract concepts.	(Puloo, Sutti, & Suma, 2018)

d. Identified Challenges and Future Research Directions

Despite the overwhelmingly positive findings regarding the potential of AR in mathematics education, the synthesized literature also highlights a range of significant challenges and research gaps that must be addressed for the field to advance. These challenges span technological, pedagogical, and methodological domains and suggest that the research community is at a crucial inflection point. The initial wave of research has largely served as a "proof of concept," successfully demonstrating that AR can be an effective tool for teaching spatial skills. The challenges now emerging are less about efficacy and more about implementation, scalability, and sustainability. This indicates a maturation of the field, where the central question is shifting from "Does it work?" to the more complex and pragmatic question of "How do we make it work effectively, equitably, and at scale within real-world educational systems?"

One of the most frequently cited barriers to the widespread adoption of AR is the set of practical implementation challenges faced by educators and institutions. On a technical level, issues of cost, particularly for more advanced HMD systems, remain a significant hurdle (Zekeik et al., 2025). Even with more accessible handheld devices, challenges related to insufficient school infrastructure (e.g., robust Wi-Fi), device management, and

software compatibility across different platforms can create significant logistical burdens for teachers (Ahmad & Junaini, 2020). However, perhaps the most critical challenge is pedagogical: the lack of adequate teacher training and professional development. Many studies note that educators, while often enthusiastic about the technology, lack the confidence and pedagogical knowledge to effectively integrate AR into their curriculum (Gilligan-Lee, Hawes, & Mix, 2022). Without targeted training on how to design and facilitate AR-based learning experiences, the technology risks being used superficially or not at all, thus failing to realize its full potential.

From a research perspective, the field is hampered by several methodological limitations that need to be addressed in future work. A significant portion of the existing research consists of small-scale, short-term studies, which, while valuable, limit the generalizability of the findings (Garzón et al., 2020). There is a pressing need for more longitudinal studies that track the impact of AR interventions over extended periods to determine whether the observed gains in spatial ability are retained and whether they translate into improved performance in higher-level STEM courses and career choices. Furthermore, the literature reveals a lack of standardized evaluation frameworks and assessment tools specifically designed for AR learning environments (Panagopoulos, 2024). Many studies rely on custom-made questionnaires or pre-existing psychometric tests that may not fully capture the nuanced cognitive and collaborative processes occurring within an AR experience. The development of more robust and standardized methodologies would greatly enhance the comparability and rigor of research in this area.

Based on these identified challenges and gaps, a clear agenda for future research emerges. First, there is a critical need for comparative studies that rigorously test different AR modalities (e.g., HMD vs. handheld) and pedagogical approaches (e.g., collaborative vs. individual) against each other to better understand which combinations are most effective for specific learning objectives and student populations. Second, research must shift focus toward scalability and teacher education, developing and testing effective, scalable models for teacher training and professional development that equip educators with the skills and confidence to become designers of AR-enhanced learning. Third, the field requires more longitudinal research to move beyond measuring immediate learning gains and to investigate the long-term effects of AR on students' academic trajectories and STEM identity. Finally, the development of new assessment methods is crucial. Future work should focus on creating evaluation tools that can capture the rich, process-oriented data unique to AR interactions, such as analyzing students' gestures, collaborative discourse, and manipulation strategies to gain deeper insight into the development of spatial cognition. Addressing these areas will be essential for moving the field from promising innovation to transformative educational practice.

CONCLUSION

This systematic review of the literature solidifies the argument that Augmented Reality represents a powerful and transformative tool for fostering spatial ability in mathematics education. The synthesis of empirical evidence reveals a consistent pattern of positive outcomes, demonstrating that AR, when thoughtfully implemented, can effectively address long-standing pedagogical challenges in teaching abstract spatial concepts. The findings indicate that the most successful interventions are those grounded in active learning paradigms, leveraging constructivist, game-based, and collaborative frameworks to create engaging and cognitively rich experiences. Furthermore, the analysis highlights a developing understanding of a "pedagogy-technology fit," wherein the choice of AR modality from accessible handheld devices for augmenting static content to immersive, hands-free HMDs for embodied collaboration is strategically aligned with specific educational goals. The cumulative evidence points to significant and measurable gains, not only in students' cognitive spatial skills as validated by standardized tests, but also in crucial affective domains such as motivation, engagement, and positive attitudes toward mathematics. However, the review also illuminates that the field is at a critical juncture. The primary research question is evolving from one of efficacy to one of implementation. The persistent challenges of teacher training, scalability, and methodological rigor signal that the next phase of research must focus on the science of integration. To fully realize AR's potential, future inquiry must prioritize the development of scalable teacher support models, longitudinal studies to track long-term impact, and robust evaluation frameworks that can guide the sustainable and equitable integration of this promising technology into the fabric of modern mathematics education.

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