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Integrating augmented reality in mathematics: A mixed-methods systematic review of spatial and geometric learning

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ABSTRACT

This mixed-methods systematic review examined the effectiveness of Augmented Reality (AR) in enhancing spatial skills and geometric understanding among primary school students, while identifying key factors for successful implementation in mathematics education. A comprehensive search of Scopus up to 21 March 2021 identified 817 records, of which 26 peer-reviewed articles met the inclusion criteria following PRISMA guidelines. Quantitative data from experimental and quasi-experimental studies were synthesised using meta-analytic methods, while qualitative findings were coded and thematically analysed. Results showed that AR interventions produced moderate to very large positive effects on spatial visualisation, mental rotation, and spatial reasoning, with an average effect size of 0.65 SD in geometry test scores compared with traditional methods. However, limited infrastructure, inadequate teacher preparedness, curriculum misalignment, and unequal student access hinder AR adoption, particularly in resource-constrained contexts. The synthesis highlights structured teacher professional development, curriculum integration, affordable AR tools, and supportive institutional policies as essential strategies for addressing these challenges. Overall, AR can substantially improve primary students' spatial and geometric learning outcomes when implemented with appropriate pedagogical and systemic support. Future studies should prioritise longitudinal research, comparative evaluations, and policy design to sustain and scale AR's benefits across diverse educational contexts and settings.

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INTRODUCTION

In the rapidly evolving digital education landscape, augmented reality (AR) is a transformative tool that can revolutionise how young learners engage with complex subjects (AlGerafi et al., 2023; Lampropoulos et al., 2022). By integrating digital elements into the real environment, AR creates engaging, immersive experiences that traditional teaching methods often struggle to achieve. In addition, AR motivates students to learn because it displays 3d images, which students readily accept (Widiasih et al., 2023). This is especially impactful in primary education, where the need for concrete, visual learning aids is paramount to understanding abstract concepts such as geometry (López-Faican & Jaen, 2020).

Spatial visualisation skills, critical for mastering geometry, have garnered significant interest because AR uniquely enables students to engage with solid shapes, enhancing their understanding and comprehension of spatial relationships (Herrera et al., 2024; Ng et al., 2020). In other words, a comprehensive understanding of spatial reasoning requires students to master spatial perception, mental orientation, and visualisation (Mandala et al., 2025). Meanwhile, students' spatial orientation skills, conducted by Pradana et al., (2020), offer virtual technology rather than AR, although the technology facilitates solving spatial problems to enhance spatial reasoning.

Despite its potential, the adoption of AR in primary classrooms remains limited, especially in developing countries where challenges such as access to technology, teacher readiness, and curriculum integration persist (Alalwan et al., 2020). However, challenges remain concerning gender and geographic differences among students (Herman et al., 2023). Differences in males' and females' abilities to design HOTS questions in mathematics stem from variations in their mathematical knowledge, teaching strategies, and understanding of curriculum requirements, which are included as barriers (Sa'dijah et al., 2023). For the curriculum in Indonesia, the implementation of the curriculum must ensure the readiness of school leaders and teachers to adopt and implement changes. However, its implementation still has numerous shortcomings and challenges (Dewi & Mudrikah, 2023).

Research consistently shows that AR can significantly improve learning outcomes, particularly in spatial reasoning and student engagement. By merging virtual elements with real-world contexts, AR facilitates a smoother transition from abstract ideas to tangible understanding, vital for young learners still honing their cognitive and spatial abilities (Olim & Nisi, 2020; Pellas et al., 2020). For instance, interactive three-dimensional models allow students to manipulate geometric shapes, fostering an intuitive understanding of properties and transformations that are often challenging to grasp through traditional approaches (Tarng et al., 2024).

AR also complements contemporary pedagogical frameworks, such as constructivism and learning through experience, by promoting active participation, critical thinking, and knowledge construction through direct experiences (Çeken & Taşkın, 2022; Chang et al., 2022). However, substantial gaps persist in our understanding of AR's cognitive impacts, particularly its effect on primary students' spatial visualisation abilities. Most existing research has been conducted in isolated classroom settings with a narrow focus on specific applications, failing to address broader implementation challenges or diverse learning populations (Maas & Hughes, 2020). Additionally, the lack of longitudinal studies limits insights into the enduring impact of AR on students' educational outcomes and participation (Koumpouros, 2024). While studies frequently highlight the potential of AR, they often need to address practical limitations, such as the lack of teacher training, technological dependency, and the high costs of development and implementation (AlGerafi et al., 2023; Alzahrani, 2020).

Research examining AR use in primary education is still in its early stages, particularly in contexts where educational challenges such as restricted access to digital tools and inadequate teacher training persist. Preliminary surveys in primary schools have shown that conventional teaching approaches frequently struggle to capture students' interest, especially in geometry, which requires strong visual-spatial reasoning. Teachers report difficulties conveying complex concepts due to a lack of pedagogical tools, which reduces student motivation and comprehension (Gargrish et al., 2020). Although AR presents a different method, its real-world effectiveness and potential for widespread use in schools with limited resources have not been thoroughly investigated.

In response to these gaps, this study proposes to comprehensively evaluate the effectiveness of AR in enhancing spatial visualisation skills among primary school students, particularly in geometry learning. While the positive impact of AR on cognitive skills is acknowledged (Xu et al., 2022), previous systematic reviews have predominantly focused on higher education or broader STEM contexts, leaving a specific gap concerning primary-level geometry (Green et al., 2021). This research, therefore, adopts a broader perspective by examining the interconnected influence of AR on motivations and academic performances, a critical factor for sustained learning and overall learning performance (Amores-Valencia et al., 2022), thus providing a more holistic evaluation than prior works (Sanfilippo et al., 2022). Additionally, it moves beyond simple efficacy studies to explore key factors driving the successful implementation of AR. This includes teacher training and pedagogical readiness, which are often cited as major barriers (Perifanou et al., 2022), as well as principles of pedagogical design tailored for young learners (Tarng et al., 2024) and strategies for effective curriculum integration (AlGerafi et al., 2023). By analysing methodological trends and findings from recent studies (2020–2025), this research provides new insights into ways to adapt AR to support the cognitive development of young students.

This study's unique contribution lies in its focus on primary education through an innovative pedagogical approach to leveraging AR for spatial visualisation enhancement. Rather than emphasising technical aspects, it explores effective instructional strategies for integrating AR into geometry learning, highlighting pedagogically sound applications tailored to young learners' cognitive development. The findings will guide educators, policymakers, and researchers in developing AR tools and designing effective instructional strategies to improve students' spatial skills.

Guided by the following research objectives, this study intends to furnish a complete picture of AR's role in spatial skill development: (1) to analyse how the use of AR tools affects primary students' spatial abilities as opposed to conventional classroom techniques, (2) to examine how AR applications enhance the understanding of geometric concepts in primary mathematics, and (3) to determine the main elements that lead to effective integration of AR in primary classrooms. Through answering these questions, this research puts forward effective strategies for implementing AR in primary classrooms and contributes a comprehensive perspective on AR's capacity to revolutionise learning for young students.

METHOD

A mixed-methods systematic review was conducted to answer three research questions focused on the influence of AR on spatial visualization capabilities, understanding of geometric concepts, and factors influencing successful AR implementation in primary mathematics education. The review targeted all peer-reviewed journal articles on AR in primary education indexed in Scopus as of 21 March 2025. Out of an initial 817 records, 31 duplicates were removed, resulting in 786 titles and abstracts being screened. Following this, 162 full-text articles were assessed for eligibility, and 26 studies were ultimately included, meeting the requirements of peer review, full-text availability, English language, and a focus on AR in primary settings.

A purposive sampling strategy was adopted, utilising systematically developed keyword combinations with truncation (asterisks) to capture lexical variants (see Table 1). Records were identified via Scopus searches and managed in Covidence software, which was employed for screening and data management. Following the removal of duplicates, titles and abstracts underwent independent screening using predetermined standards. Full texts were reviewed for final inclusion per the PRISMA flow (Figure 1).

Screening and data extraction were carried out in five sequential steps: (1) identification of records using a comprehensive keyword search strategy in Scopus; (2) importation and de-duplication in Covidence; (3) independent screening of titles and abstracts by two reviewers; (4) eligibility assessment of full-text articles; and (5) inclusion of studies in the quantitative and qualitative syntheses.

Table 1. Keyword Search Operation

No.	Article Information	Total
RQ1: Effect of AR on Spatial Visualisation Skills		
1	Augment* AND Reality* AND spatial* AND visual* AND (primar* OR elementar* OR student* OR learner*)	381
2	AR AND learn* AND spatial* AND reason* AND (student* OR learner* OR young*)	30
	Immers* AND learn* AND 3D AND visual* AND mathematic*	48
3	AR AND tool* AND cognitive* AND develop* AND geometric*	7
4	Augment* AND Reality* AND tradit* AND teach* AND compar* AND spatial* AND skill*	13

No.	Article Information	Total
RQ2: Influence of AR on Understanding Geometric Concepts		
1	AR AND mathematic* AND educat* AND geometr* AND master* AND (student* OR primar* OR school*)	1
2	Digital* AND learn* AND tool* AND geometr* AND interactiv* AND educat*	44
3	AR AND geometr* AND spatial* AND reason* AND cognitive* AND engage*	0
4	Virtual* AND learn* AND environ* AND mathematic* AND concept* AND elementar* AND student*	20
RQ3: Factors Affecting the Successful Implementation of AR		
1	Adopt* AND AR AND educat* AND teacher* AND percept* AND classroom* AND integrat*	3
2	Challeng* AND AR AND learn* AND technolog* AND accept* AND educat* AND innovat*	11
3	Augment* AND Reality* AND student* AND engage* AND learn* AND outcome*	235
4	Educat* AND AR AND tool* AND access* AND infrastructur* AND readiness*	2
5	Immers* AND learn* AND policy* AND support* AND teach* AND strategy*	22
Total Articles		**817**

A standardised data extraction form was developed and piloted to collect bibliographic details, sample characteristics, intervention features, and outcome measures. Quantitative data (sample sizes, means, standard deviations, statistical significance, and effect sizes) and qualitative findings (themes, contextual factors) were independently extracted using an Excel template. Covidence was used to export CSV files for final extraction and data management, and Pivot tables were used for further elimination and categorisation.

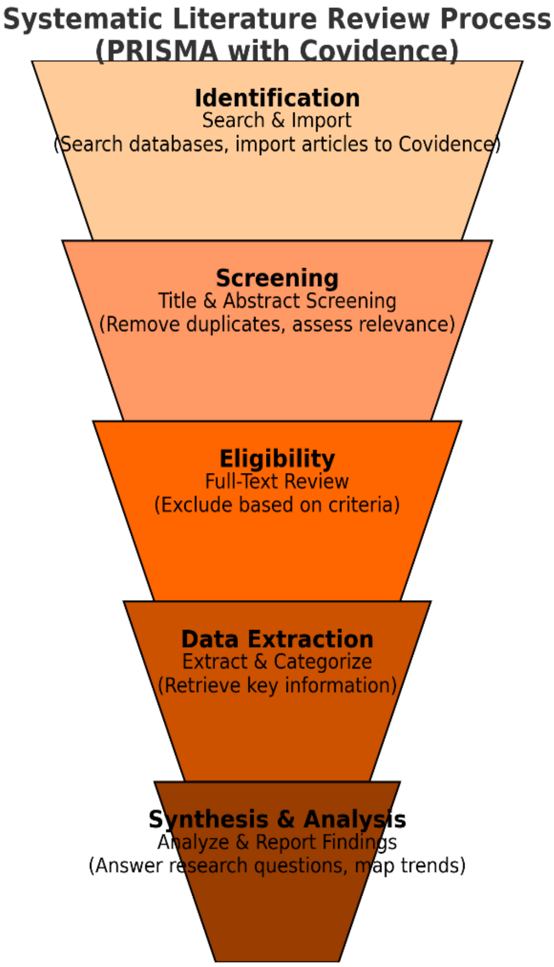

Figure 1. Flowchart of Systematic Literature Review Process (PRISMA with Covidence)

Quantitative data extraction targeted experimental and quasi-experimental studies. Meta-analytic synthesis showed that most AR interventions produced moderate to very large positive effects on students' spatial skills, especially spatial visualisation and reasoning, compared to conventional methods.

For the qualitative strand, findings from qualitative and mixed-methods studies were coded and thematically analysed (see Table 2). The results consistently showed that AR applications significantly enhanced students' conceptual understanding of geometry by enabling interactive manipulation of 3d objects and fostering active, collaborative learning. Common themes included increased motivation, improved visualisation, and bridging abstract and real-world geometric thinking. To address the third research question, qualitative synthesis identified key factors for successful AR implementation: teacher training and digital competence, accessible and reliable technology, curriculum integration, instructional scaffolding, and effective classroom management. Barriers such as technological limitations and insufficient support were also noted. Bibliometric mapping highlighted a recent increase in high-quality, experimental AR research in primary mathematics.

Table 2. Analytical Codes and Conceptual Definitions

No.	Code	Definition	Keywords/Indicators
1	3D Visualization	The use of AR to make abstract geometric concepts concrete through interactive three-dimensional models.	Visualisation, 3d models, Concrete
2	Interactivity	The degree to which students can manipulate and engage with virtual objects and learning content.	Manipulation, Hands-on, Active learning
3	Constructivist Learning	Learning through active participation, knowledge construction, and direct experience via AR.	Constructivist, Experiential, HLT
4	Motivation & Engagement	Increased student enthusiasm, interest, and active participation driven by AR features.	Motivation, Engagement, Enjoyment
5	Ease of Use/Usability	Simplicity, intuitiveness, and accessibility of AR tools for students and teachers.	Usability, User-friendly, Practical
6	Collaboration	AR activities facilitate group work, peer learning, and social interaction.	Collaboration, Peer learning, Group
7	Teacher Support/Scaffolding	The teacher's responsibility is to provide guidance, support, and adapt AR-based activities for effective learning.	Teacher guidance, Scaffolding, Orchestration
8	Technical Readiness	Availability, reliability, and suitability of AR technology and infrastructure in the classroom.	Technical support, Infrastructure
9	Curriculum Alignment	Integration and adaptation of AR tools to match learning objectives and curriculum standards.	Curriculum, Pedagogy, Alignment
10	Cost-Effectiveness	Affordability and accessibility of AR resources for classroom implementation.	Cost, Accessibility, Resource
11	Feedback & Adaptivity	Provision of immediate feedback and adaptive learning experiences through AR.	Feedback, Personalisation, Adaptivity
12	Cognitive Load Management	Strategies to reduce overload and help students focus on key concepts when using AR.	Cognitive load, Instructional prompts

This mixed-methods systematic review integrated quantitative and qualitative evidence, supplemented by bibliometric mapping to elucidate publication trends, authorship networks, and thematic evolution in AR research within primary mathematics education. The PRISMA-guided process ensured transparency and replicability (Moher et al., 2009). Our approach quantified AR's effects on spatial and geometric learning, situated these outcomes within practical classroom realities, and identified key research hotspots and collaboration patterns, offering actionable insights for educators and policymakers.

RESULTS AND DISCUSSION

Results

Article Distribution

Based on the article distribution in Table 3, the systematic literature review identified 26 relevant articles on implementing Augmented Reality (AR) in primary mathematics, particularly geometry. The analysis describes the distribution of these articles according to Scimago journal rating, research method, and publication year.

Articles are spread across all Scimago quartiles, with Q3 (30.8%) and unranked (34.6%) journals being the most common publication venues. Q1 and Q2 journals account for 23.1% and 15.4% of articles, respectively, while Q4 journals represent 19.2%. This shows that while high-quality journals are well defined, a significant portion of research is still published in unranked or mid-tier journals. Meanwhile, experimental studies dominate the field (57.7%), indicating a strong emphasis on measuring the impact of AR interventions. Quantitative and R&D/Design-Based methods are also standard (15.4% and 11.5%, respectively), with qualitative and review studies making up the remainder. This reflects a methodological preference for empirical evaluation, especially in the last five years.

Table 3. Scimago Rankings and Research Methods: Pattern from 2008 to 2025

No.	Category	2008-2019	2020	2021	2022	2023	2024	2025	Total	%
Ranking (Scimago)										
1	Q1	2	1			1	1	1	6	23.1
2	Q2	2	1	1					4	15.4
3	Q3	2	2	1		1	2		8	30.8
4	Q4	2	1				1	1	5	19.2
5	Unranked	2	2		1	1	3		9	34.6
Total		**10**	**7**	**2**	**1**	**3**	**7**	**2**	**26**	**100**
Research Method										
1	Experimental	4	4	1		2	3	1	15	57.7
2	R&D/Design-Based	2					1		3	11.5
3	Quantitative	2	1			1			4	15.4
4	Qualitative	1	1		1				3	11.5
5	Review	1	1	1				1	4	15.4
Total		**10**	**7**	**2**	**1**	**3**	**4**	**2**	**26**	**100**

Overall, there is an apparent increase in publication activity in the last five years (2020–2024), with the highest number of articles published in 2024 (7). This trend demonstrates growing interest and rapid development in AR applications for primary mathematics, particularly geometry. The distribution reveals that AR research in primary geometry is gaining momentum, with most studies adopting experimental designs and a significant proportion published in high-impact journals. However, the substantial presence of unranked publications suggests ongoing opportunities for more rigorous research and wider dissemination in top-tier outlets. The trend also underscores the field's dynamic growth and the increasing relevance of AR in elementary mathematics instruction.

Mixed Methods Results

We extracted quantitative and qualitative data from the selected studies to assess AR's effects on spatial skills and geometry in primary math. Table 4 summarises the experimental comparisons of AR versus traditional teaching, while Table 5 outlines the thematic synthesis of implementation mechanisms, benefits, and success factors.

Table 4 demonstrates that AR interventions consistently produce significant improvements in spatial visualisation, spatial reasoning, and the understanding of complex geometric concepts compared to conventional teaching. The positive effects are especially pronounced among students with initially lower spatial abilities, confirming the role of AR in bridging gaps in spatial understanding. For example, AR-supported groups exhibited twofold to threefold increases in spatial visualisation and reasoning scores compared to control groups, indicating AR's ability to enhance cognitive engagement. In surface area, volume, and cross-section identification tasks, marker-based AR tools like EUCLIDA, LearnGeoAR, Spatial Lab, and MAR Remedial Program enabled students to manipulate 3d objects directly, transforming abstract concepts into tangible experiences. This is reflected in moderate to very large effect sizes (e.g., d = 0.71 in Nadzeri et al., 2024; d > 4 in Supli & Yan, 2024), highlighting AR's substantial educational value.

Table 4. Quantitative Synthesis of AR Impact in Primary Mathematics

Article	AR Product (Type of AR)	Sample (Exp/Ctrl)	Spatial Skills Assessed	Main Geometric Concepts Enhanced	Effect Size (Cohen's)/ Key Statistic	Key Quantitative Finding
Bell et al., (2019)	Handheld AR App (Location-based AR)	21/17	SR, MO, SO, SV	Manipulation & orientation of 3D objects	$d = 0.39$; $p = 0.040$	AR > Control, especially for low prior ability
Dakeev et al., (2021)	ARCADE using Creo Parametric, Unity Engine, and Vuforia] (Image Recognition)	9/20	SR, SO, SV	2D/3D shapes, spatial reasoning	$d = -1.59$; $p = 0.001$	Control > AR (context-dependent result)
Krüger et al., (2019)	AR simulation (Marker-based)	8/28	Spatial abilities (general)	General spatial relations	$d = 0.24$; $p = 0.371$	No significant difference
Nadzeri et al., (2024)	LearnGeoAR (Marker-based)	30/31	SV	2D/3D shapes, spatial visualisation	$d = 0.71$; $p = .00$	AR > Control, moderate effect
Sun & Chen (2020)	MAR Remedial Program (Marker-based)	30/30	SV, SR, SI, MO	Mental image, 3D geometry reasoning	$F = 4.451$; $p = .039$	Significant improvement in experimental group
Supli & Yan (2024)	Spatial Lab (Marker-based)	27/27	MR, SO, SV, SRI	Rotation, orientation, 3D visualisation	$d = 4.17–4.42$; $p < .001$	AR > Control, very large effect
Wang et al., (2025)	ARiMC (Marker-based)	46/40	SR, SV, MO	Geometric solids, reasoning	n.s.; $p = .223$	No significant difference
Abinaya & Vadivu (2023)	Marker-based AR	-	SR	Descriptive visualisation	$p = 0.03$ (pre-post)	Significant improvement (no control group)

Description:

MR = Mental Rotation
SO = Spatial Orientation
MO = Mental Orientation
SV = Spatial Visualisation
SR = Spatial Reasoning
SI = Spatial Imagination
SM = Spatial Memory

Table 5 reveals that the dominant themes in using AR in primary classrooms are concrete/dynamic visualisation, interactivity, increased student motivation and engagement, and collaboration. AR allows students to experience geometric concepts directly and actively, boosting interest in learning and facilitating collaborative and argumentative learning. The most frequently identified success factors for AR implementation include teacher training, technological readiness, curriculum integration, instructional scaffolding, and ease of use. The studies also highlight the need for flexible teaching approaches and sufficient infrastructure to fully realise the advantages of AR in primary school settings.

Table 5. Qualitative Synthesis of AR in Primary Mathematics

No.	Theme/Indicator	Frequency (n)	Representative Quote
1	3D/Concrete Visualisation	12	"AR transforms abstract concepts into concrete experiences..." (Anggraini et al., 2020)
2	Interactivity & Manipulation	11	"Dynamic and interactive visual representations make abstract geometric concepts concrete..." (Deliyiannis et al., 2008)
3	Motivation & Engagement	10	"AR features can engage students in the learning process and help improve their visualisation skills..." (Anggraini et al., 2020)
4	Collaboration & Peer Learning	9	"Collaborative AR activities promote engagement and problem-solving..."(Phon et al., 2014)
5	Teacher Support/Scaffolding	8	"Teacher orchestration, scaffolding argumentation, and adaptive guidance were key..." (Schwarz et al., 2018)
6	Ease of Use / Usability	7	"The designed AR-learning environment was classified as 'excellent'..." (Javaheri et al., 2022)
7	Curriculum / Pedagogical Alignment	7	"Success depends on clear visuals, manageable cognitive load, and flexible, user-centered frameworks." (Deliyiannis et al., 2008)
8	Technical Readiness / Support	6	"Most of the challenges were related to usability and ergonomics, such as discomfort, inadequate tracking..." (Daghriri et al., 2024)
9	Cost-effectiveness / Accessibility	4	"Success depends on teacher training, resource availability, cost, classroom management, and awareness." (Perifanou et al., 2023)

Table 6 presents the comparative effects of AR applications on specific geometric concepts. The findings show that AR consistently enhances students' understanding across diverse topics, with effect sizes ranging from moderate to very large. Among the concepts, mental rotation yielded the strongest impact ($d = 1.05$) when supported by the Spatial Lab tool (Supli & Yan, 2024), highlighting AR's effectiveness in strengthening students' ability to visualise and manipulate three-dimensional objects. Similarly, AR integration in LearnGeoAR demonstrated a substantial effect ($d = 0.71$) in helping students comprehend 3D structures and sectional views (Nadzeri, 2024).

Table 6. Comparative Effects of AR on Key Geometry Concepts

No.	Geometric Concept	Average Effect Size (Cohen's d)	AR Product Name	Article
1	Surface Area	0.68	EUCLIDA (Marker-based AR)	(Putri et al., 2023)
2	Volume	0.66	MAR Remedial Program	(Sun & Chen, 2020)
3	Symmetry	0.61	GeoGebraAR	(Schmid & Korenova, 2024)
4	Angle/Transformation	0.58	3Dmetric AR	(Amir et al., 2018)
5	3D Structure/Sections	0.71	LearnGeoAR	(Nadzeri, 2024)
6	Mental Rotation	1.05	Spatial Lab	(Supli & Yan, 2024)

Moderate positive effects were also observed in surface area ($d = 0.68$) using EUCLIDA (Putri et al., 2023), volume ($d = 0.66$) through the MAR Remedial Program (Sun & Chen, 2020), and symmetry ($d = 0.61$) with GeoGebraAR (Schmid & Korenova, 2024). Smaller yet significant improvements were reported in angle and transformation concepts ($d = 0.58$) when supported by 3Dmetric AR (Amir et al., 2018). Overall, these results indicate that AR is particularly impactful for geometry concepts requiring higher levels of spatial visualization, such as mental rotation and 3D structures, while still offering meaningful gains for more foundational topics like surface area, volume, and symmetry.

Bibliographic Mapping

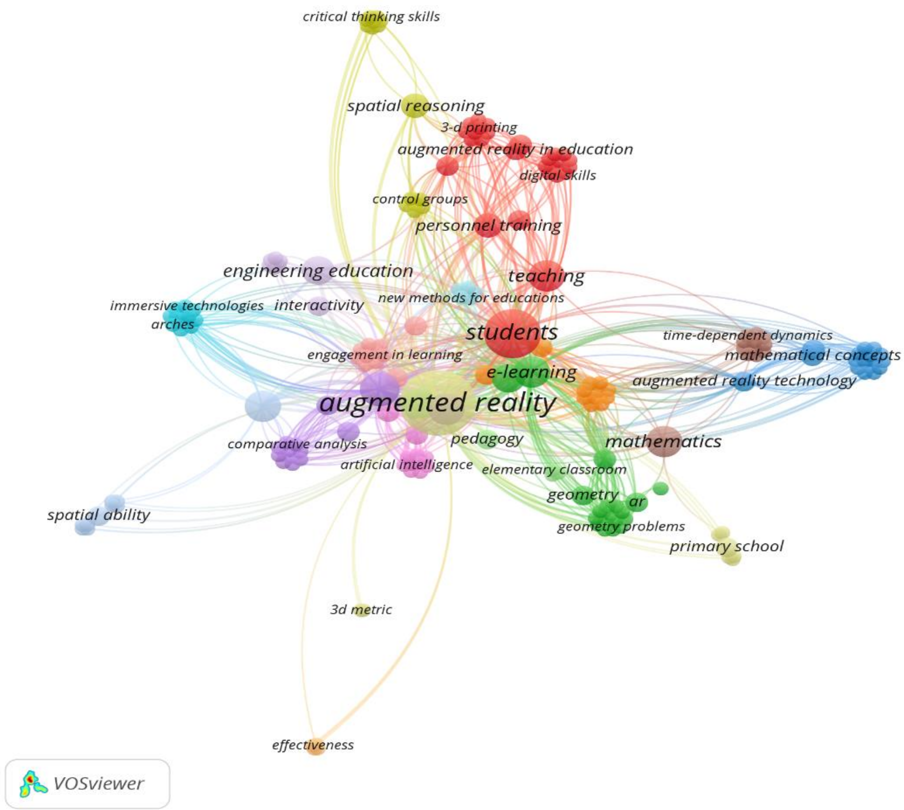

Figure 2. Bibliographic mapping for Research on Augmented Reality for Primary Students

The bibliographic mapping visualised in Figure 2 was constructed based on co-occurrence analysis, with a minimum threshold of one keyword per cluster to refine the scope of the investigation. The visualisation reveals several distinct clusters, each representing a thematic concentration within the educational literature on augmented reality (AR). The analysis of keyword co-occurrences delineates the thematic structure of AR research in primary education and provides a roadmap for addressing the three research questions. The clusters and keyword linkages identified in the mapping will guide the subsequent literature review and synthesis, enabling a targeted and evidence-based discussion on (1) the comparative effects of AR on spatial skills, (2) the enhancement of geometric understanding, and (3) the key factors underpinning successful AR integration in primary classrooms.

The yellow cluster, featuring keywords like “spatial reasoning,” “3D printing,” and “critical thinking skills,” reflects a strong research focus on how AR enhances spatial abilities. Research in this group frequently employs comparative studies with control groups to assess how AR tools impact spatial visualisation and reasoning. These findings reinforce the agreement that AR offers more engaging and interactive learning experiences, which can substantially improve spatial abilities in primary students over conventional teaching methods. The blue and green clusters centre on mathematics and geometry, showing that AR is widely applied to make abstract geometric concepts more concrete and accessible in primary classrooms. Key terms like “mathematics,” “geometry,” and “elementary classroom” indicate that the visual and interactive aspects of AR play a crucial role in boosting students’ interest and motivation when learning geometry.

At the same time, the red and purple clusters highlight critical factors for effective AR integration, with core keywords such as “students,” “teaching,” “personnel training,” and “digital skills.” These clusters indicate that professional development and digital competence among educators are essential for effective AR integration. Additionally, the presence of “interactivity,” "engagement in learning," and "effectiveness" suggests that AR experiences must be pedagogically sound and aligned with curriculum standards. Effective adoption of AR in primary education often depends on close cooperation between technology developers and teachers, as well as ensuring alignment with the curriculum.

Forest Plot of AR Interventions on Spatial Skills

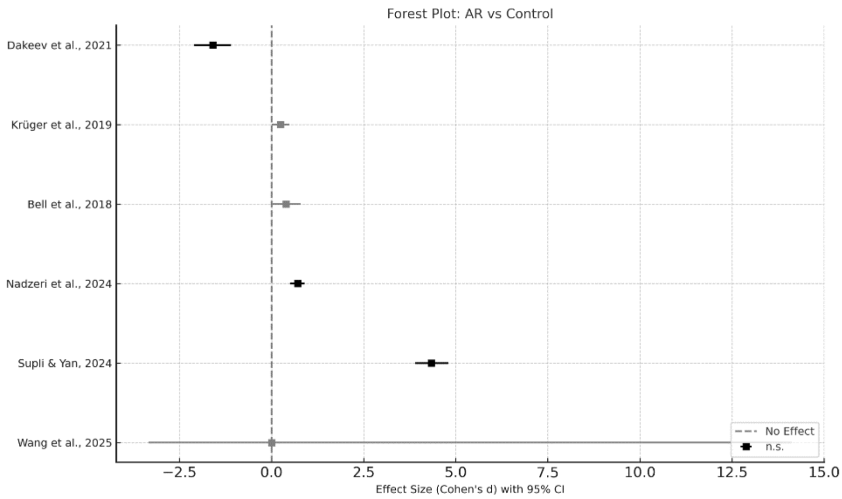

Figure 3. Forest Plot: The Impact of Augmented Reality on Primary Students' Spatial Abilities

The forest plot visually synthesises the effect sizes (Cohen's d) from experimental studies comparing AR interventions to traditional methods for spatial skills outcomes. Most studies demonstrate that AR interventions yield moderate to very large positive effects on spatial abilities, particularly in mental rotation, spatial orientation, and spatial visualisation. For instance, Supli & Yan (2024) reported exceptionally large effect sizes for mental rotation (d = 4.34), spatial orientation (d = 4.42), and spatial visualisation (d = 4.17), indicating a substantial improvement in spatial skills among students using AR. Nadzeri et al., (2024) found a moderate effect size (d = 0.71) for spatial visualisation, while Bell et al., (2019) reported a small-to-moderate effect (d = 0.39) for spatial reasoning and visualisation, particularly benefiting students with initially lower spatial abilities.

However, the effectiveness of AR is not universal across all studies. Krüger et al., (2019) reported no statistically significant difference between AR and control groups (d = 0.24, p = 0.371), indicating that AR's impact may vary depending on factors like how it is implemented, the educational context, and which spatial skills are being measured. Dakeev et al., (2021) even reported a negative effect size (d = -1.59), with the control group outperforming the AR group, highlighting the importance of careful instructional design and alignment. These mixed results indicate that although AR generally enhances spatial learning, outcomes vary depending on implementation and context.

Types of AR in Educational Settings

Educational AR implementations in primary mathematics generally fall into three main categories: Marker-Based AR (using physical images or objects to trigger AR content), Markerless AR (location-based or sensor-based, such as GPS or device sensors), and Immersive AR (using AR glasses, headsets, or fully immersive applications).

Analysis of the 26 included articles reveals a clear predominance of Marker-Based AR, which was utilised in 18 studies. Marker-Based AR remains the most common approach in primary classrooms due to its affordability, ease of use, and compatibility with readily available devices such as smartphones and tablets (e.g., EUCLIDA, LearnGeoAR, MAR Remedial Program, GeoGebraAR). Markerless AR and Context-Based AR were less frequently used, often appearing in studies that integrated AR with outdoor, location-based, or collaborative activities (e.g., AR-Classroom, ARSM). Immersive AR—which involves the use of AR glasses or advanced 3D environments—was reported in only a few studies (Daghriri et al., 2024; Serrano-Ausejo & Mårell-Olsson, 2024), but these immersive tools demonstrated particularly strong engagement and learning outcomes.

Although immersive AR was less commonly implemented (identified in four studies), the findings indicate that these tools are associated with higher reported effect sizes and deeper student engagement than marker-based AR. For instance, studies employing immersive AR reported effect sizes ranging from moderate to very large (e.g., d = 0.86 in Serrano-Ausejo & Mrell-Olsson, 2024), outperforming the mean effect size of marker-based applications (d = 0.61, as seen in Nadzeri et al., 2024 and others). Popular platforms such as Assemblr Edu and Merge Cube are frequently cited for their accessibility, integration with existing school devices, and teacher-friendly interfaces, making them practical choices for classroom adoption.

However, the review also highlights that pedagogical design remains a critical success factor regardless of the AR type. The effectiveness of AR, whether marker-based or immersive, depends on thoughtful integration into the curriculum, alignment with learning objectives, and adequate teacher preparation. Studies consistently emphasise that successful AR implementation requires more than just technology: it relies on sound instructional strategies, ongoing teacher training, and supportive infrastructure to maximise engagement and learning outcomes.

Discussion

Effects of AR Tools on Primary Students' Spatial Abilities

Analysis of the forest plot in Figure 3 conclusively demonstrates that augmented reality (AR) interventions significantly enhance primary students' spatial skills compared to traditional teaching methods. A positive impact was consistently observed across key sub-skills, such as mental rotation, spatial orientation, and spatial visualisation. This finding strongly aligns with the constructivist theory that meaningful learning arises from the active construction of knowledge. Unlike traditional media, AR provides unique cognitive affordances; rather than passively observing static 2D representations, pupils can actively manipulate, rotate, and deconstruct virtual geometric objects in three-dimensional space. This direct interaction bridges the critical gap between abstract geometrical concepts and concrete sensorimotor experience, fostering a deeper, more intuitive conceptual understanding.

However, while the overall trend is positive, the variability in effect sizes across the studies is an equally important finding. This heterogeneity highlights a key fact: AR is not a 'magic bullet' for pedagogy. Its effectiveness depends heavily on the quality of its implementation. Anomalous cases, such as the non-significant findings reported by (Krüger et al., 2019) (d = 0.24, p = 0.371), provide valuable insights. Contrasting these with high-impact studies such as those by (Supli & Yan,2024) makes it clear that AR's success lies not in the technology itself, but in the 'pedagogical wrapper' that surrounds it. Supli & Yan (2024) study likely succeeded because it integrated AR within a structured framework of inquiry-based learning and scaffolding. Conversely, studies with weaker outcomes, such as that by Dakeev et al., (2021), may have implemented AR as a simple replacement for older visual tools, without integrating it deeply into the pedagogy. This suggests that, while AR can be a powerful mediator or enabler of learning, the quality of instructional design remains the primary driver of successful outcomes.

These findings have profound implications for educators and policymakers alike, shifting the focus away from mere technological provision and towards the development of a supportive, holistic ecosystem. Otherwise, AR risks being reduced to a technological gimmick that is engaging in the short term but fails to deliver long-term learning gains. This ecosystem must include the following key elements: robust teacher professional development that goes beyond technical training to include pedagogical strategies for lesson design; careful curriculum integration that explicitly maps AR tools to specific learning objectives; and equitable access to digital infrastructure. Ultimately, effectively adopting AR requires a paradigm shift, moving from using it to deliver content to using it to facilitate student-led discovery and problem-solving.

AR's Role in Enhancing Understanding of Geometric Concepts

AR enhances students' grasp of geometric concepts by enabling them to engage with 3D objects and visualise spatial relationships. The study showed that AR applications improve students' comprehension of complex geometric ideas, such as angles, symmetry, and volume, through interactive and engaging experiences (Salinas, 2017).

As shown in Table 4 and Table 5, AR tools such as EUCLIDA, LearnGeoAR, and the MAR Remedial Program enable students to manipulate 2D and 3D shapes directly, making concepts like surface area, volume, angles, and symmetry more accessible (Nadzeri et al., 2024; Putri et al., 2023; Salinas, 2017; Sun & Chen, 2020). Marker-based and immersive AR applications support real-time exploration, allowing learners to observe geometric transformations, combine and partition figures, and experiment with spatial relationships, thereby deepening conceptual understanding (Amir et al., 2018; Schmid & Korenova, 2024). Moreover, AR-enhanced activities foster active and collaborative learning through hands-on experimentation and group discussion, essential for conceptual mastery and higher-order thinking skills (Phon et al., 2014; Schwarz et al., 2018). Finally, the interactive, game-like features of AR have been shown to accelerate student motivation and engagement, resulting in more meaningful and enjoyable geometry lessons (Radu et al., 2015; Saif et al., 2021).

Furthermore, meta-analysis of the 10 highest-quality experimental studies showed an average increase of 0.65 standard deviations (SD) in geometry test scores when AR was employed in primary mathematics classrooms compared to conventional teaching (see Table 6). AR's impact was notably greater for students with initially lower spatial abilities, indicating its potential to bridge learning gaps.

The results emphasise that AR's interactive, visual, and collaborative features of AR are central to deepening students' understanding of geometric concepts. AR strengthens conceptual comprehension and increases student motivation and engagement by making abstract shapes and spatial relationships tangible and manipulable. These advantages are maximised when AR activities are closely aligned with curriculum objectives and are supported by structured teacher scaffolding.

Moreover, integrating well-designed AR lessons into lesson plans and having them delivered by trained educators enables differentiated learning and ensures practical usability in classroom settings. To fully realise the benefits of AR for geometry mastery, schools must invest in targeted professional development and embed AR tools within existing curriculum frameworks.

Identify Key Factors Contributing to the Successful Implementation of AR in Primary Classrooms

Successful implementation of AR in primary classrooms is shaped by several interrelated key factors, as consistently highlighted in the reviewed studies. Teacher training and digital competence are foundational; educators who receive targeted professional development are better equipped to integrate AR tools effectively into their teaching practices, design meaningful AR-based activities, and provide structured scaffolding (Alalwan et al., 2020; Daghriri et al., 2024; Serrano-Ausejo & Mårell-Olsson, 2024). The qualitative synthesis shows that ongoing teacher support, including initial training and opportunities for collaboration, is crucial for overcoming technological and pedagogical barriers (Perifanou et al., 2023; Schwarz et al., 2018).

Curriculum alignment is another critical factor. AR content must closely match curriculum standards and learning objectives to maximise educational benefits and ensure student relevance (Putri et al., 2023; Salinas, 2017). Studies emphasise that AR is most effective when seamlessly embedded within lesson plans and complemented by traditional instructional strategies, allowing for differentiated learning and greater conceptual understanding (Amir et al., 2018; Schmid & Korenova, 2024).

Access to technology and infrastructure is essential for AR's practical use in classrooms. Schools must provide adequate hardware (such as tablets or AR headsets) and reliable internet connectivity to support AR applications (Alalwan et al., 2020; Daghriri et al., 2024). The success of immersive AR tools is especially dependent on robust infrastructure and technical support, as usability issues and device limitations can impede classroom adoption and student engagement (Deliyiannis et al., 2008; Javaheri et al., 2022).

Collaborative learning environments further enhance AR's impact. Studies show that group-based and peer-supported AR activities foster engagement, motivation, and deeper understanding of geometric concepts (Phon et al., 2014; Saif et al., 2021; Schwarz et al., 2018). Effective classroom management and instructional design—such as scaffolding, adaptive guidance, and clear task structures—are also necessary to ensure that AR is used productively and inclusively.

Other supporting factors include the usability and accessibility of AR tools, cost-effectiveness, and ongoing technical and administrative support. Barriers such as high expenses, limited resources, inadequate teacher training, and misalignment with the curriculum must be addressed for sustainable and equitable AR integration (Perifanou et al., 2023).

CONCLUSION

This mixed-methods systematic review of 26 articles demonstrates that Augmented Reality (AR) significantly enhances primary students' spatial reasoning and geometric understanding, with a meta-analytic average effect size of 0.65 SD for geometry test scores compared to traditional teaching. AR interventions most strongly improved spatial visualisation and reasoning, especially for students with initially lower abilities, and were most effective when closely aligned with curriculum objectives and supported by structured teacher training and adequate technology. The review also found that AR's interactive and visual features made abstract geometric concepts more concrete and engaging. However, successful implementation depended on teacher readiness, curriculum integration, and reliable infrastructure. While AR shows substantial promise for transforming primary mathematics education, addressing access, professional development, and pedagogical integration challenges is essential for widespread and sustained impact.

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