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Spatial Skill Development Through Augmented Reality in Mathematics Education: A Scoping Review

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Abstract
Spatial skills are widely recognised as foundational to success in mathematics, particularly in topics such as geometry, measurement, and visual modelling. In recent years, augmented reality (AR) has emerged as a promising educational technology capable of supporting spatial thinking through embodied and interactive experiences. However, existing research on AR's role in mathematics education remains fragmented, with limited understanding of when, how, and for whom it is most effective. This study conducted a scoping review of 23 peer-reviewed articles published between 2010 and 2024 and analysed them across five key dimensions: research trends, learning activities, AR tools, methodological approaches, and reported outcomes. The review identifies a growing global interest in AR for supporting spatial skills, particularly in Asia and Europe, and highlights its application across a range of educational levels and mathematical domains, especially in primary and junior secondary geometry and measurement. While many studies reported positive effects of AR on spatial skill development, findings remain inconsistent. These discrepancies appear to reflect not only differences in tool design and intervention period, but also a lack of attention to contextual factors, measurement approaches, and the learning process. By synthesising findings and gaps in the literature, this review contributes a more nuanced understanding of the conditions under which AR supports spatial skill development in mathematics education. In doing so, the paper highlights the need for future research to broaden content areas, improve assessment sensitivity, document carefully and investigate contextual variables, and examine learning processes in greater depth.

Keywords Augmented reality · Spatial skills · Mathematics education

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Introduction

Recognised as the ability to process spatial information mentally and physically, spatial skills encompass shapes, locations, paths, relations among entities, and the relations between entities and frames of reference (Newcombe & Shipley, 2015). They are sometimes referred to by related terms including spatial ability, spatial intelligence, spatial reasoning, and spatial thinking (Korkmaz & Morali, 2022). Since the 1920 s, spatial skills have been recognised for impacting mathematics practice, becoming a critical factor in intelligence assessment (Atit et al., 2022; Smith, 1964). In recent years, more and more studies have explored how spatial skills function in mathematics tasks and influence students' learning (Atit et al., 2022). Given that spatial skills find extensive application in tasks related to conceiving and constructing spatial models, analysing geometric objects, interpreting diagrams, and identifying functions, the cultivation of students' spatial skills emerges as a crucial component of effective mathematics learning (del Cerro Velázquez & Morales Méndez, 2021b).

Augmented reality (AR) is a technology that integrates digital objects into a real environment in real time (Azuma, 1997). Like other technologies, AR is often introduced with high expectations, but its effectiveness depends heavily on instructional or pedagogical design and several contextual factors (Gil Parga et al., 2024). The claim is that the use of AR has the potential to enhance students' learning experiences by introducing interactive 3D objects and overlaying virtual elements onto real-world spaces, facilitating ubiquitous, collaborative, and situated learning (Chang et al., 2022; Wu et al., 2013). Recent research has shown that AR-driven interventions have made inroads into various mathematical topics, including geometry, algebra, statistics, and probability (Jabar et al., 2022). Additionally, the affordance of AR in enhancing spatial skills has gained considerable attention in STEM education (del Cerro Velázquez & Morales Méndez, 2021b; Papakostas et al., 2021). However, questions remain about how AR supports the development of spatial skills across different mathematical domains and education levels.

Despite the growing interest and increasing number of applications, however, the research so far remains fragmented and inconclusive in the mathematics education field, particularly with regard to how spatial skills interact with AR's affordances and the design of associated activities and their use. There is still a lack of clarity about which types of spatial skills are being addressed, what kinds of AR tools and how they are employed, and what outcomes are achieved. As such, there is a need for a review to map and consolidate existing research, identify gaps, and offer a more nuanced understanding of the conditions under which AR supports spatial skill development in mathematics education in order to inform future practices.

In this paper, therefore, we adopt a scoping review methodology which is appropriate for synthesising an emerging but underdeveloped body of literature rather than evaluating the effectiveness of interventions per se (Arksey & O'Malley, 2005). To achieve our goals, the review should include relevant studies from early education to higher education, exploring the malleability of spatial skills with the support of AR over the long term, and contributing valuable suggestions for future practices and research. By narrowing our scope to mathematics education, this review provides a focused and domain-specific lens on the intersection between AR and spatial learning to help identify what is currently known, where the gaps lie, and what directions future research might take. Thus, the findings of this review contribute by clarifying how research on the intersection of AR and spatial skill development has evolved and advancing our understanding of how AR-mediated environments shape such skills, particularly in mathematics education. Practically, the findings will also provide insights for educators and instructional designers into the feasibility and complexity of integrating AR into mathematics teaching.

Literature Review

The Close Relationship Between Spatial Skills and Mathematics Learning

Spatial skills refer to the ability to process spatial information, including the perception, manipulation, and transformation of shapes, locations, paths, and spatial relationships among entities and frames of reference (Lohman, 1979; Newcombe & Shipley, 2015). They include a collection of cognitive functions and aptitudes, such as spatial visualisation, spatial perception, mental rotation, and spatial orientation, among others (Atit et al., 2020; Lohman, 1979). Recent work further explores the role of spatial skills within problem-solving contexts (Rafi et al., 2005). Studies suggest that even seemingly simple spatial problems increase in complexity when embedded in STEM domains, as they require the coordination of multiple cognitive processes (Atit et al., 2020; Hawes et al., 2017). At the same time, research has shown that learners can develop various spatial skills in parallel when engaged in meaningful mathematical and STEM-related activities (Hawes et al., 2017).

Within mathematics learning specifically, this link is also historical as spatial tests were used to identify individuals with mathematical aptitude (Smith, 1964). Over time, subsequent studies have revealed the positive correlation between spatial skills and achievements in mathematics education (Nagy-Kondor, 2017), a relationship that becomes apparent even in early childhood (Wang, 2020). Beyond academic performance, spatial skills also influence learners' attitudes toward mathematics (Ferguson et al., 2015). For example, Maloney et al. (2012) found that individuals with lower spatial abilities tend to experience higher levels of math anxiety. In addition to their impact on learning outcomes and attitudes, spatial skills play a foundational role in shaping mathematics instruction and pedagogical approaches (Atit et al., 2022). The impact of spatial skills spans a wide array of mathematical concepts and topics, from fundamental content like counting and basic calculations to the intricate realms of geometry, algebra, calculus, and even advanced mathematics (Hawes et al., 2017; Mix & Cheng, 2012).

AR in Mathematics Education and Its Impact on Spatial Skills

AR is an advanced technology that seamlessly integrates virtual objects into a real environment in real time (Azuma, 1997), characterised by three core features: (1) combining real and virtual elements in a real environment, (2) running interactively and synchronously, and (3) aligning real and virtual objects with each other (Azuma et al., 2001). From a theoretical perspective, researchers investigate the integration of AR into mathematics learning through the lens of instrumental genesis (Trouche, 2004). For example, Sinclair (2025) suggests that when a student keeps adjusting gestures in AR to modify function graphs, they are no longer just manipulating the interface but transforming the AR environment into an instrument of thought for testing and refining their hypotheses. This approach suggests that AR's effectiveness depends not only on the technical features but on how students internalise the technology for mathematical problem-solving (Gusteti et al., 2025). More generally, AR's educational potential has attracted growing scholarly attention, with studies demonstrating that AR enhances students' learning performance and fosters more positive attitudes toward learning (Akcayir & Akcayir, 2017; Arici et al., 2019).

Based on these advantages, researchers have shown interest in using AR to support mathematical learning across a range of topics, including geometry, probability, vectors, and covariational reasoning (Cai et al., 2020; Demitriadou et al., 2020; Jaber et al., 2023; Martin-Gonzalez et al., 2016). Several reviews have synthesised findings from research in this field, stating that AR can enhance learning outcomes, conceptual understanding, motivation, and engagement, particularly within geometry and measurement, where visualisation demands are high (Ahmad & Junaini, 2020; Hidajat, 2023; İslim et al., 2024; Korkmaz & Morali, 2022).

These reviews all have discussion on AR's potential to develop students' spatial skills. Hidajat (2023) reported that seven studies linked AR use to improvements in spatial visualisation skills. Expanding this trend, İslim et al. (2024) found that 24 studies agreed on the positive impact of AR intervention on spatial skills. Ahmad and Junaini (2020) further suggested that the teaching and learning of mathematics could be improved through the development of spatial visualisation supported by AR. In addition, Korkmaz and Morali (2022) observed that various studies target different dimensions of spatial skills, such as spatial awareness, spatial analysis, spatial visualisation, proportional reasoning, and the understanding of two-dimensional representations of three-dimensional objects.

Although these reviews have agreed on the positive impact of AR on spatial skills, they typically address this aspect only as part of broader discussions on general learning outcomes or student motivation. Consequently, the relationship of AR specifically with spatial abilities remains unclear, and there is a lack of research on which specific dimensions of spatial skills are most affected, what mathematical domains these changes occur in, and how AR should be effectively employed to support such development. A focused synthesis is therefore necessary to deepen our understanding and guide future educational practices.

Current Reviews and Research Gaps

Although a few recent reviews have begun to explore the role of AR in developing spatial skills, most have concentrated on STEM or engineering education rather than mathematics. del Cerro Velázquez and Morales Méndez (2021b) reviewed 17 studies and found that AR significantly improves spatial skills, particularly spatial visualisation, by helping students manipulate real and virtual objects to understand abstract concepts. Similarly, Papakostas et al. (2021) reviewed 32 studies in engineering education, emphasizing that AR enhances learning outcomes, but also pointed out the need for more personalised AR applications.

While these two reviews provide valuable insights into AR's role in enhancing spatial skills, their focus has primarily been on engineering and STEM education in secondary and higher educational settings. Thus, a gap remains in our understanding of whether AR can effectively enhance spatial skills in mathematics learning, especially during the early stages of education. Given the relationship between spatial skills and mathematical performance (Atit et al., 2022), and the malleability of spatial skills in young learners (Yang et al., 2020), a comprehensive review within the field of mathematics education, spanning from pre-school to university levels, is pivotal. Such an undertaking will contribute to not only exploring the connection between mathematics learning and spatial skills but also examining AR's effects on enhancing spatial skills in the early educational stages before secondary education.

Summary and Research Questions

Existing literature and previous reviews on AR in education often address spatial skills only as one component within broader learning outcomes, typically framed in the context of STEM or engineering education. Consequently, little is known about how different dimensions of spatial skills, such as spatial visualisation, spatial orientation, and spatial perception, are specifically influenced by AR in mathematics education. Moreover, the ways in which AR-based learning activities are designed to target these distinct spatial skills across various mathematical domains remain underexplored. Given this landscape and the identified research gaps, this review aims to provide a focused synthesis of the role of AR in enhancing spatial skills within mathematics education. To scope this investigation, we address the following research questions:

RQ1: What are the research trends on AR and spatial skills in mathematics education?

RQ2: What mathematical learning activities have been conducted to improve students' spatial skills based on AR?

RQ3: What kind of learning tools with AR technology have been employed in the mathematical learning activities?

RQ4: How have researchers studied AR's effects on enhancing spatial skills in the mathematical learning activities?

RQ5: What conclusions about AR's effects on enhancing spatial skills have been proposed by researchers?

Methodology

Research Process

This scoping review adheres to the framework proposed by Kitchenham (2004), which is acknowledged as suitable for research on the topic of digital tools. In accordance with this framework, the study was structured into three distinct phases: planning the review, conducting the review, and reporting the review.

During the initial phase of review planning, a comprehensive review protocol was formulated in alignment with our research objectives. The primary focus was to explore the use of AR for the enhancement of students' spatial skills within mathematical education. This phase included the development of search strategies, criteria for paper selection, and the identification of specific data collection parameters. The protocol was thoroughly discussed and refined within the research team to ensure the appropriateness of the scope and search terms. Subsequently, the second phase involved the identification and selection of relevant studies in accordance with the established protocol, along with the extraction of pertinent data from each selected study. Additionally, two of the authors piloted the coding on two sample studies in collaboration with three other researchers to refine our criteria and ensure coding consistency. This rigorous approach was implemented to ensure methodological rigour and comprehensiveness in the analysis. The third phase resulted in the presentation of the cumulative findings obtained from these systematic processes.

In the following sections, we will introduce the process of study selection and data collection, clarifying how the results of this review were derived.

Selecting Studies

The PRISMA 2020 flow diagram (Page et al., 2021) served as a guiding reference during the planning and implementation phases for study selection in this review. Figure 1 illustrates the search and selection process employed in this study.

Initially, this study explored two central topics derived from the research questions: AR and spatial skills. To ensure the retrieval of pertinent articles, we identified and applied key terms frequently used in prior literature on these topics. Based on this, two query strings, "Augmented Reality" OR "Augmenting Reality" OR "AR" OR "Mixed Reality" OR "MR" and "Spatial Intelligence" OR "Spatial Ability" OR "Spatial Skill" are used to search. In terms of the time span and database selection, we conducted searches within the Web of Science and Scopus databases, employing a time frame spanning from 2000 to 2024, since the concept of AR was distinctly defined by Azuma et al. (2001). The search was performed iteratively and finalised on the 22nd of November, 2024, yielding 888 records. Subsequently, 723 papers underwent screening after eliminating duplicates.

To ensure the relevance and rigour of included studies, we first established inclusion and exclusion criteria aligned with our research questions, as detailed in Table 1. Two researchers first independently evaluated the publication details

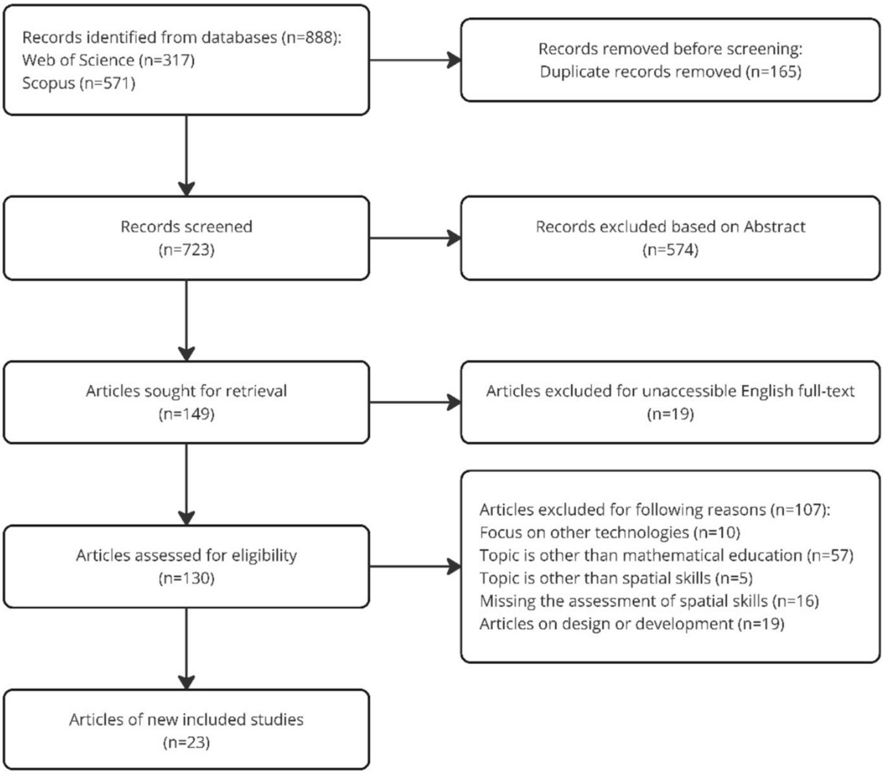


Fig. 1 The search and selection process of this study

Table 1 Inclusion and exclusion criteria

Inclusion	Exclusion
Articles from journals or conference proceedings	Sources such as book chapters, theses, dissertations, reports, or non-peer-reviewed publications
Available in English full-text	Articles only available in summary or not English languages
Articles focusing on AR	Articles that focus on environments such as virtual reality and mixed reality
Articles involving and testing spatial skills	Articles that mention spatial skills without any form of measurement
Articles concerning mathematical education	Articles that focus on professional training, games, or other subjects
Empirical articles	Editorials, reviews, and articles on design or development

and abstracts of 723 papers and then resolved the discrepancies through discussion, with unresolved cases retained for full-text review. In this phase, 574 papers were excluded as they were either originating from non-peer-reviewed or informal sources, or lacking a focus on AR, spatial skills, or education. Then, 19 additional papers were excluded during full-text retrieval due to the unavailability of English versions, as accurate interpretation could not be guaranteed in other languages. Consequently, 130 articles progressed to full-text assessment.

Furthermore, this study established inclusion and exclusion criteria aligned with research questions, as detailed in Table 1, to facilitate the literature screening process. Two researchers independently read the full texts of all 130 articles and made inclusion decisions based on the predefined criteria. Studies were required to report empirical research involving participants using AR tools in the context of mathematics learning. The identification of AR was based on whether the technology integrated virtual content with the physical environment, as defined by Azuma et al. (2001). Additionally, studies needed to assess spatial skills, either specific (e.g. mental rotation or spatial visualisation) or composite, using clearly described and appropriate measurement tools. Articles were excluded if they lacked measurable spatial outcomes, focused on professional or vocational training, or employed technologies unrelated to AR, such as purely virtual or mixed reality environments. Disagreements occurred in four cases, which were reviewed by another researcher who recommended the inclusion of 3 among them. Ultimately, the analysis encompassed a total of 23 articles.

Collecting and Analysing Data

The study aims to examine the current state and emerging trends concerning the integration of AR for fostering spatial skills within mathematical education. To achieve this, a content analysis approach was employed for coding the articles, subsequently facilitating their categorisation based on shared attributes (Hsu et al., 2013). An evaluative framework was utilised to gather pertinent data from the selected 13 articles, thereby addressing the research inquiries. For each research question, a set of criteria was established, outlined in Fig. 2.

In response to RQ1, this study examines research trends and progress in AR and spatial skills within mathematics education over different time periods by focusing on the year of research publication. Additionally, the educational stage of intervention is considered, determining whether subjects are from pre-school, elementary school, junior high school, senior high school, or university. Lastly, the geographical location of the intervention is investigated because variations in educational systems and needs across regions potentially affect research interests in AR and spatial skills (del Cerro Velázquez & Morales Méndez, 2021b).

For RQ2, mathematics activities are analysed in terms of content, context, and duration/frequency. Learning modules are aligned with the curriculum standards established by the National Council of Teachers of Mathematics in the UK (National Council of Teachers of Mathematics, 2000). Contextual information includes the number of students partaking in the learning activity, student recruitment methods, the physical setting (classroom or laboratory), and whether learning is conducted individually or in groups.

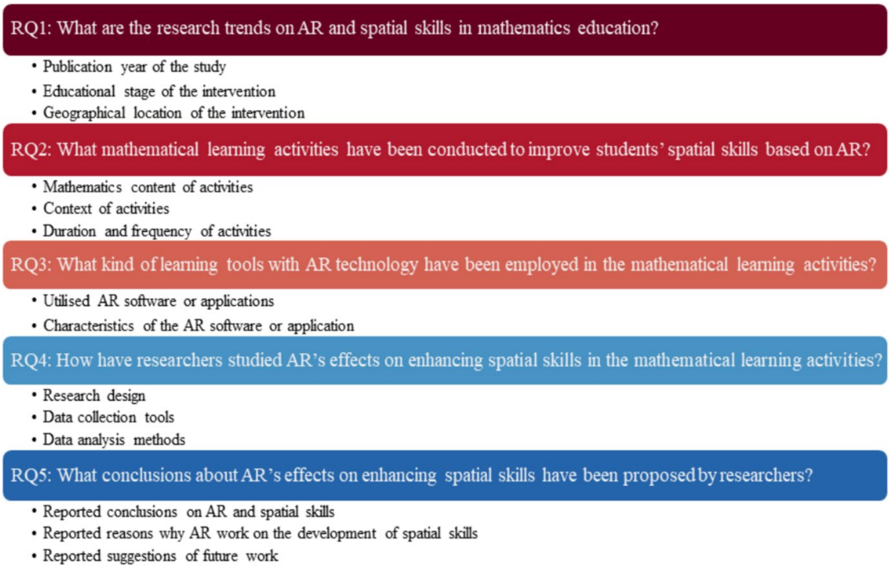


Fig. 2 The criteria for collecting and analysing data

In addressing RQ3, we first identify the specific AR technology systems in the research and examine their characteristics by exploring the hardware utilised, the type of interaction employed, and the level of embodied interaction. Embodied interaction levels are classified into categories "symbols and text", "low-embodied", "high-embodied", and "high-embodied with narrative" based on the framework developed by Johnson-Glenberg and Megowan-Romanowicz (2017).

Regarding RQ4, we examine the research design, determining whether researchers employed quantitative, qualitative, or mixed research methods to investigate the relationship between AR and spatial skills. Subsequently, we look into the data collection tools utilised in assessing various aspects of spatial skills as well as the data analysis methods used to draw conclusions regarding the connection between AR and spatial skills.

Turning to RQ5, we initially focus on the reported conclusions pertaining to the impact of AR on spatial skills, and the findings and outcomes as established by researchers. We then look into the rationale underpinning the role and features of the AR learning experience that the authors of the selected papers provide as support for the positive influence on spatial skill development. Lastly, we investigate whether the papers provide suggestions for future endeavours, elucidating the potential directions and areas of improvement in forthcoming AR and spatial skills research.

A structured online survey instrument containing the inquiries was established to gather information from each individual article. Three researchers participated in the process of reading the full texts and coding information. For each study, two researchers filled in the online survey to answer questions based on the data collection criteria. Cohen's Kappa coefficient was used to measure the consistency of the researchers' answers, yielding a value of 0.990, indicating a high level of agreement among the researchers' perspectives on the same articles. The inconsistent items were then discussed to reach a consensus, and based on the information that was collectively accepted, the research questions were answered.

Results

This review includes 23 empirical studies published between 2015 and 2024, all focusing on the use of augmented reality (AR) to enhance students' spatial skills in mathematics education. The basic information of these 23 studies is presented in Table 2. A detailed list of these studies and the extracted data is provided in the Appendix. The following sections will sequentially address the five research questions posed in this study.

RQ1: What Are the Research Trends on AR and Spatial Skills in Mathematics Education?

As illustrated in the bar graph of Fig. 3, the research concerning the integration of AR in the enhancement of students' spatial skills within mathematical education emerged in 2015, gaining substantial development after 2020, marked by a noticeable increase in the number of studies. This indicative pattern suggests a rising research interest in AR's potential impact on students' development of spatial skills within the realm of mathematical education since the year 2020, and this interest has continued to persist.

In relation to the educational stages depicted in the pie chart located at the lower left corner of Fig. 3, all five categories have been encompassed by these studies, reflecting the consistent exploration of the effectiveness of AR in improving students' spatial skills at every phase of education, from pre-school to higher education. Predominantly, the research has concentrated on the elementary school and junior high school levels, underscoring that the development of spatial skills is deemed significant within the foundational stages of education (Hawes et al., 2017; Yang et al., 2020). Hence, these studies also contribute to our understanding of the development of spatial skills at a young age. This finding indicates the significance of studying AR's effect on students' development of spatial skills in mathematical learning, as research in STEM subjects and engineering education predominantly addresses secondary and higher education levels (del Cerro Velázquez & Morales Méndez, 2021b; Papakostas et al., 2021).

The geographic scope of research exploring the application of AR in enhancing spatial skills within mathematical education extends to multiple regions, including Luxemburg, Turkey, Iraq, Kazakhstan, India, Malaysia, Indonesia, China mainland, Taiwan, the USA, and Spain, as shown in the pie chart located at the lower right side of Fig. 3. This multifaceted geographical distribution underscores the global interest in AR as a potential instrument for fostering students' spatial skills in mathematical learning, especially in Asian and European regions. The local encouragement and support of the utilisation of digital technologies in mathematics education may provoke research in this area. Studies from Spain and Kazakhstan (S02, S09, S20) mentioned active exploration of the use of AR and other digital tools in education, in response to the requirement of improving students' learning autonomy. Additionally,

Table 2 Selected studies in the review

Study number	Primary author (year of publication)	Title of research	Publication
S01	Lin et al. (2015)	Assessing the effectiveness of learning solid geometry by using an augmented reality-assisted learning system	Interactive Learning Environments
S02	de Ravé et al. (2016)	DiedricAR: A mobile augmented reality system designed for the ubiquitous descriptive geometry learning	Multimedia Tools and Applications
S03	Gün and Atasoy (2017)	The effects of augmented reality on elementary school students' spatial ability and academic achievement	Education and Science
S04	Amir et al. (2020)	Elementary students' perceptions of 3Dmetric: A cross-sectional study	Heliyon
S05	Rohendi and Wihardi (2020)	Learning three-dimensional shapes in geometry using mobile-based augmented reality	International Journal of Interactive Mobile Technologies
S06	Flores-Bascuñana et al. (2020)	On augmented reality for the learning of 3D-geometric contents: A preliminary exploratory study with 6-grade primary students	Education Sciences
S07	Gecu-Parmaksiz and Delialioğlu (2020)	The effect of augmented reality activities on improving preschool children's spatial skills	Interactive Learning Environments
S08	Sun and Chen (2020)	Utilising MAR for remedial teaching of compound-cube-surface area at elementary school in Taiwan	International Journal of Information and Communication Technology Education
S09	Del Cerro Velázquez and Morales Méndez (2021a)	Application in augmented reality for learning mathematical functions: A study for the development of spatial intelligence in secondary education students	Mathematics
S10	Haas et al. (2021)	Case study on augmented reality, digital and physical modelling with mathematical learning disabilities students in an elementary school in Luxemburg	International Journal for Technology in Mathematics Education

Table 2 (continued)

Study number	Primary author (year of publication)	Title of research	Publication
S11	Hou et al. (2021)	Designing an alternate reality board game with augmented reality and multi-dimensional scaffolding for promoting spatial and logical ability	Interactive Learning Environments
S12	Guntur and Setyaningrum (2021)	The effectiveness of augmented reality in learning vector to improve students' spatial and problem-solving skills	International Journal of Interactive Mobile Technologies
S13	Shaghaghian et al. (2022)	Design and evaluation of an augmented reality app for learning spatial transformations and their mathematical representations	2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops
S14	Hanid et al. (2022)	Effects of augmented reality application integration with computational thinking in geometry topics	Education and Information Technologies
S15	Majeed and ALRikabi (2022)	Effect of augmented reality technology on spatial intelligence among high school students	International Journal of Emerging Technologies in Learning
S16	Özçakır and Çakıroğlu (2022)	Fostering spatial abilities of middle school students through augmented reality: Spatial strategies	Education and Information Technologies
S17	Koparan et al. (2023)	Integrating augmented reality into mathematics teaching and learning and examining its effectiveness	Thinking Skills and Creativity
S18	Tiwari et al. (2024)	Designing and evaluating an augmented reality system for an engineering drawing course	Smart Learning Environments
S19	Supli and Yan (2024)	Exploring the effectiveness of augmented reality in enhancing spatial reasoning skills: A study on mental rotation, spatial orientation, and spatial visualisation in primary school students	Education and Information Technologies
S20	Beisenbayeva et al. (2024)	Evaluating the impact of an augmented reality app on geometry learning in Kazakh secondary schools	Journal of Information Technology Education: Research

Table 2 (continued)

Study number	Primary author (year of publication)	Title of research	Publication
S21	Wang et al. (2024)	Exploring the impact of an augmented reality-integrated mathematics curriculum on students' spatial skills in elementary school	International Journal of Science and Mathematics Education
S22	Yuan et al. (2024)	Examining the impact of head-mounted augmented reality on learning engineering drawings: A case study for three-view drawing	Computer Applications in Engineering Education
S23	Burte et al. (2024)	Learning 3D matrix algebra using virtual and physical manipulatives: Statistical analysis of quantitative data evaluating the efficacy of the AR-Classroom	Learning and Collaboration Technologies. HCII 2024

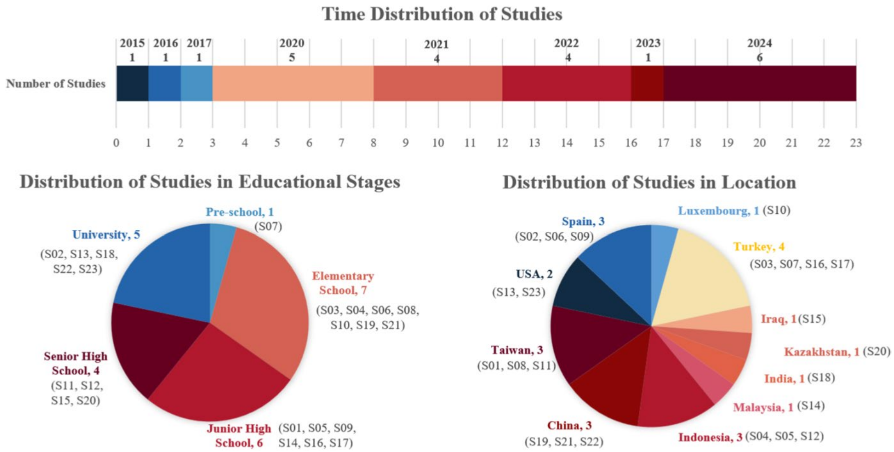


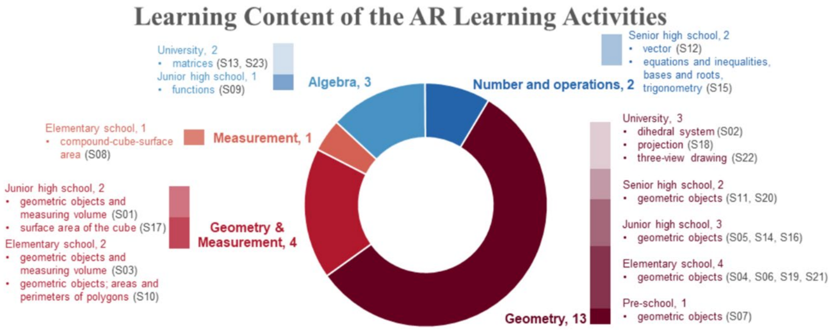
Fig. 3 The current state of the studies

S04 from Indonesia reported that AR had been employed in several schools to facilitate students' comprehension of geometric concepts. Furthermore, nine studies from Spain, Turkey, China mainland, Taiwan, Indonesia, Malaysia, and the USA (S01, S02, S05, S11, S13, S14, S17, S22, S23) received support from their respective ministries. Notably, S19 was funded through a collaborative initiative between China and Malaysia, suggesting the potential for cross-border cooperation in this field.

RQ2: What Mathematical Learning Activities Have Been Conducted to Improve Students' Spatial Skills Based on AR?

In terms of learning activities, this study places its focus on the analysis of both learning content and context. Regarding learning content, we have systematically coded specific knowledge points and their corresponding learning modules. As depicted in Fig. 4, among the 23 studies analysed, 13 incorporated AR into the teaching and learning of geometry to enhance students' spatial skills, including tasks ranging from identifying basic 3D shapes in pre-school settings to advanced calculations involving dihedral systems and projection in post-secondary-level education. Notably, the concept of 3D shapes emerged as a widely adopted knowledge area across various educational levels. Furthermore, four studies combined geometric objects with measurement and examined the use of AR to facilitate the calculation of objects' perimeter, area, and volume. Additionally, the potential of AR to improve spatial skills was explored in the context of learning functions, matrices, vectors, and complex calculations.

In the context of learning, we conducted an investigation that encompassed various dimensions, including the number of students participating in the learning activities, methods of student recruitment, the learning setting (whether in real classrooms or laboratories), student involvement in group activities, and the duration and frequency of these learning activities, as detailed in the Appendix.



Learning Content	Pre-school (1)	Elementary school (7)	Junior high school (6)	Senior high school (4)	University (5)
Geometry (13)	geometric objects (S07)	geometric objects (S04, S06, S19, S21)	geometric objects (S05, S14, S16)	geometric objects (S11, S20)	dihedral system (S02) projection (S18) three-view drawing (S22)
Geometry & Measurement (4)		geometric objects and measuring volume (S03) geometric objects; areas and perimeters of polygons (S10)	geometric objects and measuring volume (S01) surface area of the cube (S17)		
Measurement (1)		compound-cube-surface area (S08)			
Algebra (3)			functions (S09)		matrices (S13, S23)
Number and operations (2)				vector (S12) equations and inequalities, bases and roots, trigonometry (S15)	

Fig. 4 Learning content of the AR learning activities

Concerning the number of participants, 16 of the studies involved more than 50 students in these activities, with five studies incorporating over 100 students. Recruitment methods varied, with nine studies employing convenience sampling and nine studies opting for targeted sampling based on criteria such as learning background, age, and digital literacy. Additionally, a test of spatial skills was utilised to select eight participants from a pool of 26 in S16. In contrast to the other studies, which used convenience or targeted sampling, S12 randomly selected two classes to receive treatments at SMAN 1 Ngemplak, Indonesia. Likewise, S18 recruited 392 students at random from the first-year undergraduate engineering course for their research. Consequently, the majority of students were drawn from class units, leading to the conduct of learning activities in real classrooms across 17 studies. In contrast, four studies opted for laboratory settings due to a smaller participant pool and a focus on in-depth learning process analysis. The rationale for one of S11's choices of a laboratory setting was special facilities. Furthermore, S13 and S18 were conducted remotely due to the COVID-19 pandemic or a specific focus on self-paced learning. With regard to the learning units, five studies implemented group learning, while students completed all learning activities individually in three studies. However, 15 studies did not report whether students worked in groups, suggesting that influence from peers may have been overlooked by researchers, despite its close association with AR learning (Wu et al., 2013). Finally, in terms of activity duration and frequency, 13 studies featured activities lasting nearly or exceeding 1 month or requiring multiple sessions. In contrast, five studies conducted activities in a single, limited session, while four studies did not provide information on this aspect.

RQ3: What Kind of Learning Tools with AR Technology Have Been Employed in the Mathematical Learning Activities?

This study places an emphasis on AR systems and their characteristics, as presented in the Appendix, where data related to the hardware used, interactive types, and the level of embodied interaction of the AR system are collected. It is noteworthy that the majority of researchers designed and developed their own AR systems, with 16 studies featuring self-developed systems. Notably, S03 mainly focused on building models as it used the AR building platform BuildAR to easily generate the AR system by uploading 3D models and marker images. Additionally, GeoGebra AR is the only system employed by more than one study, particularly in support of learning activities related to both geometry and algebra.

In terms of hardware, 20 studies used camera lenses to capture the real environment and present an integrated real-virtual interface on a screen. To be specific, mobile devices, especially tablets, have emerged as the preferred hardware choices. S16 and S22 also explored the feasibility of wearable devices by incorporating smart glasses. S15 did not report the hardware and the features of the AR system they used for practice. Regarding the interactive type of systems, GeoGebra AR and the system developed by S22 relied on a real plane for location and interaction, while other systems utilised image or model markers to seamlessly manipulate real and virtual elements. The virtual models alter as their corresponding markers are moved or rotated. The majority of studies employed colourful images with specific learning content related to virtual objects represented as markers, while three studies utilised black and white fiducial markers, including ARToolkit and QR Code. Two recent studies incorporated tangible interaction into AR systems by utilising LEGO models (S23) and the Magic Cube Puzzle Toy (S19). These systems provided corresponding virtual information that dynamically changed in response to modifications made by students to the physical objects, thereby enhancing students' engagement and interaction within the AR environments. As for the level of embodied interaction within the systems, it is noteworthy that all 22 systems support a high level of embodied interaction, enabling students to move around the environment, observing objects from various perspectives. Furthermore, in cases where image or model markers were employed, students could engage in physical interactions with the AR environment by moving and rotating the markers. In addition, the system used by S11 integrated a storyline titled "Lost in Space", where students' interactions became an integral part of the narrative, resulting in a high-embodied level of narrative interaction. In general, all AR systems enable students to navigate the AR environment, examine objects from different perspectives, and engage in physical interactions. The occurrence of these embodied interactive behaviours may constitute a pivotal factor in the development of students' spatial skills (S08, S09, S11). This aligns with the findings of research conducted by Lee-Cultura and Giannakos (2020), which suggests that embodied interactive capabilities contribute to the enhancement and cultivation of spatial skills.

RQ4: How Have Researchers Studied AR's Effects on Enhancing Spatial Skills in the Mathematical Learning Activities?

To understand how researchers examined whether the use of AR improved students' spatial skills, this study explores their research methods, how they assessed spatial skills, and their data analysis techniques, with specific details available in the Appendix.

The 23 studies reviewed consisted of 18 quasi-experimental studies, 2 mixed-method studies that combined quasi-experiments with interviews, and 3 case studies. Among the 20 quasi-experimental studies, 14 compared students' performance in spatial skills tests before and after learning activities under AR and non-AR conditions, while 3 grouped students based on their mathematical or spatial ability to examine the impact of AR intervention on different students (S01, S04, S18). S13 employed a single-group pre-test and post-test design without a control group, focusing on within-group changes only. Two recent studies set two experimental groups to explore the influence of different AR interactive features. In S22, one group of students used tablet-based AR, while the other group utilised a head-mounted device that supported multimodal interactions, including gesture, voice, and gaze inputs. Similarly, in S23, one group manually adjusted the rotation angle through touchscreen operations to update the rotation matrix, whereas the other group used an AR system that automatically captured the rotation angle of a handheld LEGO model to update the matrix. While quasi-experimental studies focused on measuring the effects of AR interventions and comparing different AR designs, the three case studies provided in-depth analyses of students' learning processes to uncover how AR supported the development of their spatial skills. Likewise, S01 and S04 incorporated interviews alongside quasi-experiments to explore students' perceptions of the AR systems and tasks, offering additional insights into their learning experiences.

To investigate the connection between AR use and students' spatial skills, all studies tried to evaluate students' spatial skills objectively. Twenty-one studies used tests for this purpose. Moreover, S05 developed a specific observation scale with categories for manual coding of students' behaviours, while S10 prepared questions for an interview format. Regarding the specific spatial skills tested, spatial visualisation, mental rotation, and spatial skills within specific knowledge content were the most tested factors, as shown in Fig. 5. Some studies used proven tools, such as Purdue Spatial Visualisation Test (Guay, 1977), Differential Aptitude Test (Bennett et al., 1973), MGMP Spatial Ability Test (Ben-Chaim et al., 1988), while ten studies developed new assessment tools tailored to specific learning content (S01, S06, S08, S11, S12, S15, S17, S20, S21, S22).

In terms of data analysis, all 20 experimental studies employed descriptive statistics to summarise students' performance before and after the learning activities. Among them, 16 studies further conducted inferential statistical analyses, using either parametric or non-parametric tests, to determine whether there were significant differences between experimental and control groups or significant pre-post differences within groups, thereby evaluating the effect of AR on spatial skill development. Three case-study studies (S05, S10, S16) applied manual coding to analyse students' learning processes. Regarding variable configuration, spatial skills were treated as the

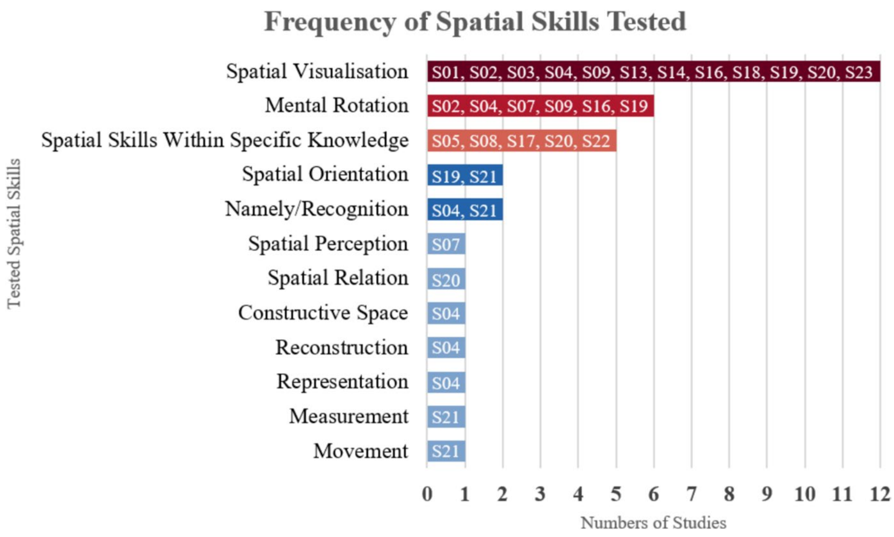


Fig. 5 Distribution of spatial skills tested across studies

dependent variable in 21 studies. The two exceptions were S04 and S18, which categorised students into different groups based on their spatial skill levels to investigate whether AR provided equal benefits to students with varying spatial abilities. Moreover, S16 used spatial skills both as a dependent variable and as a grouping variable.

RQ5: What Conclusions About AR's Effects on Enhancing Spatial Skills Have Been Proposed by Researchers?

This study synthesises the findings of 23 selected studies on AR's impact on students' spatial skills. While many studies suggest AR can enhance spatial skills, the results are not entirely consistent, indicating the complexity of AR's influence on learning.

Seventeen studies focused on examining the effectiveness of AR interventions on spatial skills development. Among these studies, 13 conducted statistical comparisons of students' test scores between experimental and control groups. Eight studies reported significant advantages for students in the AR intervention group (S07, S08, S09, S12, S14, S15, S17, S19), while three found no significant differences between groups but observed significant pre-post improvements within the AR group (S03, S11, S23). Besides, S21 identified significant effects only in a specific sub-dimension, *Movement of Graphics*, and S22 found that using head-mounted glasses AR and the non-AR desktop system was equally effective, though both outperformed handheld AR devices. For four studies not conducting inferential statistical tests for between-group comparisons, two of them observed greater improvement in the AR group over time (S02, S20), while three reported higher post-test scores for students using AR (S06, S13, S20).

Three studies explored the influence of students' individual characteristics on their response to AR-based learning, yielding varied results. S01 found that AR significantly benefited students with average and low mathematical abilities but had no significant effect on high-performing students. And S04 observed differences in students' perceptions of AR systems and tasks based on their spatial skill levels. Meanwhile, S18 suggested that AR was beneficial for all students, regardless of their initial level of spatial skills.

Three case studies provided qualitative insights into how the AR experience contributes to spatial skills by analysing students' learning processes. S05 reported that AR effectively increases students' spatial learning activities. S10 found that, with the use of AR, students began to envisage the global strategy of possible solutions to problems before executing procedures, indicating an improvement in spatial reasoning. S16 indicated that the positive effects of AR persisted after the intervention, as students continued to apply spatial thinking and mental rotation when answering questions in the post-test.

Two studies compared different types of hardware for AR and reached opposing conclusions. S16 found no significant difference in the impact on students' spatial skills, regardless of whether they used AR via tablets or smart glasses. In contrast, S22 reported that head-mounted AR resulted in greater gains, attributing this to the richer hands-on manipulation it facilitated.

Given the inconsistent results regarding AR's influence on spatial skills, which reflect the complexity of its impact on learning, this study explores researchers' perspectives on the underlying reasons why AR-based learning may enhance students' spatial skills, as illustrated in Fig. 6. The most widely recognised advantage, supported by eight studies, is the manipulability of AR objects, which allows students to interact with and modify virtual elements dynamically, fostering deeper spatial understanding (S08, S09, S11, S17, S18, S19, S21, S22). The second most frequently mentioned benefit, supported by six studies, is AR's seamless integration into the real environment (S03, S04, S09, S11, S16, S22). In addition to these core factors, AR's ability to present objects from multiple perspectives (S07, S09, S11, S16) and its three-dimensional nature (S08, S10, S18, S20) are separately recognised by four studies as important contributors to spatial skill development. S16 further explained that embedding virtual objects into the real environment and enabling observation from various angles allow students to describe objects using object-centred attributions,

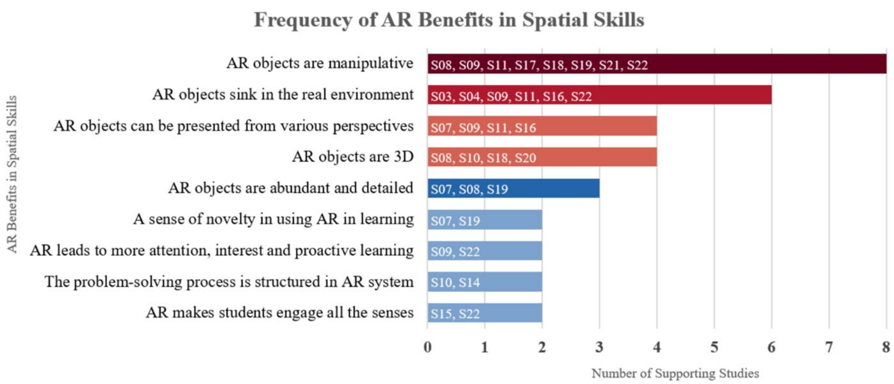


Fig. 6 Frequency of AR benefits in spatial skills

rather than partner-centred or egocentric perspectives. Object-centred attributions encompass objects' relative locations and their inherent spatial characteristics, facilitating a comprehensive understanding of the objects (Schober, 2009).

Several additional advantages of AR are noted in the literature, though less frequently. Three studies (S07, S08, S19) emphasise the richness and detail of AR objects, suggesting that highly detailed virtual representations support more accurate spatial reasoning. The sense of novelty that students experience when encountering AR in learning, mentioned in S07 and S19, is believed to enhance engagement, while its ability to capture attention, stimulate interest, and encourage proactive learning is similarly recognised in S09 and S22. Furthermore, AR's potential to structure problem-solving processes (S10, S14) and engage multiple senses (S15, S22) is also discussed, suggesting cognitive and perceptual processes may be related to spatial skills.

Based on the complex results and various reasons regarding the impact of AR on spatial skills, this study also gathers researchers' suggestions for future practice and research. As some studies confirmed the positive impact of AR on students' spatial skills, researchers advocated for the encouragement of AR use in mathematical education and the inclusion of more knowledge content (S01, S02, S06, S07, S09, S10, S11, S12, S17, S21, S22). They also recommend additional training for educators to better support the integration of AR in teaching and learning (S09, S15). Technically, dynamic and authorable objects are recommended to improve the interactive level of the AR systems (S01, S18, S23), as cloud technology is suggested to enhance the performance of AR systems (S02). In terms of research, most researchers believe it is necessary to investigate the impact of AR on a broader range of students, especially those from different age groups (S01, S03, S04, S07, S10, S13, S21). S09 calls for a conclusive study such as qualitative meta-analysis, to draw definitive conclusions about the impact of AR across different age groups. Extending the scope of participants will also support the investigation of potential contextual factors, such as task design, material, setup, and participants' gender, major, and academic aptitudes (S06, S18, S19, S21, S22, S23). Some researchers emphasise the importance of innovations in assessing spatial skills and propose self-evaluation methods (S02) and integration with mathematics course assessments (S01, S10). In a different vein, S18 suggests the exploration of embedding assessment experiences directly within AR activities. They also propose collecting log data to track students' learning processes. Similarly, other researchers also ask for more in-depth analyses of students' learning processes, particularly focusing on their mental activities (S06, S07) and behavioural patterns (S11) when learning with AR.

Discussion and Conclusion

In contrast to previous reviews that examined AR's effect on spatial skills primarily as part of broader learning outcomes or mainly in STEM or engineering contexts, this study focused specifically on reviewing the use of AR in mathematics education in relation to students' spatial skills. Following the PRISMA 2020 guidelines, 23 studies across all education levels were selected and then examined in five key dimensions: research trends, learning activities, tools, methods, and conclusions.

The discussion first summarises the main findings from these five dimensions to delineate the current state of knowledge in this domain. It is then organised around four perspectives designed to present the core findings of this review while also making visible the gaps that still constrain our understanding of how AR supports spatial skill development: cognitive (AR as a problem-solving instrument), technological (the accessibility and adaptability of AR tools), contextual (the role of classroom and instructional factors), and methodological (how AR's impact is measured and interpreted). Finally, directions for future research are suggested.

The collected data reveals growing global interest, especially across Asia and Europe, and the wide application of interactive AR tools. This may be related to government initiatives in these regions, including special funding and regular public activities that promote the application of AR technologies (Du, 2025; Tomás, 2022). Other factors, such as economic, cultural, and institutional differences, may also contribute, but exploring these complex underlying causes calls for further investigation (Jung et al., 2018).

Since 2020, studies have increased steadily and now span all educational levels, with over half focused on primary and junior high schools. AR is widely used across various topics, from the identification of basic 3D shapes to more advanced mathematical concepts such as measurements and complex calculations. Most tools employ plane recognition or image targets to support embodied interaction, while newer studies explore wearable devices and tangible objects to enhance interactivity.

As for findings, AR's effectiveness remains varied, highlighting the need for deeper investigation. While the majority of studies suggest AR can effectively support the development of students' spatial skills in mathematics education, as statistically significant improvements were frequently observed under AR conditions, some studies found no significant differences between groups or identified significant progress only in specific skill subdomains, highlighting the importance of task design and contextual variables. Emerging research has begun to explore the impact of learner characteristics, interaction types, and hardware differences in mediating AR's effectiveness on spatial skills. Moreover, qualitative studies explore AR's potential from a mechanistic perspective, suggesting its effectiveness may lie in shaping students' problem-solving strategies, promoting active exploration, and sustaining engagement throughout the learning process.

These findings reinforce earlier reviews (Hidajat, 2023; İslim et al., 2024) that reported AR's potential to enhance spatial skills, particularly in geometry and measurement. Yet, the observed inconsistencies in learning outcomes across these studies suggest that its impact is shaped by more than just technological features. While supporting claims that embodied and interactive AR tools play an important role in spatial skill development (Lee-Cultura & Giannakos, 2020), the review also underscores the importance of contextual integration, such as collaboration, instructional scaffolding, classroom design, and assessment approaches, in realising AR's full potential in mathematics education.

As previous reviews (del Cerro Velázquez & Morales Méndez, 2021b; Papakostas et al., 2021) that addressed AR's impact on spatial skills primarily as part of broader discussions within STEM or engineering education, this study offers a more domain-specific and nuanced synthesis within mathematics education. It identifies not only the types of spatial skills and AR tools involved but also highlights under-explored variables such as learning contexts, instructional strategies, and learner characteristics. Furthermore, it draws attention to key methodological gaps, including the limited use of qualitative approaches, inconsistent assessment instruments, and a lack of focus on early learners. These findings collectively point to the need for more fine-grained research into the conditions and mechanisms through which AR supports spatial skill development, framing the discussion that follows, which explores four key issues shaping the future use of AR in mathematics education.

The Unique Contribution of AR in Mathematics Education: As a Problem-Solving Strategy

Selected studies span all educational levels and cover diverse mathematical topics, from basic 3D shapes to advanced measurements and calculations, reflecting the general close relationship between spatial skills and mathematical learning, where spatial skills are recognised as a cognitive strategy in problem-solving (Casey & Fell, 2018). This study offers insight into how such strategies are enacted within AR learning environments by referring to empirical findings from S10, which observed that students using AR exhibited more structured problem-solving strategies, and S16, which found that AR-supported tasks encouraged object-centred exploration. These findings suggest that AR enables students to actively engage spatial skills in ways that structure their problem-solving processes. In this sense, AR supports not only the development of spatial skills but also its use as a cognitive strategy for problem-solving. This aligns with the framework of instrumental genesis (Trouche, 2004), where digital tools like AR are internalised by learners and become instruments of thought. For instance, Turgut and Drijvers (2021) demonstrate how dynamic geometry software helps students develop specific instrumentation schemes for problem-solving. Similarly, AR enables students to develop new strategies for mathematical tasks through interaction with objects in spatial and object-centred approaches. This characteristic makes AR's application extensive, spanning a wide range of educational levels—from preschool to university, and encompassing diverse mathematical domains, including geometry, measurement, algebra, and arithmetic operations.

The Accessibility Gap: Custom AR Tools vs. Classroom Realities

Many reviewed studies employed custom-developed AR tools featuring high interactivity through marker-based, tangible, or multimodal interactions. While these designs offer rich embodied learning experiences that influence the development of spatial skills (Lee-Cultura & Giannakos, 2020), their integration into everyday classroom practice may face significant challenges. On the one hand, their reliance on specialised hardware and technical support limits their practicality in everyday classrooms (Elkoubaiti & Mrabet, 2018). On the other hand, they relate to teachers' limited willingness to adopt tools that cannot be modified to suit their pedagogical needs (Silva et al., 2023). For educators, most AR platforms are difficult to adapt because they demand advanced technical expertise to modify content (Villanueva et al., 2020). One proposed solution to these challenges is the development of authoring tools that enable teachers and even students to design and create personalised AR content (Silva et al., 2023; Villanueva et al., 2020). Moreover, as Oliveira da Silva et al. (2019) argue, overcoming these constraints also requires broader institutional support, including sustained teacher professional development and school-level strategies for meaningful technology integration.

When AR Alone Is Not Enough: Overlooking Contextual Factors

Many of the reviewed studies were not published in mathematics education journals, suggesting that current research has often prioritised technological affordances over subject-specific pedagogical integration. This focus reflects the widespread interest in exploring the features of AR as a rapidly developing technology in educational contexts. Previous research has suggested that AR's features such as 3D representation and embodied interaction (Lee-Cultura & Giannakos, 2020), as well as extended intervention duration (Gavish et al., 2015), are key factors contributing to AR's educational effectiveness. However, this review indicates that these technological affordances alone may not fully explain learning outcomes. Nearly all reviewed studies incorporated 3D representations, high-level embodied interactions, and were conducted over extended periods, but their findings varied. While some studies reported significant improvements in spatial skills compared to control groups, others found no significant differences between conditions.

The inconsistency may be due to AR's effectiveness depending not only on its technical affordances, but also on how it is integrated into teaching and learning contexts (Bower et al., 2014). As Price (2015) states, employing advanced technologies in learning often requires the orchestration of contextual factors, such as collaborative settings, teacher guidance, and overall lesson design. For example, S08 reported they used operation sheets and structured group discussions to scaffold students' learning under AR conditions, showing how AR can be embedded within broader pedagogical strategies and lending more credibility to the reported learning gains. By contrast, many studies reviewed offered limited information about whether students used AR individually or collaboratively, or how the instruction design incorporated the technology. This lack of contextual information may lead to misconceptions about how AR should be implemented in classroom settings and ultimately weakens the credibility of claims about its effectiveness. Therefore, future research should consider reporting contextual factors, such as collaboration, teacher involvement, and task design, to build a more nuanced understanding of when and how AR can support spatial skill development in mathematics education.

Exploring the Mechanisms of AR's Impact: From Outcomes to Processes

The reviewed studies used a range of instruments to evaluate spatial skills, covering traditional cognitive dimensions such as visualisation, perception, mental rotation, and orientation, as well as context-specific tools designed to capture spatial skills within particular mathematical problem situations. This diversity reflects not only the multidimensional nature of spatial skills but also their inherent complexity when enacted in problem-solving processes (Atit et al., 2020; Lohman, 1979).

Many studies rely on standardised tools for pre- and post-tests, which, while useful for capturing changes in specific dimensions, may overlook meaningful developments due to the interrelated and dynamic nature of spatial thinking (Kane et al., 2024). Some studies have addressed this issue by selecting or developing tools aligned with specific learning content, which appear more sensitive to targeted skill gains (Creswell, 2012).

Beyond measuring outcomes, as several researchers have suggested, deeper insights may come from examining students' learning processes, particularly their mental activities (S06, S07) and behavioural patterns (S11) during AR-supported tasks. Furthermore, integrating data collection methods such as eye-tracking and interaction logs, as well as employing longitudinal designs, can help reveal not only immediate outcomes but also how spatial skills develop and transfer over time (Argelagós Castañ et al., 2018; Nozaki & Study,2024).

To guide future research on the use of AR in supporting the development of spatial skills within mathematics education, and drawing from the findings of this review as well as suggestions identified in the included studies, the following directions are proposed:

(1) Test generalisability of conclusions: expand the range of mathematical content examined and assess the impact of AR on spatial skills across more mathematical scenarios, especially regular classes. Conduct longitudinal studies to investigate the long-term effects of AR technology on spatial skills at various educational stages
(2) Explore contextual factors: investigate how student characteristics, teaching methods, equipment, collaboration, and more generally the classroom environment or other contextual factors influence the role of AR in developing spatial skills in mathematics learning
(3) Improve measurement accuracy: develop new measurement tools, especially real-time and behaviour-based measures to capture the full scope of cognitive processes related to spatial skills when using AR
(4) Deepen understanding of the learning process: employ mixed methods to explore the student learning process with AR, providing further insights into how AR aids in the development of spatial skills

While this review offers valuable insights, it also has limitations. First, publication bias may have led to an overestimation of the positive effects of AR on spatial skills. Moreover, as our review primarily relies on the screening and analysis of existing literature, the selection of databases and search terms may have influenced the results. Additionally, researchers may also consider expanding the coding criteria to encompass additional aspects of the investigation, as the current criteria were influenced by the authors' backgrounds and research interests.

Appendix

Table 3 Evaluation summary of key findings from selected studies

Study number	Primary author (year of publication)	Learning content			Learning context					AR system				Research design				
		Mod	Kno	ES	No	Sam	Set	Uni	D&F	Sys	Har	IT	EIL	RM	Sub	Tes	Ana	Var
S01	Lin et al. (2015)	G & M	Geometric objects and measuring volume	J	42/76	TS	Cla	I	N	sd	CL	Ima	H	Mix	SV	T (sd)	D&I	D
S02	de Ravé et al. (2016)	G	Dihedral system	U	50/100	TS	Cla	N	N	DiedricAR (sd)	CL (M)	Ima	H	Quan: qe	SV; MR	T: P & D	D	D
S03	Gün and Atasoy (2017)	G & M	Geometric objects and measuring volume	E	44/88	CS	Cla	N	4 w	BuildAR (sm)	CL (C)	Ima: QRc	H	Quan: qe	SV	T: M	D&I	D
S04	Amir et al. (2020)	G	Geometric objects	E	36	TS	Cla	G	1 m	3Dmetric	CL (P)	Ima	H	Mix	*	T: S	D&I	C
S05	Rohendi and Wihardi (2020)	G	Geometric objects	J	150	N	Cla	N	N	sd	CL (P)	Ima	H	Qual: cs	SK	O (sd)	M&D	D
S06	Flores-Bascuñana et al. (2020)	G	Geometric objects	E	15/30	N	Cla	N	5 s: 45 min/s	Geometry & Quiver	CL (T)	Ima	H	Quan: qe	N	T (sd)	D	D
S07	Gecu-Parmaksiz and Delialioğlu (2020)	G	Geometric objects	P	36/72	TS	Cla	G: 3–4	4 w: 40–45 min/w	Augment	CL (T)	Ima	H	Quan: qe	SP; MR	T: R & SP	D&I	D

Table 3 (continued)

Study number	Primary author (year of publication)	Learning content			Learning context					AR system				Research design				
		Mod	Kno	ES	No	Sam	Set	Uni	D&F	Sys	Har	IT	EIL	RM	Sub	Tes	Ana	Var
S08	Sun and Chen (2020)	M	Compound-cube-surface area	E	30/60	CS	Cla	N	6 w: 5 c/w; 40 min/c	AURASMA (sd)	CL (T)	Ima	H	Quan: qe	SK	T (sd)	D&I	D
S09	Del Cerro Velázquez and Morales Méndez (2021a)	A	Functions	J	23/48	CS	Cla	N	3 w: 12 c	GeoGebra AR	CL (T)	Pla	H	Quan: qe	SV; MR	T: P	D&I	D
S10	Haas et al. (2021)	G & M	Geometric objects; areas and perimeters of polygons	E	2	TS	Lab	I	5 w: 2 c/w; 55 min/c	GeoGebra AR	CL (T)	Pla	H	Qual: cs	N	I & O	M	D
S11	Hou et al. (2021)	G	Geometric objects	S	58/127	CS	Lab	G	1 c: 40 min	Lost in Space (sd)	CL (T)	Ima	H-N	Quan: qe	N	T (sd)	D&I	D
S12	Guntur and Setyaningrum (2021)	N	Vector	S	35/70	RS	Cla	N	2 m	N	CL	Ima: QRc	H	Quan: qe	N	T (sd)	D&I	D
S13	Shaghaghian et al. (2022)	A	Matrices	U	7	TS	Re	I	5 w: 30–40 min/w	BRICKxAR/T (sd)	CL (T)	Ima: QRc	H	Quan: qe	SV	T: P	D	D
S14	Hanid et al. (2022)	G	Geometric objects	J	62/124	TS	Cla	N	4 w	GeoAR (sd)	CL (T)	Ima	H	Quan: qe	SV	T: MP	D&I	D

Table 3 (continued)

Study number	Primary author (year of publication)	Learning content			Learning context					AR system				Research design				
		Mod	Kno	ES	No	Sam	Set	Uni	D&F	Sys	Har	IT	EIL	RM	Sub	Tes	Ana	Var
S15	Majeed and ALRikabi (2022)	N	Equations and inequalities, bases and roots, trigonometry	S	30/60	N	Cla	N	N	N	N	N	N	Quan: qe	N	T (sd)	D&I	D
S16	Özçakır and Çakıroğlu (2022)	G	Geometric objects	J	8	TS	Lab	G: 2	11 h	SPATIAL-AR (sd)	CL (T) & HMD	Ima	H	Qual: cs	SV; MR	T: P; I (sd)	M	C&D
S17	Koparan et al. (2023)	G&M	Surface area of the cube	J	52/98	CS	Cla	N	N	sd	CL (P)	Ima	H	Quan: qe	SK	T (sd)	D&I	D
S18	Tiwari et al. (2024)	G	Projection	U	196/392	RS	Re	N	1 w	EDINAR (sd)	CL (M)	Ima	H	Quan: qe	SV	T: P	D&I	C
S19	Supli and Yan (2024)	G	Geometric objects	E	27/54	CS	Cla	N	4 w: 40–45 min/w	sd	CL (T)	Ima & Mod	H	Quan: qe	SV; MR; SO	T: SRI	D&I	D
S20	Beisenbayeva et al. (2024)	G	Geometric objects	S	42/82	CS	Cla	N	5 c: 40 min/c	Geometria (sd)	CL (P)	Ima	H	Quan: qe	SV; SK; SR	T (sd)	D	D
S21	Wang et al. (2024)	G	Geometric objects	E	46/86	TS	Cla	G	3 m	sd	CL (P)	Ima	H	Quan: qe	4Ds	T (sd)	D&I	D
S22	Yuan et al. (2024)	G	Three-view drawing	U	15–15/45	CS	Lab	N	80–110 min	sd	CL (T) & HMD	Pla	H	Quan: qe	SK	T (sd)	D&I	D
S23	Burte et al. (2024)	A	Matrices	U	20–20/60	CS	Cla	N	2 h	AR-Classroom (sd)	CL (C)	Mod	H	Quan: qe	SV	T: P	D&I	D

Table 3 (continued)

Mod, module: *G*, geometry; *M*, measurement; *A*, algebra; *N*, number and operations

Kno, knowledge

ES, educational stage: *P*, pre-school; *E*, elementary school; *J*, junior high school; *S*, senior high school; *U*, university

No., number of students: participants under AR conditions/participants across all conditions

Sam, sample methods: *TS*, target sampling; *CS*, convenience sampling; *RS*, random sampling; *N*, not specified

Set, activity setting: *Cla*, real class; *Lab*, laboratory; *Re*, remote setting

Uni, activity unit: *G*, group; *N*, not specified; *I*, individual

D&F, duration and frequency: *N*, not specified; *c*, class; *min*, minute; *h*, hour; *lh*, lesson hour; *s*, session; *w*, week; *m*, month

Sys, AR system: *sd*, self-developed system; *sm*, self-modelled system; *N*, not specified

Har, hardware: *CL*, camera lens; *M*, mobile devices; *C*, computer; *P*, mobile phone; *T*, tablet; HMD, head-mounted display equipment; *N*, not specified

IT, interactive type: *Img*, image-based; *Pla*, plane-based; *QRc*, QRcode; *Mod*, model-based; *N*, not specified

EIL, embodied interaction level: *H*, high-embodied; *H-N*, high embodied-with narrative; *N*, not specified

RM, research method: *Quan*, quantitative method; *qe*, quasi-experiment; *Qual*, qualitative method; *cs*, case study; *Mix*, mixed method

Sub, sub-competence of spatial skills tested: *SV*, spatial visualisation; *MR*, mental rotation; *namely, representation, visualisation, rotation, reconstruction, constructive space; *SP*, spatial perception; *SK*, spatial skills within specific knowledge; *N*, not specified; *SR*, spatial relationships; *4Ds*, four dimensions: recognition, movement, orientation, and measurement

Tes, test method and tool: *T*, test; *O*, observation; *I*, interview; *P*, Purdue Spatial Visualisation Test Rotations: mental rotation combined with visualisation (Guay, 1977); *D*, Differential Aptitude Test (DAT-5: SR level 2): spatial visualisation (Bennett et al., 1973); *M*, MGMP Spatial Ability Test (Ben-Chaim et al., 1988); *S*, Spatial Ability Scale (Kozhevnikov et al., 2007); *R*, Picture Rotation Test (Quaiser-Pohl, 2003); *SP*, Spatial Perception Scale (Tığcı, 2003); *MP*, Minnesota Paper Form Board Test (Likert & Quasha, 1969); *SRI*, Spatial Reasoning Instrument (Ramful et al., 2017); *sd*, self-developed

Ana, analysing method: *D*, descriptive statistics; *I*, inferential statistics; *M*, manual coding

Var, variable type of SS data: *D*, dependent variable; *C*, categorical variable

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Author Contribution All authors contributed to the study design, data analysis, writing and review of the manuscript. In addition, Yang and Wenfei conducted the studies screening, coding, organisation of coding data, and prepared the figures. Yang as the first author managed the process of study and writing.

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Declarations

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