



Developing spatial ability in mathematics education: A systematic review and bibliometric analysis of instructional interventions

Niki Pujarwati*

Universitas Lampung,
INDONESIA

Chika Rahayu

Universitas Lampung,
INDONESIA

Sugeng Sutaarso

Universitas Lampung,
INDONESIA

Tina Yunarti

Universitas Lampung,
INDONESIA

Caswita

Universitas Lampung,
INDONESIA

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Abstract

Background: Research on spatial ability in mathematics education has increasingly incorporated diverse instructional approaches and digital technologies; however, evidence regarding how these approaches support spatial development remains dispersed across educational levels, spatial constructs, and intervention designs.

Aims: This study synthesizes research published between 2015 and 2026 to identify instructional interventions for developing spatial ability and examine thematic and temporal patterns within mathematics education.

Method: A PRISMA-guided systematic review was conducted using records retrieved from Dimensions and Scopus through Publish or Perish. Studies were screened using predefined eligibility criteria, resulting in 17 articles for systematic content analysis. VOSviewer was additionally employed to map keyword co-occurrence, thematic clusters, temporal patterns, and topic density.

Results: The synthesis identified geometry, spatial reasoning, visualization, mental rotation, and mathematical problem solving as prominent themes. Reported instructional approaches included visualization and object manipulation, AR/VR, CAD and 3D printing, collaborative and metacognitive scaffolding, ethnomathematics, realistic mathematics education, and STEM-oriented activities. Outcomes varied across instructional designs and learning contexts.

Conclusion: The evidence suggests that spatial development is better supported when visualization and object manipulation are embedded within structured, pedagogically scaffolded mathematics instruction.

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INTRODUCTION

Despite growing recognition of spatial reasoning in mathematics education, a persistent instructional challenge remains because spatial processes are not always explicitly articulated in curriculum standards or systematically translated into classroom practices. Spatial reasoning is frequently embedded implicitly within mathematical tasks, particularly at early educational levels, leaving teachers with limited guidance on how spatial skills should be intentionally developed, scaffolded, and assessed (Pinilla, 2024). This issue is consequential because mathematical learning requires students to visualize, manipulate, interpret, and represent spatial relationships when engaging with geometry, measurement, and other visually demanding mathematical concepts (Schenck & Nathan, 2024). These processes enable learners to move between concrete objects, visual

*Corresponding author:

Niki Pujarwati, Universitas Lampung, Indonesia
nikipujarwati@gmail.com ✉

representations, and abstract mathematical ideas, thereby extending the relevance of spatial ability beyond the recognition of shapes or configurations. Spatial thinking has also been identified as an important link between mathematics learning and broader STEM development, although its curricular positioning remains less explicit than that of other mathematical competencies (Gilligan-Lee et al., 2022). When spatial processes remain implicit, opportunities to deliberately cultivate them may depend largely on individual teachers' instructional decisions rather than on coherent curricular expectations. This condition creates a pedagogical concern because students may encounter tasks requiring spatial reasoning without receiving corresponding instructional support for developing the underlying spatial processes. Consequently, the educational issue is not limited to establishing whether spatial ability contributes to mathematical performance but extends to determining how it can be deliberately cultivated through mathematics instruction. Addressing this issue requires greater attention to the relationship between spatial constructs, mathematical content, instructional activities, and the forms of support provided during learning. The central challenge for mathematics education, therefore, is to understand how spatial processes can be transformed from an implicit component of mathematical activity into an intentionally designed dimension of teaching and learning.

Evidence across educational levels indicates that spatial ability can be developed through instruction, but the contribution of spatial activities appears to depend substantially on how they are designed and integrated with mathematical learning. At the elementary level, spatial interventions appear more beneficial when activities are organized around explicit mathematical objectives rather than implemented as isolated spatial exercises (Mix et al., 2021; Pinilla, 2024). At the secondary level, spatial training has been associated with improvements in spatial performance and selected mathematical outcomes, particularly in geometry and measurement, although transfer to mathematics may vary according to the intervention and targeted competency (Adams et al., 2023; Kyaw & Vidákovich, 2025). These findings suggest that spatial development should be understood in relation to the pedagogical conditions under which learners interact with spatial representations rather than as an automatic consequence of exposure to spatial tasks. Within STEM-oriented learning, spatial development has consequently been approached through explicit spatial training, spatialized curricula, integrated practices, and informal spatial experiences, indicating considerable variation in the mechanisms through which spatial skills are supported (Zhu et al., 2023). Digital technologies have further broadened this instructional landscape by enabling learners to manipulate, rotate, transform, and examine mathematical objects through dynamic and interactive representations (Cirneanu & Moldoveanu, 2024). Augmented reality, in particular, provides learning environments that may support visualization, engagement, motivation, and spatial interaction with mathematical objects by connecting virtual representations with physical or mathematical contexts (Kaźmierczak et al., 2025; Wulandari et al., 2026). Nevertheless, technology alone cannot explain reported learning outcomes because intervention design, pedagogical scaffolding, duration, learning context, and assessment procedures may shape how students benefit from these environments (Yang et al., 2026). Reviews of spatial learning in Asian mathematics education similarly demonstrate developments across spatially embedded tasks, technology-supported environments, and instructional strategies, suggesting that spatial learning increasingly involves combinations of pedagogical and technological components (Putri et al., 2025). Taken together, this evidence shifts the analytical focus from identifying whether a particular technology or activity supports spatial learning toward examining which instructional characteristics and pedagogical configurations are associated with the development of particular spatial and mathematical outcomes.

A further challenge arises from conceptual and methodological fragmentation within the literature on spatial ability in mathematics education. Spatial cognition is represented through overlapping terms such as *spatial ability*, *spatial reasoning*, *spatial visualization*, *mental rotation*,

spatial relations, and *spatial orientation*, although these constructs are related without necessarily being conceptually interchangeable (Schenck & Nathan, 2024). This variation is not merely terminological because different constructs may involve distinct cognitive processes, instructional activities, measurement instruments, and expected relationships with mathematical learning (Cai & Leikin, 2020; Mu et al., 2022; Papageorgiou et al., 2025). Consequently, studies may implement apparently similar instructional interventions while measuring different dimensions of spatial performance, or they may employ similar terminology while operationalizing spatial ability in substantially different ways. Such conceptual variation complicates comparisons across studies and makes it difficult to determine whether differences in reported outcomes reflect intervention characteristics, targeted spatial constructs, assessment choices, or educational contexts. This problem becomes particularly visible in technology-mediated research, where similar digital tools can be implemented through substantially different pedagogical designs and forms of learner interaction. Although augmented reality provides opportunities for visualization and manipulation of mathematical objects, reported outcomes remain influenced by technology design, intervention duration, learning context, and assessment procedures (Yang et al., 2026). Previous systematic evidence on augmented reality in mathematics education likewise indicates a need to clarify how digital media interact with instructional strategies and mathematical abilities instead of attributing educational outcomes primarily to the technology itself (Bulut & Ferri, 2023). Accordingly, technology-mediated approaches such as AR, VR, CAD, and 3D representations need to be interpreted alongside contextual and pedagogical approaches so that the instructional mechanisms supporting spatial development can be more clearly distinguished. A coherent synthesis is therefore required to connect spatial constructs with intervention characteristics, educational contexts, pedagogical support, and mathematical outcomes across an increasingly heterogeneous body of research.

Although research on instructional interventions and spatially oriented learning has expanded, the literature remains fragmented across pedagogical, technological, and mathematical domains. Previous reviews have examined instructional interventions through problem-based learning, constructivist approaches, learning analytics, and critical-thinking development, but these studies do not specifically explain how instructional designs support the development of spatial ability in mathematics education (Arega & Hunde, 2025; Lee et al., 2020; Liu & Pásztor, 2022; Wang & Abdullah, 2024). Studies more closely related to mathematics have addressed problem-solving strategies and developments in geometry teaching and learning, including spatial reasoning, yet their scope does not provide an integrated synthesis of spatial constructs, intervention characteristics, and mathematical learning outcomes across educational levels (Jablonski & Ludwig, 2023; Szabo et al., 2020). Meanwhile, technology-oriented reviews have demonstrated the potential of augmented reality and interactive visualization for supporting spatial abilities, but such evidence is generally examined within particular technological environments rather than comparatively alongside broader pedagogical approaches (Alzahrani, 2020). Consequently, it remains unclear how different instructional interventions target specific dimensions of spatial ability, how technology-based and pedagogically oriented approaches differ in their instructional characteristics, and what mathematical outcomes are reported across these interventions. Addressing this gap requires a synthesis that moves beyond cataloguing individual strategies or technologies by systematically connecting spatial constructs, instructional intervention characteristics, educational contexts, and reported mathematical outcomes. Therefore, the present study integrates systematic review and bibliometric analysis to clarify these relationships while mapping the thematic structure and development of research on instructional interventions for spatial ability in mathematics education.

Against this background, the present study aims to systematically review and bibliometrically analyze research published between 2015 and 2026 concerning instructional interventions for developing spatial ability in mathematics education. First, the study examines the

thematic and temporal development of the literature to determine how research priorities related to spatial ability and mathematics learning have evolved over the review period. Second, it identifies the spatial constructs targeted across the literature, including spatial reasoning, spatial visualization, mental rotation, spatial relations, spatial orientation, and related dimensions. Third, the review analyzes the instructional characteristics through which these spatial constructs are intentionally supported within mathematics learning environments. Particular attention is given to technology-mediated approaches, including AR, VR, CAD, and 3D-based learning, alongside contextual and pedagogical approaches such as collaborative learning, metacognitive scaffolding, ethnomathematics, and realistic mathematics education. Rather than ranking these approaches solely according to effectiveness, the study examines their targeted spatial constructs, instructional characteristics, forms of visualization and object interaction, educational levels, pedagogical scaffolding, and reported mathematical outcomes. Systematic content analysis is employed to synthesize evidence concerning intervention characteristics and reported educational outcomes, while bibliometric analysis is used to examine conceptual relationships, thematic clusters, temporal patterns, and topic density within the research landscape. Integrating these analytical perspectives enables the study to relate the pedagogical evidence reported in individual investigations to the broader conceptual and thematic development of spatial-ability research. In this way, the review seeks to establish an integrated understanding of the relationships among spatial constructs, instructional interventions, and mathematical learning outcomes, while identifying convergent patterns and areas where the available evidence remains limited or heterogeneous. Ultimately, the study is intended to provide an evidence-informed conceptual basis for future research and for designing mathematics instruction that supports students' spatial development more explicitly and systematically.

LITERATURE REVIEW

Spatial ability represents a multidimensional cognitive domain concerned with perceiving, representing, transforming, and reasoning about spatial information. Within mathematics education, this domain is commonly discussed through related constructs such as *spatial reasoning*, *spatial visualization*, *mental rotation*, *spatial relations*, and *spatial orientation* (Schenck & Nathan, 2024). Although these constructs share an emphasis on spatial information, they represent different cognitive operations and therefore should not be treated as fully interchangeable. Spatial visualization generally involves mentally manipulating complex spatial information, whereas mental rotation emphasizes imagining the rotation of objects or representations from different orientations (Salehi & Dixit, 2026; Schenck & Nathan, 2024; Zhou et al., 2022). Spatial relations and orientation further concern recognizing positional relationships and understanding how objects are situated relative to one another. These distinctions are educationally important because different mathematical activities may activate different combinations of spatial processes. Geometry and measurement, for example, frequently require learners to coordinate representations, recognize transformations, and reason about relationships among objects and dimensions (Adams et al., 2023; Kyaw & Vidákovich, 2025). Spatial thinking also contributes to broader STEM learning because students frequently encounter diagrams, models, representations, and transformations that require coordination between spatial and quantitative information (Gilligan-Lee et al., 2022). Consequently, spatial ability is better conceptualized as a set of interrelated processes that can contribute differently depending on the mathematical task and learning context. This multidimensional perspective provides an important conceptual foundation for examining how instructional interventions target and develop particular components of spatial ability.

The relationship between spatial ability and mathematics learning has encouraged increasing attention to whether spatial processes can be deliberately strengthened through instruction. Evidence from elementary education suggests that spatially structured activities can support mathematics learning when spatial experiences are explicitly connected with mathematical objectives (Mix et al., 2021; Pinilla, 2024). Similar evidence at secondary levels indicates that spatial reasoning interventions may contribute to spatial performance and selected mathematics outcomes, particularly in geometry and measurement (Adams et al., 2023; Kyaw & Vidákovich, 2025). These findings indicate that spatial development is not necessarily independent of mathematical content but can occur through learning environments in which spatial processes are intentionally activated. However, transfer from spatial training to mathematical achievement should not be assumed to occur uniformly across interventions or mathematical domains. Differences in task structure, targeted spatial process, duration, instructional support, and outcome measurement can influence the extent to which spatial experiences contribute to mathematical learning (Adams et al., 2023; Gilligan et al., 2020; Lowrie et al., 2021; Schenck & Nathan, 2024). This issue becomes particularly relevant when spatial ability is implicitly required by mathematical tasks but is not explicitly supported through instruction (Pinilla, 2024). Within STEM education, the instructional development of spatial ability has similarly involved explicit spatial training, spatialized curricula, integrated STEM activities, and informal spatial experiences (Zhu et al., 2023). These approaches collectively suggest a transition from viewing spatial ability primarily as an individual cognitive characteristic toward conceptualizing it as a competence that can be intentionally supported through educational experiences. Accordingly, the relationship between spatial ability and mathematical competence should be examined together with the instructional conditions through which spatial processes are developed.

Instructional interventions for spatial development encompass a broad range of activities, representations, pedagogical models, and learning environments. Visualization-oriented instruction provides learners with opportunities to construct, interpret, transform, and coordinate representations rather than relying exclusively on symbolic procedures. Manipulation of physical or visual objects can similarly externalize spatial relationships and provide concrete reference points for understanding mathematical structures. Beyond these approaches, collaborative learning can encourage students to articulate spatial relationships, compare representations, and negotiate alternative strategies through interaction with peers. Metacognitive scaffolding may further support spatial learning by prompting learners to plan representational strategies, monitor transformations, and evaluate whether spatial solutions are mathematically appropriate (Atman Uslu et al., 2022; Felkel et al., 2025; Mannan et al., 2026). Contextual approaches, including ethnomathematics and realistic mathematics education, can situate spatial relationships within culturally or experientially meaningful objects and situations. Spatial development within STEM learning has likewise been associated with combinations of explicit training, curricular integration, and problem-oriented spatial activities (Zhu et al., 2023). Existing evidence therefore suggests that interventions should not be classified only according to their visible instructional media because similar spatial processes may be supported through different pedagogical mechanisms. The educational contribution of an intervention depends on how learners are required to interact with spatial information, how these interactions are scaffolded, and how they are connected to mathematical objectives. A meaningful synthesis of instructional interventions should consequently examine not only *what* strategy is used but also *which spatial construct it targets, how spatial activity is organized, and what mathematical outcome is reported*.

Technology-mediated learning has substantially expanded the range of representations and interactions available for developing spatial ability in mathematics education. Augmented reality can superimpose digital representations onto physical environments, allowing learners to inspect and

manipulate mathematical objects through interactive spatial experiences (Każmierczak et al., 2025; Wulandari et al., 2026). Virtual reality extends this possibility by providing immersive environments in which three-dimensional structures can be explored from multiple perspectives. CAD and 3D-based environments can likewise facilitate the construction, transformation, and examination of geometric representations that may be difficult to visualize using conventional two-dimensional media. These technological affordances are particularly relevant to spatial learning because they can make transformations, orientations, and relationships among mathematical objects more perceptually accessible. Nevertheless, the presence of sophisticated visualization technology does not itself establish instructional effectiveness. Evidence from technology-mediated spatial research indicates that outcomes may vary according to technology design, learning context, intervention duration, instructional organization, and assessment procedures (Yang et al., 2026). Systematic evidence on augmented reality in mathematics education likewise emphasizes the importance of examining the interaction between digital media, instructional strategies, and targeted mathematical abilities (Bulut & Ferri, 2023). Technology should therefore be understood as part of an instructional configuration in which pedagogical scaffolding, task design, learner interaction, and mathematical objectives jointly determine the learning experience. Comparing technology-mediated and non-technological interventions according to these characteristics provides a more informative basis for understanding how different instructional environments may support spatial development.

Taken together, the literature portrays spatial ability as a multidimensional and instructionally responsive domain whose development is shaped by interactions among cognitive constructs, mathematical content, pedagogical strategies, and representational environments. Existing studies nevertheless vary substantially in the terminology used to define spatial ability, the interventions implemented to develop it, and the outcomes selected to evaluate learning (Schenck & Nathan, 2024). Research also extends across educational levels and instructional contexts, making direct comparisons difficult when interventions are categorized only according to their technological or pedagogical labels (Bernacki et al., 2021; Hamilton et al., 2021; Pardo et al., 2025; Patiño Hernández et al., 2026; Yang et al., 2024). Reviews of spatial learning have documented spatially embedded tasks, technological environments, and instructional strategies, but these categories require closer connection with the spatial processes and mathematical outcomes targeted by instruction (Putri et al., 2025). Similarly, evidence concerning AR and related technologies indicates that technological affordances should be interpreted in conjunction with instructional design rather than as independent determinants of learning (Bulut & Ferri, 2023; Yang et al., 2026). A useful analytical perspective therefore requires simultaneous attention to the spatial construct, intervention characteristics, educational level, pedagogical scaffolding, forms of learner interaction, and reported mathematical outcomes. Such a framework permits technology-mediated interventions, contextual approaches, collaborative strategies, and visualization-based activities to be examined within a shared conceptual structure. It also allows bibliometric patterns to be interpreted alongside substantive instructional evidence rather than treating research trends and pedagogical findings as disconnected dimensions. Accordingly, integrating systematic content synthesis with bibliometric analysis can clarify both how the field is conceptually organized and how instructional interventions for spatial development have been represented within that field. This conceptual foundation guides the present review in examining the development of spatial ability as an instructional problem situated at the intersection of spatial cognition, mathematics learning, pedagogy, and educational technology.

METHOD

Research Design

This study employed a Systematic Literature Review (SLR) method to identify, select, analyze, and synthesize scholarly articles addressing spatial ability in mathematics education. The SLR approach was adopted to ensure that the literature review process was conducted systematically, transparently, and rigorously. The article selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, which consists of four stages: identification, screening, eligibility, and inclusion (Page et al., 2021). The use of PRISMA aimed to ensure that the articles included in the review were closely aligned with the focus of the study, namely spatial ability in mathematics learning, instructional strategies, and their implications for students' mathematical competence.

The data sources for this study consisted of scholarly articles relevant to the investigation of spatial ability in mathematics education. The articles were retrieved from two primary sources, namely the Dimensions database and Publish or Perish using the Scopus database. The literature search was conducted using combinations of the keywords spatial ability, spatial skills, spatial reasoning, spatial thinking, spatial visualization, mathematics education, mathematics learning, mathematics teaching, and students OR learners OR pupils. The publication period was limited to 2015–2026 to ensure that the reviewed literature reflected recent developments and remained relevant to the focus of the study. Articles were selected purposively based on predefined inclusion and exclusion criteria applied during the PRISMA selection process.

The analyzed articles included publications that addressed spatial ability, spatial skills, spatial reasoning, spatial thinking, spatial visualization, mental rotation, spatial orientation, or spatial relations within the context of mathematics education. Based on the selection process following the PRISMA framework, a total of 17 articles met the eligibility criteria and were included as the primary data sources for the in-depth analysis. The research procedure was conducted through four stages in accordance with the PRISMA framework: identification, screening, eligibility, and inclusion. The research procedure followed four PRISMA stages: identification, screening, eligibility, and inclusion. The progression of records across these stages is summarized in Figure 1.

Identification Stage

The identification stage began with a literature search conducted in two data sources, namely Dimensions and Publish or Perish based on Scopus. The search was performed using a combination of the keywords spatial ability, spatial skills, spatial reasoning, spatial thinking, spatial visualization, mathematics education, mathematics learning, mathematics teaching, and students OR learners OR pupils. A total of 359 initial articles were retrieved from the Dimensions database, while 189 initial articles were obtained from Publish or Perish based on Scopus.

Screening Stage

During screening, retrieved records were assessed using publication year, publication type, accessibility, title, abstract, and relevance to the predefined scope. Of the 359 Dimensions records initially retrieved, 324 remained after restricting publication years to 2015–2026, and further screening by publication type reduced the number to 213. Application of the accessibility criteria resulted in 26 Dimensions records proceeding to full-text eligibility assessment. From the 189 records retrieved from Scopus through Publish or Perish, 172 remained after applying the publication-year restriction, and subsequent screening resulted in 12 records proceeding to full-text review. Records whose titles and abstracts clearly indicated that spatial concepts were investigated outside mathematics education without a substantive educational connection were excluded at this stage. Importantly, database indexing, publication status, and accessibility were treated as screening

characteristics rather than evidence of methodological quality. Methodological quality was therefore evaluated separately through a formal critical appraisal of the studies retained for synthesis.

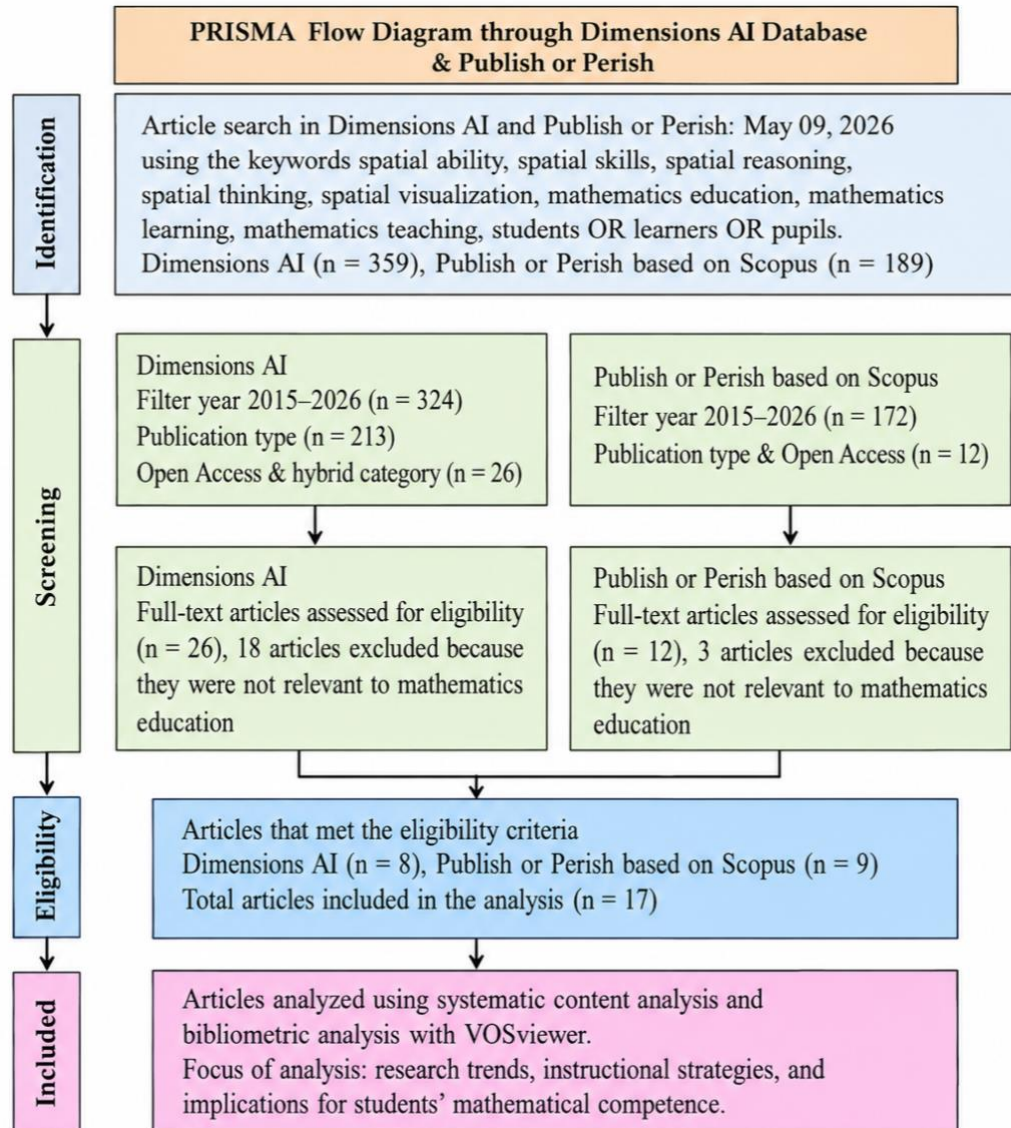


Figure 1. PRISMA Flow Diagram for Article Selection

Eligibility Stage

Full-text eligibility assessment was conducted for the records remaining after screening. Of the 26 Dimensions articles assessed in full text, 18 were excluded because they did not specifically address spatial ability within mathematics education or did not provide sufficient relevance to the instructional focus of the review. Eight Dimensions articles consequently satisfied the eligibility requirements. Among the 12 Scopus records assessed in full text, three were excluded because their substantive focus did not meet the mathematics-education eligibility criteria, leaving nine eligible articles. The final systematic synthesis therefore comprised 17 studies, consisting of eight articles identified through Dimensions and nine through the Scopus-based search. Reasons for full-text exclusion were documented according to the predefined eligibility criteria rather than judgments of presumed study quality. Methodological quality was subsequently examined using a separate critical appraisal procedure described below.

Including and Exclusion Criteria

Eligibility criteria were established before full-text assessment to maintain alignment between the research questions and the evidence included in the synthesis. The principal requirements concerned publication period, spatial construct, mathematics-education context, methodological transparency, accessibility, and relevance to instructional interventions or educational implications. Studies were excluded when spatial concepts were investigated outside mathematics education without a substantive mathematical-learning connection, when publication information was insufficient, or when full-text evidence was unavailable for reliable assessment. Although the reviewer recommended moving the complete criteria to supplementary material, Table 1 is retained here to preserve the existing manuscript structure and transparently report the operational criteria used during study selection.

Table 1. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Research Topic	Articles addressing spatial ability, spatial reasoning, spatial visualization, spatial thinking, mental rotation, spatial orientation, or spatial relations within the context of mathematics education.	Articles that do not address spatial ability or discuss spatial ability outside the context of mathematics education.
Research Context	Articles situated within mathematics education, geometry learning, mathematical problem-solving, STEM education involving mathematics, mathematics instructional strategies, or mathematics standards/curricula.	Articles focusing on other fields such as geography, medicine, architecture, pure engineering, arts, sports, or other school subjects without a direct connection to mathematics education.
Population	Articles involving students, university students, pre-service teachers, teachers, or educational documents/standards related to the development of spatial ability in mathematics education.	Articles involving populations or research subjects outside the context of mathematics education and without relevance to the development of spatial ability in mathematics learning.
Publication Type	Peer-reviewed journal articles, empirical studies, development studies, literature reviews, systematic reviews, scoping reviews, conceptual reviews, or document/standards analyses with a DOI or clear publication identity.	Editorials, opinion papers, popular articles, non-peer-reviewed conference proceedings, book chapters, institutional reports, unpublished theses/dissertations, or documents without clear publication information.
Publication Year	Articles published between 2015 and 2026.	Articles published before 2015 or outside the specified time range.
Accessibility	Articles with accessible abstracts and/or full texts available for eligibility assessment.	Articles without accessible full texts, incomplete metadata, or content that cannot be adequately reviewed.
Methodology	Articles with clearly defined methods or research focuses, including quantitative, qualitative, mixed-methods, development studies, literature reviews, systematic reviews, scoping reviews, conceptual reviews, or document/standards analyses.	Articles that do not clearly describe their methodology or research focus, making them unsuitable for literature synthesis.
Instructional Strategies or Educational Implications	Articles discussing instructional strategies, learning media, technology, interventions, assessment, curriculum, educational standards, or the implications of spatial ability for mathematical competence.	Articles discussing spatial ability in general without connections to learning, instructional strategies, learning media, assessment, curriculum, educational standards, or mathematical competence.
Database Source	Articles retrieved from the Dimensions database or Publish or Perish based on Scopus.	Articles not retrieved through the databases used in this study.

The final corpus of 17 studies was determined through the sequential application of these predefined criteria. The reduction from the initially identified records primarily reflected the specific intersection between spatial constructs and formal mathematics education required by the research questions. In particular, records using spatial terminology in unrelated disciplinary contexts were excluded, as were studies that lacked sufficient instructional or educational information for synthesis. The size of the final corpus should therefore be interpreted in relation to the review's deliberately bounded conceptual scope rather than as an indicator of the overall volume of research involving spatial concepts.

Data Analysis

Data were analyzed using two complementary techniques: systematic content analysis and bibliometric analysis. Systematic content analysis was employed to examine the content of the 17 selected articles, with particular attention to research trends, instructional strategies, learning media, technologies used, and the implications of spatial ability for students' mathematical competence. The findings from the reviewed articles were subsequently synthesized to address the three research questions: (1) research trends concerning spatial ability in mathematics education, (2) instructional strategies employed to develop students' spatial abilities, and (3) the influence of spatial ability on students' mathematical competence.

Bibliometric analysis was conducted using VOS viewer version 1.6.20 with the keyword co-occurrence method. This analysis was used to generate network visualization, overlay visualization, and density visualization maps. Network visualization was utilized to examine relationships among research topics and identify thematic clusters. Overlay visualization was employed to analyze the evolution of research trends over time. Density visualization was used to identify dominant research topics as well as potential research gaps in the study of spatial ability within mathematics education.

RESULTS AND DISCUSSION

Results

Table 2. Article Review Findings

Authors	Title	Review Findings
Schenck & Nathan (2024)	Navigating Spatial Ability for Mathematics Education: A Review and Roadmap	Spatial ability is essential for mathematical thinking and STEM learning; however, the diversity of taxonomies and assessment instruments makes measurement and intervention difficult to implement consistently. Therefore, clear guidance is needed for selecting appropriate taxonomies and assessment tools.
Bertrand et al. (2024)	Exploring AR and VR Tools in Mathematics Education Through Culturally Responsive Pedagogies	The integration of AR/VR and digital storytelling enhances students' spatial ability, engagement, motivation, and understanding of mathematical concepts while incorporating cultural contexts into learning.
Dilling & Vogler (2021)	Fostering Spatial Ability Through Computer-Aided Design: A Case Study	The use of CAD and 3D printing technologies improves five dimensions of spatial ability, including spatial perception, spatial visualization, mental rotation, spatial relations, and spatial orientation, demonstrating the potential of digital tools for developing students' spatial skills.
Mohammed Luaibi (2025)	Formal Thinking in Mathematics and Its Relationship to Spatial Ability	A significant correlation exists between formal mathematical thinking and spatial ability, indicating that both variables mutually

	Among Middle School Female Students	reinforce mathematical understanding among female middle school students.
Muhammad et al. (2026)	The Role of Augmented Reality (AR) in Enhancing Conceptual Understanding of Geometry in Mathematics Education: Systematic Review	AR enhances spatial ability, visualization, motivation, engagement, and conceptual understanding of geometry. However, its implementation requires teacher training and more affordable technological solutions.
Moussa et al. (2025)	Developing Spatial Thinking in Cartesian Coordinate Tasks: The Impact of the Think-Pair-Share Strategy on Sixth-Grade Learners	The Think-Pair-Share strategy significantly improves sixth-grade students' spatial thinking, particularly spatial perception and visual-spatial reasoning in Cartesian coordinate tasks.
Gustina et al. (2025)	Augmented Reality-Based Ethnomathematics Learning Media to Enhance Spatial Ability in 3D Geometry for Fifth-Grade Elementary Students	The integration of AR and ethnomathematics improves fifth-grade students' spatial ability by facilitating 3D visualization and contextualized understanding of geometric concepts within cultural settings.
Rabab'h & Veloo (2015)	Spatial Visualization as Mediating Between Mathematics Learning Strategy and Mathematics Achievement Among 8th Grade Students	Spatial visualization mediates the relationship between motivation, attitudes, mathematics anxiety, and mathematics achievement, highlighting the importance of developing spatial skills to improve learning outcomes.
Awi et al. (2025)	Spatial Geometry Learning in Higher Education Through Flipped Classroom with Metacognitive Scaffolding: A Mixed-Methods Study	A flipped classroom model combined with metacognitive scaffolding effectively enhances university students' spatial abilities, particularly in 3D visualization and geometric transformations.
Mawarsari et al. (2024)	Students' Geometric Thinking Processes in Terms of Spatial Intelligence	Students' geometric thinking processes are influenced by their spatial abilities, involving four main stages ranging from information identification to reasoning processes used in problem-solving.
Ozcakir & Cakiroglu (2021)	An Augmented Reality Learning Toolkit for Fostering Spatial Ability in Mathematics Lessons: Design and Development	An AR-based learning toolkit was designed to improve middle school students' spatial abilities by enabling 3D object manipulation and virtual interaction that strengthen mathematical concept understanding.
Medina Herrera et al. (2024)	Enhancing Mathematical Education with Spatial Visualization Tools	Spatial visualization tools such as AR, VR, and 3D printing effectively improve university students' spatial visualization abilities and mathematical problem-solving skills.
Pinilla (2024)	Spatial Reasoning in Mathematics Standards: Identifying How Early Elementary Educators Are Systematically Supported to Teach Spatial Skills	An analysis of U.S. educational standards revealed that spatial skills are often insufficiently emphasized, making professional support for early elementary teachers essential for fostering students' spatial development.
Kurt et al. (2023)	An Investigation of Middle School Students' Spatial Reasoning Skills	The study found variations in middle school students' spatial abilities across three subcomponents—mental rotation, spatial orientation, and spatial visualization—which differed by grade level but not significantly by gender.
Johar et al. (2025)	Developing Local Instruction Theory Through Ethnomathematics and Technology-Based Realistic Mathematics Education to Support Students' Spatial Ability	A Local Instruction Theory (LIT) approach integrating ethnomathematics and Realistic Mathematics Education (RME) enhances middle school students' spatial abilities through contextual activities and digital object manipulation.
Sukestiyarno et al. (2023)	Learning Trajectory of Non-Euclidean Geometry Through Ethnomathematics	An ethnomathematics-based approach to non-Euclidean geometry significantly improves

	Approaches to Improve Spatial Ability	students' spatial abilities through a systematic learning trajectory.
Buckley et al. (2019)	Investigating the Use of Spatial Reasoning Strategies in Geometric Problem Solving	Students' levels of spatial ability influence their approaches to solving geometric problems. Students with lower spatial ability tend to rely more on external representations and models to reduce the demand for spatial reasoning.

Based on Table 2, the review of the 17 selected articles reveals several major patterns in research on spatial ability within mathematics education. First, spatial ability is most frequently associated with geometry learning, object visualization, mental rotation, spatial orientation, and mathematical problem-solving. Second, the dominant instructional strategies involve visualization- and technology-based approaches, including augmented reality (AR), virtual reality (VR), computer-aided design (CAD), 3D printing, and other spatial visualization tools. Third, contextual approaches such as ethnomathematics and Realistic Mathematics Education (RME) have emerged as promising strategies for connecting spatial concepts with students' real-life experiences and cultural backgrounds. However, findings from several studies also indicate that the effectiveness of technology does not operate independently; rather, it is strongly influenced by task design, intervention duration, scaffolding, student readiness, and the alignment between instructional media and learning objectives. Furthermore, several methodological gaps remain, including the limited number of longitudinal studies, comparative investigations across educational levels, and research that systematically integrates technology-based and contextual approaches. Therefore, the synthesis of these studies suggests the need for an integrative instructional model that combines visualization, object manipulation, digital technologies, metacognitive scaffolding, and cultural contexts to effectively develop students' spatial abilities in mathematics learning.

A bibliometric analysis of 548 articles was conducted using VOSviewer through the keyword co-occurrence method with a minimum occurrence threshold of 10. This threshold was applied to ensure that the generated map included only the most relevant keywords with strong interconnections. The mapping results were analyzed using network visualization to identify research clusters and relationships among topics, overlay visualization to examine the evolution of research trends over time, and density visualization to identify dominant themes as well as potential research gaps. The results of the VOSviewer analysis are presented in the figures below.

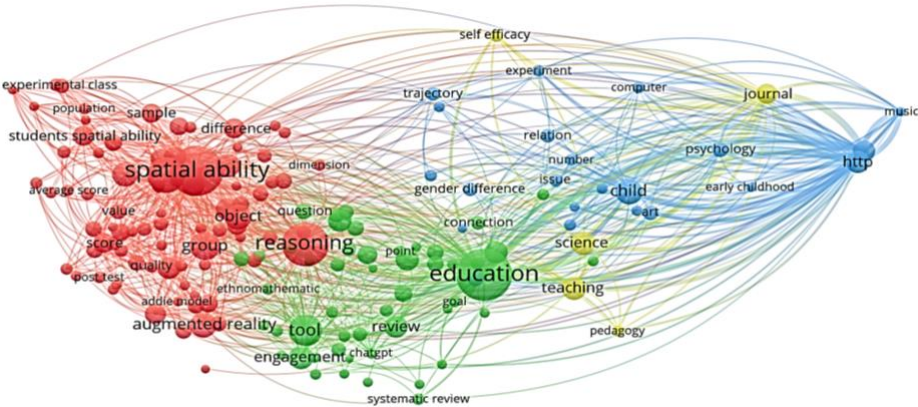


Figure 2. Network visualization

Based on Figure 3, the network visualization shows that the keywords meeting the threshold criteria form several major clusters. Dominant nodes such as spatial ability, spatial reasoning, mathematics education, education, and augmented reality indicate that research on spatial ability

extends beyond cognitive dimensions and is closely connected to instructional strategies, STEM education, and visual technologies (Krüger et al., 2022; Zhu et al., 2023). The strong links among these keywords suggest that spatial ability is increasingly being viewed as a multidimensional construct that supports mathematical learning through both cognitive development and technology-enhanced instructional practices.

Based on Figure 3, the overlay visualization reveals a shift in research trends over time. In the earlier period, studies primarily focused on the fundamental concepts of spatial ability and mathematical reasoning. In more recent years, however, increasing attention has been directed toward *augmented reality*, educational technology, student engagement, and systematic reviews. This trend indicates that the field is moving toward more applied and intervention-based research approaches (Yang et al., 2026). Based on Figure 4, the density visualization shows that spatial ability, spatial reasoning, education, and mathematics education are the topics with the highest density. Meanwhile, topics such as augmented reality, engagement, and 3D visualization still exhibit relatively lower density and can therefore be considered promising opportunities for future research development (Yang et al., 2026).

Discussion

RQ1: What are the research trends on spatial ability in mathematics education, including the topics addressed over the past decade?

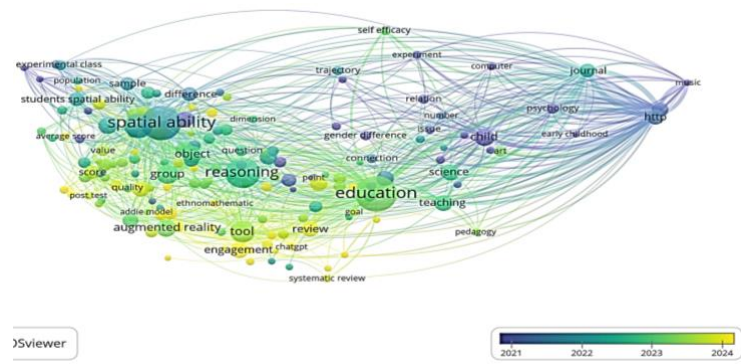


Figure 3. Overlay visualization

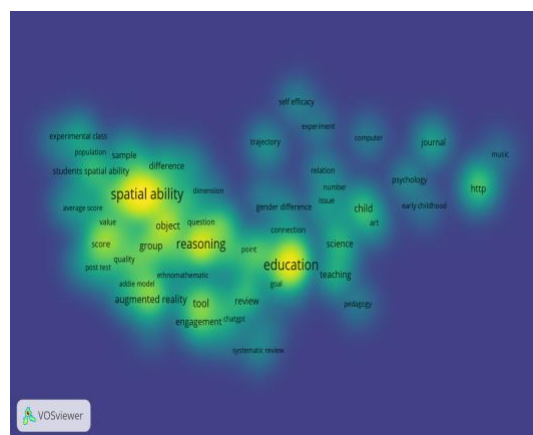


Figure 4. Density visualization

Bibliometric analysis using VOSviewer's overlay, network, and density maps indicates that spatial ability remains a central focus in mathematics education research. However, its connections with other topics reveal a more complex pattern than simple keyword frequency alone. The strong

relationships among spatial ability, reasoning, and education in the network map suggest that research in this area is not conducted in isolation. Rather, spatial ability is frequently examined alongside mathematical reasoning and instructional strategies. Additional nodes, such as augmented reality and engagement, emerge as links between theoretical research and practical interventions, indicating a shift toward the development of innovative technology-based instructional strategies.

The overlay map reveals significant temporal changes in research trends. At the beginning of the decade, studies primarily emphasized the definition, taxonomy, and theoretical measurement of spatial ability. By the middle of the decade, the focus shifted toward instrument evaluation and integration with instructional strategies. In recent years, emerging topics have included the use of augmented reality and technology-based interventions, as well as systematic reviews and evidence-based pedagogical design. The density map shows a high concentration of studies on reasoning, education, and spatial ability, whereas augmented reality and engagement appear less frequently, suggesting considerable potential for further investigation in these important areas.

The relationship between research topics and temporal trends is supported by recent international literature. Studies indicate that technology-based instructional strategies, including augmented reality and interactive digital tools, contribute significantly to the development of spatial reasoning skills, particularly in students' visualization, spatial orientation, and mental rotation abilities (Dayyinati Fa'izulloh et al., 2026; Yang et al., 2026; Zhu et al., 2023). Other studies further demonstrate that spatial reasoning plays a causal role in mathematics achievement, with varying contributions across content domains such as geometry and data analysis, highlighting the importance of integrating spatial aspects into pedagogical strategies (Harris, 2023; Xu et al., 2025). Overall, the findings suggest that research over the past decade has not only reaffirmed the importance of spatial ability in mathematics education but has also highlighted a transformation from theoretical investigations toward evidence-based intervention studies that utilize technology as a primary means of developing spatial skills.

RQ2: What instructional strategies have been implemented to develop students' spatial abilities, and how effective are these strategies?

Based on the reviewed articles, instructional strategies for developing students' spatial abilities can be categorized into four major patterns: the use of 3D visual technologies, visualization- and object-manipulation-based learning, collaborative and metacognitive strategies, and contextual approaches grounded in culture or ethnomathematics. These patterns indicate that the development of spatial ability cannot be achieved solely through verbal explanations. Students need opportunities to actively observe, rotate, compare, manipulate, and represent mathematical objects. Consequently, the most frequently reported strategies in the literature include augmented reality (AR), virtual reality (VR), computer-aided design (CAD), 3D printing, spatial visualization tools, Think-Pair-Share, flipped classrooms with metacognitive scaffolding, ethnomathematics, and Realistic Mathematics Education (RME).

From an analytical perspective, visualization- and technology-based strategies demonstrate the strongest effectiveness because they directly address one of the primary challenges in geometry learning: the transition between two-dimensional objects, three-dimensional objects, symbolic representations, and mental imagery. A meta-analysis of 41 studies found that visualization interventions produced a moderate effect on mathematics achievement ($g = 0.504$). However, technology-based approaches were not always superior to non-digital visualization methods when task design was weak. This suggests that technology is effective not because of its digital nature, but because it enhances representations, reduces abstraction, and provides opportunities for object manipulation. These findings are consistent with studies on spatial visualization tools that reported a 25% improvement in spatial visualization skills among experimental groups, compared with only a 5% improvement among control groups (Schoenherr et al., 2024).

Augmented reality and virtual reality have also proven effective, particularly in learning topics involving solid geometry, coordinate systems, three-dimensional models, and spatial relationships. AR and VR provide more concrete learning experiences by enabling students to interact with virtual objects that are difficult to visualize through static images alone. Nevertheless, the effectiveness of AR and VR is conditional. Recent scoping reviews indicate that AR can support spatial thinking through interactive and embodied learning experiences, but outcomes remain influenced by factors such as tool design, intervention duration, classroom context, and assessment methods. Therefore, AR and VR should be viewed as pedagogical support tools rather than standalone solutions (Yang et al., 2026).

Furthermore, the synthesis of the 17 selected articles reveals a distribution of instructional strategies tailored to students' cognitive characteristics across educational levels. Augmented Reality (AR)-based interventions and contextual approaches such as ethnomathematics and RME appear to be more dominant and effective at the elementary and middle school levels. This is because students at these stages still require concrete bridges to transform abstract objects into meaningful mental representations. In contrast, strategies involving advanced visualization tools such as CAD, 3D printing, and collaborative learning models with metacognitive scaffolding are more commonly implemented at the secondary and higher education levels. Students at these stages generally possess more advanced formal thinking abilities, allowing interventions to focus on complex digital manipulation and analytical spatial reasoning.

Strategies based on CAD, 3D printing, and spatialized curricula have also demonstrated positive outcomes because they encourage students to establish relationships among shape, size, position, and transformation. CAD supports the development of spatial perception, visualization, mental rotation, spatial relations, and spatial orientation through digital object design. Similarly, spatialized curricula have been shown to significantly improve students' spatial visualization abilities and mathematics performance compared with conventional instruction. These findings suggest that spatial abilities develop more effectively when spatial activities are embedded directly within mathematics content rather than taught as separate exercises (Dilling & Vogler, 2021).

Collaborative and metacognitive strategies, such as Think-Pair-Share and flipped classrooms with metacognitive scaffolding, are effective because they encourage students to articulate their spatial thinking processes. In Cartesian coordinate tasks, Think-Pair-Share helps students compare representations, correct positional perceptions, and strengthen visual-spatial reasoning. Its effects are evident not only in final answers but also in how students construct representations and explain relationships among objects. However, evidence for these strategies remains relatively context-specific, and their effectiveness should be examined across broader mathematical topics and educational levels (Moussa et al., 2025).

Ethnomathematics, Realistic Mathematics Education, and culturally responsive pedagogy make important contributions by connecting spatial concepts with students' cultural backgrounds and real-life experiences. These approaches are particularly effective in making abstract geometric concepts more meaningful. Studies on non-Euclidean geometry through ethnomathematics have demonstrated positive effects on students' spatial abilities. Likewise, AR/VR interventions grounded in culturally responsive pedagogy indicate that the integration of technology, storytelling, and cultural contexts can enhance engagement, motivation, and conceptual understanding. Thus, the effectiveness of contextual approaches lies in their ability to transform mathematical objects from abstract symbols into visual and social experiences that are meaningful to students (Sukestiyarno et al., 2023).

In summary, the reviewed studies identified a wide range of strategies, including AR/VR, CAD, 3D printing, spatial visualization tools, spatialized curricula, Think-Pair-Share, flipped classrooms with scaffolding, ethnomathematics, RME, and authentic STEM learning. Overall, these strategies

tend to produce positive outcomes, although their effectiveness varies. The strongest evidence supports approaches that combine visualization, object manipulation, explicit spatial tasks, and scaffolding. Technology-based strategies are most effective when integrated with clear pedagogical designs, whereas collaborative and contextual approaches are effective because they help students consciously construct and communicate spatial relationships.

RQ3: How does spatial ability influence the development of students' mathematical competence, and what are its implications for mathematics teaching practices and curriculum design?

Spatial ability serves as a significant cognitive foundation for the development of students' mathematical competence. Empirical studies indicate that spatial ability facilitates the understanding of geometric relationships, object transformations, spatial orientation, and abstract visualization, all of which are critical components of solving complex mathematical problems (Xu et al., 2025; Zhu et al., 2023). Research suggests that students with strong spatial abilities are better able to connect two-dimensional geometric concepts with three-dimensional representations and to develop more flexible problem-solving strategies. Spatial ability is also associated with formal thinking and mathematical reasoning more broadly, thereby supporting deeper mathematical understanding. These findings emphasize that spatial reasoning is not only a predictor of success in geometry but also a contributor to problem-solving performance across a wider range of mathematical domains.

The impact of spatial ability on teaching practice can be observed through the effectiveness of instructional strategies that explicitly target its development. Technology-based interventions such as augmented reality, virtual reality, CAD, and 3D printing provide visual and manipulative representations that strengthen students' understanding of abstract concepts (Bertrand et al., 2024; Dilling & Vogler, 2021; Medina Herrera et al., 2024). Collaborative strategies, including Think-Pair-Share and flipped classrooms with metacognitive scaffolding, encourage students to explain their spatial thinking processes and compare mental representations, thereby enhancing spatial perception, visualization, and orientation (Awi et al., 2025; Moussa et al., 2025). Additionally, contextual approaches such as ethnomathematics and culturally responsive pedagogy situate spatial concepts within students' cultural and real-world experiences, allowing spatial skills to develop alongside socially and cognitively meaningful mathematical understanding (Gustina et al., 2025; Sukestiyarno et al., 2023).

The implications for mathematics curricula are substantial. Spatial ability should be systematically integrated into curriculum content, instructional strategies, and assessment instruments. Curricula should support manipulative and visualization activities through both digital tools, such as AR, VR, and CAD, and physical learning materials, enabling students to construct strong mental representations of mathematical objects (Medina Herrera et al., 2024; Zhu et al., 2023). Spatial reasoning should become an explicit component of geometry, coordinate geometry, and authentic STEM learning, and it should be assessed systematically to allow teachers to implement appropriate instructional strategies and interventions. Moreover, contextual approaches such as ethnomathematics have been shown to enhance student engagement, motivation, and understanding by linking spatial concepts to learners' cultural backgrounds and everyday experiences (Gustina et al., 2025; Sukestiyarno et al., 2023). Therefore, spatial ability should be regarded as a core component of mathematical competence one that integrates conceptual understanding, visualization skills, and problem-solving ability rather than as an isolated supplementary skill.

Implications

This study has several limitations. First, the number of articles analyzed was relatively limited, consisting of only 17 articles retrieved from the Dimensions database and Publish or Perish based on Scopus. Second, the review included only articles that met the predefined inclusion and

exclusion criteria; therefore, it is possible that other relevant studies were not captured during the search process. Third, the bibliometric analysis conducted using VOSviewer relied on the metadata and keywords available in the selected articles, meaning that the mapping of research trends may have been influenced by the completeness and quality of publication data. Fourth, this study focused on the synthesis of existing literature and did not directly examine the effectiveness of spatial ability-based instructional strategies in classroom settings.

Limitations and Suggestions for Future Research

Several limitations should be considered when interpreting the findings of this systematic review and bibliometric analysis. First, the systematic synthesis was based on 17 eligible articles identified through Dimensions and Scopus via Publish or Perish, which may not represent the full range of research on spatial ability in mathematics education. The restricted evidence base reflects the predefined eligibility criteria but may have excluded relevant studies indexed in other databases or published in different formats. Future reviews should therefore expand database coverage to sources such as Web of Science, ERIC, and other relevant educational indexes while maintaining transparent and reproducible search procedures. Second, the reviewed studies were heterogeneous in terms of educational level, spatial constructs, instructional interventions, research designs, and outcome measures, which limits direct comparison of intervention effectiveness. Future research could address this limitation through more focused systematic reviews or meta-analyses examining specific spatial constructs, mathematical domains, educational levels, or intervention types. Third, bibliometric patterns based on keyword co-occurrence indicate thematic concentration and relationships within the literature but cannot independently establish the effectiveness of instructional approaches or confirm substantive research gaps. Future bibliometric studies should therefore integrate additional techniques, such as co-citation, bibliographic coupling, and thematic evolution analysis, to provide a more comprehensive representation of the intellectual structure of the field. Longitudinal and comparative empirical studies are also needed to determine whether improvements in spatial ability are sustained over time and transferred to specific mathematical competencies. Particular attention should be given to comparing technology-mediated approaches, including AR, VR, CAD, and 3D-based learning, with collaborative, metacognitive, ethnomathematical, and realistic mathematics approaches across different educational contexts. Such research would strengthen the evidence base for identifying which instructional configurations, pedagogical supports, and contextual conditions are most appropriate for developing particular dimensions of spatial ability in mathematics education.

CONCLUSION

Based on the findings of the Systematic Literature Review and bibliometric analysis using VOSviewer, spatial ability has been shown to be a crucial component in the development of students' mathematical competence. The results indicate that spatial ability supports visualization, spatial orientation, mental rotation, spatial reasoning, understanding of geometric concepts, and mathematical problem-solving skills. Research trends over the past decade also reveal a shift from conceptual studies of spatial ability toward more applied research focusing on technology-based instructional interventions and contextual learning approaches.

The instructional strategies most frequently employed to develop spatial ability include augmented reality (AR), virtual reality (VR), computer-aided design (CAD), 3D printing, spatial visualization tools, Think-Pair-Share, flipped classrooms with metacognitive scaffolding, ethnomathematics, Realistic Mathematics Education (RME), and authentic STEM learning. Overall,

these strategies are effective when they incorporate explicit visualization activities, object manipulation, structured spatial tasks, and appropriate scaffolding that aligns with students' characteristics and learning needs. Therefore, educational technology should not be viewed as a standalone solution but rather as a tool that must be integrated within a strong pedagogical framework.

The theoretical contribution of this study lies in its mapping of the relationships among spatial ability, instructional strategies, and students' mathematical competence. From a practical perspective, the findings provide guidance for teachers and curriculum developers to integrate spatial activities more systematically into mathematics instruction, particularly in topics such as geometry, coordinate systems, transformations, and STEM-related contexts. Furthermore, spatial ability should be assessed explicitly as an integral component of mathematical competence rather than being regarded merely as an additional or supplementary skill.

AUTHOR CONTRIBUTIONS STATEMENT

Niki Pujarwati contributed to conceptualization, methodology, literature search, data curation, systematic review, formal analysis, visualization, and writing the original draft. Chika Rahayu contributed to literature screening, data extraction, validation, formal analysis, and manuscript review and editing. Sugeng Sutaarso contributed to conceptualization, methodology, supervision, interpretation of the findings, and manuscript review and editing. Tina Yunarti contributed to validation, interpretation of the findings, supervision, and critical revision of the manuscript. Caswita contributed to methodological validation, bibliometric interpretation, supervision, and manuscript review and editing. All authors contributed to the interpretation of the findings, critically reviewed the manuscript, and read and approved the final version.

REFERENCES

- Adams, J., Resnick, I., & Lowrie, T. (2023). Supporting senior high-school students' measurement and geometry performance: Does spatial training transfer to mathematics achievement? *Mathematics Education Research Journal*, 35(4), 879–900. <https://doi.org/10.1007/s13394-022-00416-y>
- Alzahrani, N. M. (2020). Augmented reality: A systematic review of its benefits and challenges in e-learning contexts. *Applied Sciences*, 10(16), 5660. <https://doi.org/10.3390/app10165660>
- Arega, N. T., & Hunde, T. S. (2025). Constructivist instructional approaches: A systematic review of evaluation-based evidence for effectiveness. *Review of Education*, 13(1), e70040. <https://doi.org/10.1002/rev3.70040>
- Atman Uslu, N., Yildiz Durak, H., & Ay, G. M. (2022). Comparing reflective and supportive scaffolding in 3D computer-aided design course: Engineering students' metacognitive strategies, spatial ability self-efficacy, and spatial anxiety. *Computer Applications in Engineering Education*, 30(5), 1454–1469. <https://doi.org/10.1002/cae.22531>
- Awil, Sutamin, Ihsan, H., Nasir, N., Naufal, M. A., & Ikram, M. (2025). Spatial geometry learning in higher education through flipped classroom with metacognitive scaffolding: A mixed-methods study. *Online Learning in Educational Research*, 5(2), 583–600. <https://doi.org/10.58524/oler.v5i2.817>
- Bernacki, M. L., Greene, M. J., & Lobczowski, N. G. (2021). A systematic review of research on personalized learning: Personalized by whom, to what, how, and for what purpose(s)? *Educational Psychology Review*, 33(4), 1675–1715. <https://doi.org/10.1007/s10648-021-09615-8>

- Bertrand, M. G., Sezer, H. B., & Namukasa, I. K. (2024). Exploring AR and VR tools in mathematics education through culturally responsive pedagogies. *Digital Experiences in Mathematics Education*, 10(3), 462–486. <https://doi.org/10.1007/s40751-024-00152-x>
- Buckley, J., Seery, N., & Canty, D. (2019). Investigating the use of spatial reasoning strategies in geometric problem solving. *International Journal of Technology and Design Education*, 29(2), 341–362. <https://doi.org/10.1007/s10798-018-9446-3>
- Bulut, M., & Ferri, R. B. (2023). A systematic literature review on augmented reality in mathematics education. *European Journal of Science and Mathematics Education*, 11(3), 556–572. <https://doi.org/10.30935/scimath/13124>
- Cai, J., & Leikin, R. (2020). Affect in mathematical problem posing: Conceptualization, advances, and future directions for research. *Educational Studies in Mathematics*, 105(3), 287–301. <https://doi.org/10.1007/s10649-020-10008-x>
- Cirneanu, A.-L., & Moldoveanu, C.-E. (2024). Use of digital technology in integrated mathematics education. *Applied System Innovation*, 7(4), 66. <https://doi.org/10.3390/asi7040066>
- Dayyinati Fa'izulloh, Z., Susilo, B. E., Agoestanto, A., Mariani, S., & Semarang, U. N. (2026). Spatial ability in mathematics learning: A systematic review from the perspective of technology and learning models. *Mathema Journal*, 8(1). <https://doi.org/10.33365/jm.v8i1.1106>
- Dilling, F., & Vogler, A. (2021). Fostering spatial ability through computer-aided design: A case study. *Digital Experiences in Mathematics Education*, 7(2), 323–336. <https://doi.org/10.1007/s40751-021-00084-w>
- Felkel, P., Magana, A. J., Sloup, J., & Boček, J. (2025). Teaching transformations in computer graphics with support from an interactive tool. *Education and Information Technologies*, 30(18), 26457–26493. <https://doi.org/10.1007/s10639-025-13787-z>
- Gilligan, K. A., Thomas, M. S. C., & Farran, E. K. (2020). First demonstration of effective spatial training for near transfer to spatial performance and far transfer to a range of mathematics skills at 8 years. *Developmental Science*, 23(4), e12909. <https://doi.org/10.1111/desc.12909>
- Gilligan-Lee, K. A., Hawes, Z. C. K., & Mix, K. S. (2022). Spatial thinking as the missing piece in mathematics curricula. *npj Science of Learning*, 7(1). <https://doi.org/10.1038/s41539-022-00128-9>
- Gustina, D. M., Mariana, N., & Wiryanto, W. (2025). Augmented reality-based ethnomathematics learning media to enhance spatial ability in 3D geometry for fifth grade elementary students. *Journal of Innovation and Research in Primary Education*, 4(2), 273–280. <https://doi.org/10.56916/jirpe.v4i2.1229>
- Hamilton, D., McKechnie, J., Edgerton, E., & Wilson, C. (2021). Immersive virtual reality as a pedagogical tool in education: A systematic literature review of quantitative learning outcomes and experimental design. *Journal of Computers in Education*, 8(1), 1–32. <https://doi.org/10.1007/s40692-020-00169-2>
- Harris, D. (2023). Spatial reasoning in context: Bridging cognitive and educational perspectives of spatial-mathematics relations. *Frontiers in Education*, 8. <https://doi.org/10.3389/feduc.2023.1302099>
- Jablonski, S., & Ludwig, M. (2023). Teaching and learning of geometry—A literature review on current developments in theory and practice. *Education Sciences*, 13(7), 682. <https://doi.org/10.3390/educsci13070682>
- Johar, R., Fauzan, A., Sugiman, S., Anwar, L., Sa'dijah, C., & Khairunnisak, C. (2025). Developing local instruction theory through ethnomathematics and technological-based realistic mathematics education to support students' spatial ability. *Asian Journal for Mathematics Education*, 4(4), 553–587. <https://doi.org/10.1177/27527263251383572>
- Kaźmierczak, R., Grunwald, G., Skowroński, R., Kaźmierczak, L., & Kowalczyk, C. (2025). Augmented reality tools for mathematics and geoscience education. *Scientific Reports*, 15(1). <https://doi.org/10.1038/s41598-025-02090-z>
- Krüger, J. M., Palzer, K., & Bodemer, D. (2022). Learning with augmented reality: Impact of dimensionality and spatial abilities. *Computers and Education Open*, 3, 100065. <https://doi.org/10.1016/j.caeo.2021.100065>

- Kurt, G., Önel, F., & Çakıoğlu, Ö. (2023). An investigation of middle school students' spatial reasoning skills. *International Electronic Journal of Elementary Education*, 16(1), 123–141. <https://doi.org/10.26822/iejee.2023.319>
- Kyaw, K. M., & Vidákovich, T. (2025). The relationship between spatial reasoning and geometric reasoning in teachers. *Eurasia Journal of Mathematics, Science and Technology Education*, 21(8). <https://doi.org/10.29333/ejmste/16718>
- Lee, J., Kim, H., Kim, K. H., Jung, D., Jowsey, T., & Webster, C. S. (2020). Effective virtual patient simulators for medical communication training: A systematic review. *Medical Education*, 54(9), 786–795. <https://doi.org/10.1111/medu.14152>
- Liu, Y., & Pásztor, A. (2022). Effects of problem-based learning instructional intervention on critical thinking in higher education: A meta-analysis. *Thinking Skills and Creativity*, 45, 101069. <https://doi.org/10.1016/j.tsc.2022.101069>
- Lowrie, T., Harris, D., Logan, T., & Hegarty, M. (2021). The impact of a spatial intervention program on students' spatial reasoning and mathematics performance. *The Journal of Experimental Education*, 89(2), 259–277. <https://doi.org/10.1080/00220973.2019.1684869>
- Mannan, A. M. K., Bajuri, M. R., Abdul Rahim, S. S., & Abdullah, N. A. (2026). How do digital tools support metacognition in mathematics learning? A systematic review of research on GeoGebra and problem-solving. *Educational Research Review*, 52, 100827. <https://doi.org/10.1016/j.edurev.2026.100827>
- Mawarsari, V. D., Sukestiyarno, Y. L., Mariani, S., & Junaedi, I. (2024). Students' geometric thinking processes in terms of spatial intelligence. *Journal of Ecohumanism*, 3(8), 8666–8683. <https://doi.org/10.62754/joe.v3i8.5482>
- Medina Herrera, L. M., Juárez Ordóñez, S., & Ruiz-Loza, S. (2024). Enhancing mathematical education with spatial visualization tools. *Frontiers in Education*, 9. <https://doi.org/10.3389/feduc.2024.1229126>
- Mix, K. S., Levine, S. C., Cheng, Y. L., Stockton, J. D. S., & Bower, C. (2021). Effects of spatial training on mathematics in first and sixth grade children. *Journal of Educational Psychology*, 113(2), 304–314. <https://doi.org/10.1037/edu0000494>
- Mohammed Luaibi, Y. (2025). Formal thinking in mathematics and its relationship to spatial ability among middle school female students. *Himalayan Journal of Humanities and Cultural Studies*, 6(1), 1–8. <https://doi.org/10.47310/hjhcs.2025.v06i01.002>
- Moussa, M. A., Ahmed, S. A. G., & Al-Adamat, O. (2025). Developing spatial thinking in Cartesian coordinate tasks: The impact of the Think-Pair-Share strategy on sixth-grade learners. *The New Educational Review*, 81(3), 151–164. <https://doi.org/10.15804/tner.2025.81.3.10>
- Mu, J., Bayrak, A., & Ufer, S. (2022). Conceptualizing and measuring instructional quality in mathematics education: A systematic literature review. *Frontiers in Education*, 7. <https://doi.org/10.3389/feduc.2022.994739>
- Muhammad, H., Musa, N. A., Ahmad, A., Adamu, N., & Adamu, N. (2026). The role of augmented reality (AR) in enhancing conceptual understanding of geometry in mathematics education: Systematic review. *International Journal of Education, Management, and Technology*, 4(1), 29–47. <https://doi.org/10.58578/ijemt.v4i1.8073>
- Ozcakir, B., & Cakiroglu, E. (2021). An augmented reality learning toolkit for fostering spatial ability in mathematics lesson: Design and development. *European Journal of Science and Mathematics Education*, 9(4), 145–167. <https://doi.org/10.30935/scimath/11204>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71. <https://doi.org/10.1136/bmj.n71>
- Papageorgiou, E., Wong, J., Liu, Q., Khalil, M., & Cabo, A. J. (2025). A systematic review on student engagement in undergraduate mathematics: Conceptualization, measurement, and learning outcomes. *Educational Psychology Review*, 37(3), 66. <https://doi.org/10.1007/s10648-025-10046-y>

- Pardo, F., Cánovas, Ó., & Clemente, F. J. G. (2025). Audio features in education: A systematic review of computational applications and research gaps. *Applied Sciences*, 15(12), 6911. <https://doi.org/10.3390/app15126911>
- Patiño Hernández, J. F., Chiappe, A., & Ortega González, E. (2026). From digital competence to AI-responsive pedagogy: A scoping review of technology-supported teacher education. *Frontiers in Education*, 11. <https://doi.org/10.3389/feduc.2026.1949296>
- Pinilla, R. K. (2024). Spatial reasoning in mathematics standards: Identifying how early elementary educators are systematically supported to teach spatial skills. *Frontiers in Education*, 9, 1407388. <https://doi.org/10.3389/feduc.2024.1407388>
- Putri, R. O. E., Zulnaidi, H., & Abdul Rahim, S. S. (2025). Investigating current patterns in spatial learning within the context of mathematics education in Asia: A systematic review. *Contemporary Mathematics and Science Education*, 6(1), ep25006. <https://doi.org/10.30935/conmaths/16110>
- Rabab'h, B., & Veloo, A. (2015). Spatial visualization as mediating between mathematics learning strategy and mathematics achievement among 8th grade students. *International Education Studies*, 8(5), 1–11. <https://doi.org/10.5539/ies.v8n5p1>
- Salehi, F., & Dixit, M. K. (2026). Effects of visual-body axis misalignment on spatial ability under altered visuospatial conditions. *Acta Astronautica*, 249, 414–427. <https://doi.org/10.1016/j.actaastro.2026.07.032>
- Schenck, K. E., & Nathan, M. J. (2024). Navigating spatial ability for mathematics education: A review and roadmap. *Educational Psychology Review*, 36(3), 90. <https://doi.org/10.1007/s10648-024-09935-5>
- Schoenherr, J., Strohmaier, A. R., & Schukajlow, S. (2024). Learning with visualizations helps: A meta-analysis of visualization interventions in mathematics education. *Educational Research Review*, 45, 100639. <https://doi.org/10.1016/j.edurev.2024.100639>
- Sukestiyarno, Y. L., Nugroho, K. U. Z., Sugiman, S., & Waluya, B. (2023). Learning trajectory of non-Euclidean geometry through ethnomathematics learning approaches to improve spatial ability. *Eurasia Journal of Mathematics, Science and Technology Education*, 19(6). <https://doi.org/10.29333/ejmste/13269>
- Szabo, Z. K., Körtesi, P., Guncaga, J., Szabo, D., & Neag, R. (2020). Examples of problem-solving strategies in mathematics education supporting the sustainability of 21st-century skills. *Sustainability*, 12(23), 10113. <https://doi.org/10.3390/su122310113>
- Wang, Q., & Abdullah, A. H. (2024). Enhancing students' critical thinking through mathematics in higher education: A systemic review. *SAGE Open*, 14(3), 21582440241275651. <https://doi.org/10.1177/21582440241275651>
- Wulandari, T., Susanti, E., & Hiltrimartin, C. (2026). Developing a PMRI-based augmented reality learning trajectory to support students' problem-solving skills in circle geometry. *Jurnal Elemen*, 12(1), 89–109. <https://doi.org/10.29408/jel.v12i1.32435>
- Xu, T., Sun, S., & Kong, Q. (2025). Spatial reasoning and its contribution to mathematical performance across different content domains: Evidence from Chinese students. *Journal of Intelligence*, 13(4), 41. <https://doi.org/10.3390/jintelligence13040041>
- Yang, S., Baird, M., O'Rourke, E., Brennan, K., & Schneider, B. (2024). Decoding debugging instruction: A systematic literature review of debugging interventions. *ACM Transactions on Computing Education*, 24(4), Article 45. <https://doi.org/10.1145/3690652>
- Yang, Y., Du, W., Mavrikis, M., & Geraniou, E. (2026). Spatial skill development through augmented reality in mathematics education: A scoping review. *Digital Experiences in Mathematics Education*. <https://doi.org/10.1007/s40751-025-00187-8>
- Zhou, Y., Xu, T., Yang, H., & Li, S. (2022). Improving spatial visualization and mental rotation using FORSpatial through shapes and letters in virtual environment. *IEEE Transactions on Learning Technologies*, 15(3), 326–337. <https://doi.org/10.1109/TLT.2022.3170928>
- Zhu, C., Leung, C. O. Y., Lagoudaki, E., Velho, M., Segura-Caballero, N., Jolles, D., Duffy, G., Maresch, G., Pagkratidou, M., & Klapwijk, R. (2023). Fostering spatial ability development in and for authentic STEM learning. *Frontiers in Education*, 8, 1138607. <https://doi.org/10.3389/feduc.2023.1138607>