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Educational Interventions for Developing Spatial Reasoning in School Mathematics: A Systematic Literature Review of Empirical Studies

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Abstract. Spatial reasoning is increasingly recognised as a foundational cognitive competency underpinning geometry achievement and broader mathematical performance, yet a comprehensive synthesis of recent empirical studies on such interventions is lacking. This systematic literature review aimed to examine the characteristics, effectiveness, and thematic trends of empirical studies on educational interventions designed to develop spatial reasoning in school mathematics. Following the PRISMA 2020 guidelines, a systematic search was conducted across Scopus, Web of Science, and the Excellence in Research for Australia databases. A total of 20 peer-reviewed empirical studies published between 2021 and 2026 satisfied the predefined inclusion criteria and were retained for synthesis. Findings indicate that technology-mediated interventions—including dynamic geometry software, augmented reality environments, and digital construction tools—were the most prominent approaches, consistently yielding measurable gains in spatial visualisation and mental rotation. Manipulative-based and activity-orientated interventions such as LEGO construction, origami integration, and outdoor geometry tasks also produced positive spatial outcomes, particularly in near-transfer domains. Although most interventions effectively improved students' spatial reasoning abilities, evidence for transfer to broader mathematical achievement remained limited and domain dependent, with the strongest effects observed for geometry-proximate outcomes. These findings affirm that spatial reasoning is a malleable competency that is responsive to purposeful instructional design. The review offers evidence-informed implications for geometry curriculum development, classroom practice, and teacher preparation while identifying secondary-level instruction and Southeast Asian educational contexts as priority areas for future investigation.

Keywords: spatial reasoning; educational interventions; school mathematics; mathematics learning; systematic literature review

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1. Introduction

Spatial reasoning, including mental rotation, spatial visualisation, and spatial orientation is increasingly recognised as a fundamental component of mathematical thinking (Harris, 2023; Xu et al., 2025). These abilities support students' understanding of geometric representations, algebraic reasoning, and three-dimensional concepts and are strongly associated with mathematics achievement and STEM participation (Adams et al., 2023; Gilligan-Lee et al., 2022; Hawes et al., 2022). Despite its importance, many students continue to experience difficulties with spatial tasks such as mental transformations and 2D–3D visualisation (Hasanah et al., 2024; Juman et al., 2022; Wahyuni et al., 2024). Such challenges are often reinforced by teacher-centred instructional approaches that emphasise procedural learning over spatial exploration and visual reasoning (Harris et al., 2021; Hawes et al., 2022).

Research indicates that technology-enhanced, manipulative-based, problem-based, and game-based interventions can effectively improve students' spatial reasoning and mathematical learning (Dung et al., 2025; Habeeb, 2025; Ikhsan et al., 2024). These approaches align with constructivist and embodied cognition perspectives by promoting engagement with multiple representations and deeper conceptual understanding (Anwar et al., 2025; Nathan et al., 2021). However, their implementation remains inconsistent across educational contexts because of variations in teacher expertise, curriculum priorities, and technological infrastructure (Gagnier et al., 2022; Sunzuma & Maharaj, 2020).

Despite growing evidence on spatial reasoning interventions, several gaps remain. First, no systematic review has comprehensively synthesised empirical studies published between 2021 and 2026, a period marked by the rapid expansion of digital learning environments (Hawes et al., 2022; Suparman et al., 2024). Second, limited attention has been given to how interventions target specific spatial reasoning constructs such as mental rotation, spatial visualisation, and spatial orientation despite their distinct relationships with mathematics learning (Hawes et al., 2022; Schenck & Nathan, 2024). Third, existing evidence is dominated by studies from Western contexts, limiting the generalisability of findings across diverse educational settings (Almubarak et al., 2025; Weigand et al., 2025). Furthermore, many studies focus on a single intervention type or short implementation period, resulting in a fragmented evidence base (McDougal et al., 2024; Özçakır & Çakıroğlu, 2022).

To address these gaps, this study conducted a systematic literature review (SLR) of empirical research on educational interventions for developing spatial reasoning in school mathematics. The review examined intervention characteristics, targeted spatial constructs, research designs, educational levels, and reported learning outcomes. By identifying effective approaches, research trends, and remaining gaps, the study provides evidence-informed implications for teaching, curriculum development, and future research.

An SLR requires a structured framework to develop focused and answerable research questions. While the PICO model is commonly used in clinical research, its emphasis on comparison groups and measurable outcomes limits its suitability for educational studies (Cooke et al., 2012). Consequently, this review adopted the SPIDER framework (Sample, Phenomenon of Interest, Design, Evaluation, and Research Type), which is more appropriate for educational research because it accommodates diverse participant groups, learning phenomena, and both quantitative and qualitative forms of evaluation (Cooke et al., 2012).

Table 1: SPIDER model

No.	SPIDER Element	Model
1.	S: Sample	Students across primary and secondary school levels (typically aged 6–18 years) involved in formal mathematics education settings; may also include mathematics teachers where relevant to intervention implementation.
2.	PI: Phenomenon of Interest	Educational interventions designed to develop spatial reasoning in school mathematics, including technology-based interventions (dynamic geometry software, virtual/augmented reality), hands-on manipulatives, spatial visualisation and mental rotation training, inquiry-based learning, problem-based learning, STEM-integrated instruction, embodied learning, and structured instructional programmes.
3.	D: Design	Empirical research employing a quantitative, qualitative, or mixed-method approach, including experimental, quasi-experimental, and design-based research; longitudinal studies; case studies; and classroom-based intervention studies.
4.	E: Evaluation	Measured outcomes related to development of spatial reasoning (spatial visualisation, mental rotation, spatial orientation, spatial perception) and mathematics learning outcomes (conceptual understanding, problem-solving skills, reasoning ability, academic achievement, transfer of learning).
5.	R: Research Type	Peer-reviewed empirical studies conducted in school mathematics contexts focusing on intervention effectiveness, implementation processes, and learning impact.

The research questions were developed using the SPIDER framework as presented in Table 1.

1. What are the characteristics of the empirical studies on educational interventions for developing spatial reasoning in the school of mathematics?
2. What are the reported effects of these educational interventions on students' spatial reasoning abilities and mathematics learning outcomes?
3. What thematic trends, research focuses, and emerging gaps can be identified on educational interventions for developing spatial reasoning in school mathematics?

2. Literature Review

2.1 Conceptual Foundations of Spatial Reasoning in School Mathematics

Spatial reasoning is widely recognised as a multidimensional cognitive construct involving the ability to perceive, represent, manipulate, transform, and reason about spatial relationships among objects and representations (Harris, 2023; Kurt et al., 2023). Although definitions vary across disciplines, there is broad agreement that spatial reasoning encompasses both static and dynamic operations in space and plays a fundamental role in mathematics learning (Adams et al., 2023; Hawes et al., 2022). Establishing a clear conceptual understanding is important because variations in how spatial reasoning is defined and measured have contributed to inconsistencies across educational research (Bansil & Yabut, 2025; Harris, 2023).

The literature consistently identifies mental rotation, spatial visualisation, and spatial orientation as the core dimensions of spatial reasoning (Bansil & Yabut, 2025; Kurt et al., 2023). Additional components such as spatial structuring and perspective-taking further contribute to complex mathematical reasoning, particularly in geometry and three-dimensional contexts (Fujita et al., 2022). Spatial skills support learning in geometry, measurement, algebraic thinking, proportional reasoning, and mathematical problem solving (Kurt et al., 2023; Schenck & Nathan, 2024). Evidence from meta-analytic and empirical studies indicates that improvements in spatial reasoning can transfer to mathematics performance, particularly when mathematical tasks involve visualisation, abstraction, and representational coordination (Adams et al., 2023; Hawes et al., 2022).

2.2 Theoretical Perspectives Supporting Spatial Reasoning Development

The development of spatial reasoning in mathematics education is commonly explained through constructivist learning theory and embodied cognition theory, both of which emphasise learners' active engagement with mathematical ideas and representations (Crompton & Ferguson, 2024; Palatnik et al., 2025).

Constructivist learning theory views learning as an active process in which students construct knowledge through exploration, inquiry, and problem solving (Crompton & Ferguson, 2024). In mathematics education, this perspective underpins approaches such as dynamic geometry software, inquiry-based learning, problem-based learning, and STEM-integrated activities. Studies have shown that learning environments emphasising exploration and multiple representations can enhance students' spatial reasoning and mathematical understanding (Adams et al., 2023; Suparman et al., 2024).

Embodied cognition theory posits that learning is grounded in bodily actions and perceptual experiences (Palatnik et al., 2025). From this perspective, spatial understanding develops through interaction with physical and visual-spatial environments. Accordingly, interventions such as manipulatives, origami, augmented reality (AR), virtual reality (VR), and three-dimensional modelling have been shown to support spatial visualisation, mental rotation, and geometric reasoning (Fitriyana et al., 2025; Hanid et al., 2022).

Together, constructivism and embodied cognition provide a conceptual framework for understanding how educational interventions support spatial reasoning development. Both perspectives emphasise active engagement, visualisation, and interaction with multiple representations, offering a useful lens for interpreting intervention characteristics and learning outcomes across educational contexts.

2.3 Educational Interventions for Developing Spatial Reasoning
Research indicates that spatial reasoning is responsive to targeted instruction and can positively influence mathematics learning (Hawes et al., 2022). Accordingly, a range of interventions has been developed, including technology-enhanced approaches, manipulative-based learning, inquiry- and problem-based pedagogies, and immersive learning environments (Hawes et al., 2022; Lowrie & Logan, 2023).

2.3.1 Technology-Enhanced Interventions
Tools such as dynamic geometry software, computer-aided design environments, and interactive simulations allow learners to manipulate and explore geometric objects dynamically, supporting visualisation and representational coordination (Alves et al., 2022; Chivai et al., 2022). Evidence consistently suggests that these technologies promote exploratory learning, reduce the cognitive demands of abstract reasoning, and strengthen spatial understanding across educational levels (Fitriawan et al., 2026; Suparman et al., 2024).

2.3.2 Manipulative-Based and Embodied Learning Interventions
Activities involving geometric solids, tangrams, geoboards, origami, and physical model construction encourage learners to visualise, transform, and reason about spatial relationships through direct interaction with objects (Bansil & Yabut, 2025; Ridgley et al., 2025). These approaches complement technology-based interventions by grounding mathematical understanding in tactile and embodied experiences, thereby facilitating the transition from concrete to abstract reasoning.

2.3.3 Inquiry-Based and Problem-Based Approaches
Inquiry-based, problem-based, and STEM-integrated approaches emphasise active exploration of mathematical situations and the application of spatial thinking to authentic problems (Korkmaz & Yilmaz, 2022; Thom et al., 2024). Rather than focusing on specific tools, these approaches prioritise instructional design that encourages investigation, reasoning, collaboration, and reflection. Evidence suggests that such pedagogies support deeper conceptual understanding and promote the flexible application of spatial reasoning across mathematical and interdisciplinary contexts (Fitriawan et al., 2026; Harris, 2023).

2.3.4 Emerging Immersive and Innovative Interventions
Recent advances in AR, VR, mixed reality, and gamified learning environments have expanded opportunities for the development of spatial reasoning (Muhammad et al., 2026; Yang et al., 2025). These immersive technologies enable learners to interact with three-dimensional representations in ways that are difficult to achieve through conventional instruction. Although findings generally indicate positive effects on spatial visualisation and geometry learning, evidence regarding long-term effectiveness, scalability, and implementation conditions remains limited (Harris, 2023; Yang et al., 2025).

Although evidence supporting spatial reasoning interventions continues to grow, the literature remains fragmented across intervention types, educational levels, and research contexts. Differences in intervention duration, implementation quality, participant characteristics, and assessment methods complicate cross-study comparison and limit the development of generalisable recommendations (Hawes et al., 2022; Schenck & Nathan, 2024).

2.4 Effects of Spatial Reasoning Interventions on Mathematics Learning

Research indicates that targeted spatial reasoning interventions can improve both spatial competencies and mathematics achievement, although their effectiveness varies across educational contexts and intervention designs (Adams et al., 2023; Hawes et al., 2022). Spatial reasoning interventions most consistently improve spatial visualisation, mental rotation, and other spatial abilities, with additional gains reported in spatial orientation and structuring (Bansil & Yabut, 2025; Hawes et al., 2022). These improvements are often associated with enhanced mathematics learning, particularly in geometry, representation interpretation, and problem solving (Adams et al., 2023; Kurt et al., 2023).

Beyond cognitive gains, spatial reasoning interventions often enhance students' engagement, motivation, and confidence in mathematics learning (Borboeva et al., 2025; Haqq et al., 2025). However, their effectiveness depends on factors such as implementation quality, teacher expertise, learner characteristics, and available resources, while methodological limitations continue to restrict evidence regarding long-term impacts (Adams et al., 2023; Hawes et al., 2022).

3. Methodology

3.1 Research Design

This study employed an SLR as its research design. An SLR is a rigorous, transparent, and reproducible approach for identifying, evaluating, and synthesising empirical evidence relevant to a clearly defined research question (Page et al., 2021). The SLR design was selected because it enables comprehensive and systematic examination of evidence while minimising bias in addition to facilitating comparison and synthesis of findings across studies and supporting the identification of research patterns and gaps (Booth et al., 2016; Kitchenham, 2004; Page et al., 2021; Petticrew & Roberts, 2006). The review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021).

3.2 Review Protocol

A review protocol was developed prior to the commencement of the study to ensure consistency and rigour throughout the review process. The protocol defined the review objectives, eligibility criteria, search strategy, data extraction process, and synthesis methods according to the PRISMA 2020 framework (Page et al., 2021).

3.2.1 Review Objectives

This SLR was conducted to (1) identify and analyse the methodological and contextual characteristics of empirical studies on educational interventions for developing spatial reasoning in school mathematics published between 2021 and

2026; (2) examine the types and effects of educational interventions on students' spatial reasoning abilities and mathematics learning outcomes across different educational levels and contexts; and (3) identify thematic trends, research focuses, methodological patterns, and emerging gaps in the literature to inform future research and evidence-based instructional practices in geometry education.

3.2.2 Eligibility Criteria

Predefined inclusion and exclusion criteria (Table 2) were established prior to the search process and applied systematically at each screening stage.

Table 2: Inclusion and exclusion criteria for study selection

No.	Inclusion Criteria	Exclusion Criteria
1	Studies published between 2021 and 2026	Studies published before 2021 or after 2026
2	Studies written in English	Studies not published in English
3	Studies indexed in Scopus, Web of Science (WoS), or Excellence in Research for Australia (ERA) databases	Studies not indexed in the selected databases
4	Studies classified under the Social Sciences subject area	Studies outside the Social Sciences subject classification
5	Peer-reviewed journal articles (empirical studies or literature reviews)	Conference papers, book chapters, theses, grey literature, or non-article documents
6	Studies focused on educational interventions for developing spatial reasoning in school mathematics	Studies not relevant to spatial reasoning or school mathematics
7	Openly accessible full-text articles	Articles not available in open access
8	Studies containing empirical data or constituting a systematic literature review	Duplicate records

Note. Criteria were applied sequentially during the identification, screening, and eligibility stages of the PRISMA 2020 process (Page et al., 2021).

3.2.3 Information Sources and Search Strategy

The databases used in this study were Scopus, Web of Science (WoS), and the Excellence in Research for Australia (ERA) register. Scopus was selected because it is recognised as the largest abstract and citation database of peer-reviewed literature spanning multiple disciplines, including education and social sciences (Mongeon & Paul-Hus, 2016), while WoS complements this through its rigorous editorial selectivity, indexing only journals that meet stringent quality and impact criteria (Gusenbauer & Haddaway, 2020). The ERA journal list was included to ensure quality-assured coverage of education and mathematical sciences journals relevant to the Asia-Pacific context, given that research from non-Western regions may be underrepresented in the two major citation indices (Mongeon & Paul-Hus, 2016). Search strings were constructed using Boolean operators (AND/OR) combining three thematic keyword clusters: (1) types of educational interventions, (2) spatial reasoning and related constructs, and (3) mathematics education contexts. The complete search strings are presented in Table 3.

Table 3: Search strings applied across each database

Database	Search String
Scopus	TITLE-ABS-KEY(("intervention*" OR "educational intervention*" OR "instructional intervention*" OR "teaching intervention*" OR "pedagogical intervention*" OR "learning intervention*" OR "classroom intervention*" OR "training program*")) AND TITLE-ABS-KEY(("spatial reasoning" OR "spatial ability" OR "spatial thinking" OR "spatial skill*" OR "spatial visualization" OR "visual-spatial ability" OR "visuospatial skill*" OR "mental rotation" OR "spatial orientation" OR "spatial perception" OR "geometric visualization")) AND TITLE-ABS-KEY(("mathematics education" OR "mathematics teaching" OR "mathematics learning" OR "math education" OR "math teaching" OR "math learning" OR "mathematics instruction" OR "school mathematics" OR "geometry education" OR "geometry teaching"))
Web of Science (WoS)	TS=(("intervention*" OR "educational intervention*" OR "instructional intervention*" OR "teaching intervention*" OR "pedagogical intervention*" OR "learning intervention*" OR "classroom intervention*" OR "training program*" OR "experimental program*" OR "quasi-experimental*" OR "experimental stud*" OR "treatment group*" OR "design-based research")) AND TS=(("spatial reasoning" OR "spatial ability" OR "spatial thinking" OR "spatial skill*" OR "spatial visualization" OR "visual-spatial ability" OR "visuospatial skill*" OR "mental rotation" OR "spatial orientation" OR "spatial perception" OR "geometric visualization")) AND TS=(("mathematics education" OR "mathematics teaching" OR "mathematics learning" OR "math education" OR "math teaching" OR "math learning" OR "mathematics instruction" OR "school mathematics" OR "geometry education" OR "geometry teaching"))
ERA	("intervention*" OR "educational intervention*" OR "instructional intervention*" OR "teaching intervention*" OR "pedagogical intervention*" OR "learning intervention*" OR "classroom intervention*" OR "training program*" OR "experimental program*") AND ("spatial reasoning" OR "spatial ability" OR "spatial thinking" OR "spatial skill*" OR "spatial visualization" OR "visual-spatial ability" OR "visuospatial skill*" OR "mental rotation" OR "spatial orientation" OR "spatial perception" OR "geometric visualization") AND ("mathematics education" OR "mathematics teaching" OR "mathematics learning" OR "math education" OR "math teaching" OR "math learning" OR "mathematics instruction" OR "school mathematics" OR "geometry education" OR "geometry teaching")

3.3 Selection Protocol and Data Collection

3.3.1 Selection Strategy

Study selection followed three sequential stages—identification, screening, and eligibility—guided by the PRISMA 2020 framework (Page et al., 2021). At the identification stage, 168 records were retrieved (Scopus: n = 66; WoS: n = 70; ERA: n = 32). Records were excluded prior to screening based on publication year and subject classification, retaining 71 records for the screening phase. During screening, 16 records were excluded as non-peer-reviewed articles (Scopus: n = 8; WoS: n = 8). Of the 55 reports sought for full-text retrieval, 14 were inaccessible due to restricted open access (Scopus: n = 6; WoS: n = 5; ERA: n = 3), leaving 41 reports for the eligibility stage. At eligibility, one WoS record was excluded for non-English language, and 20 duplicates were removed (WoS: n = 11; ERA: n = 9). All remaining articles met the quality threshold; accordingly, 20 studies satisfied all the inclusion criteria and were retained for final synthesis.

3.3.2 Sampling Method

The sampling method employed was purposive sampling, a non-probability technique in which studies are deliberately selected based on their relevance to predefined research criteria (Creswell & Creswell, 2018; Patton, 2015). In this SLR, purposive sampling was operationalised through the inclusion and exclusion criteria outlined in Section 3.2.2, with each study being selected based on its focus on spatial reasoning interventions in school mathematics, methodological rigour, publication period (2021–2026), language, subject classification, and accessibility. This approach is widely recognised as standard practice in SLR for enhancing transparency, reproducibility, and quality of the evidence base (Etikan et al., 2016; Page et al., 2021; Sarkis-Onofre et al., 2021). The use of three databases with comprehensive Boolean search strings further ensured broad literature coverage within the defined scope.

3.4 PRISMA Flow Diagram

The PRISMA 2020 flow diagram (Figure 1) illustrates the complete progression of records across all selection stages, providing a transparent account of screening and selection decisions consistent with the reporting standards of Page et al. (2021).

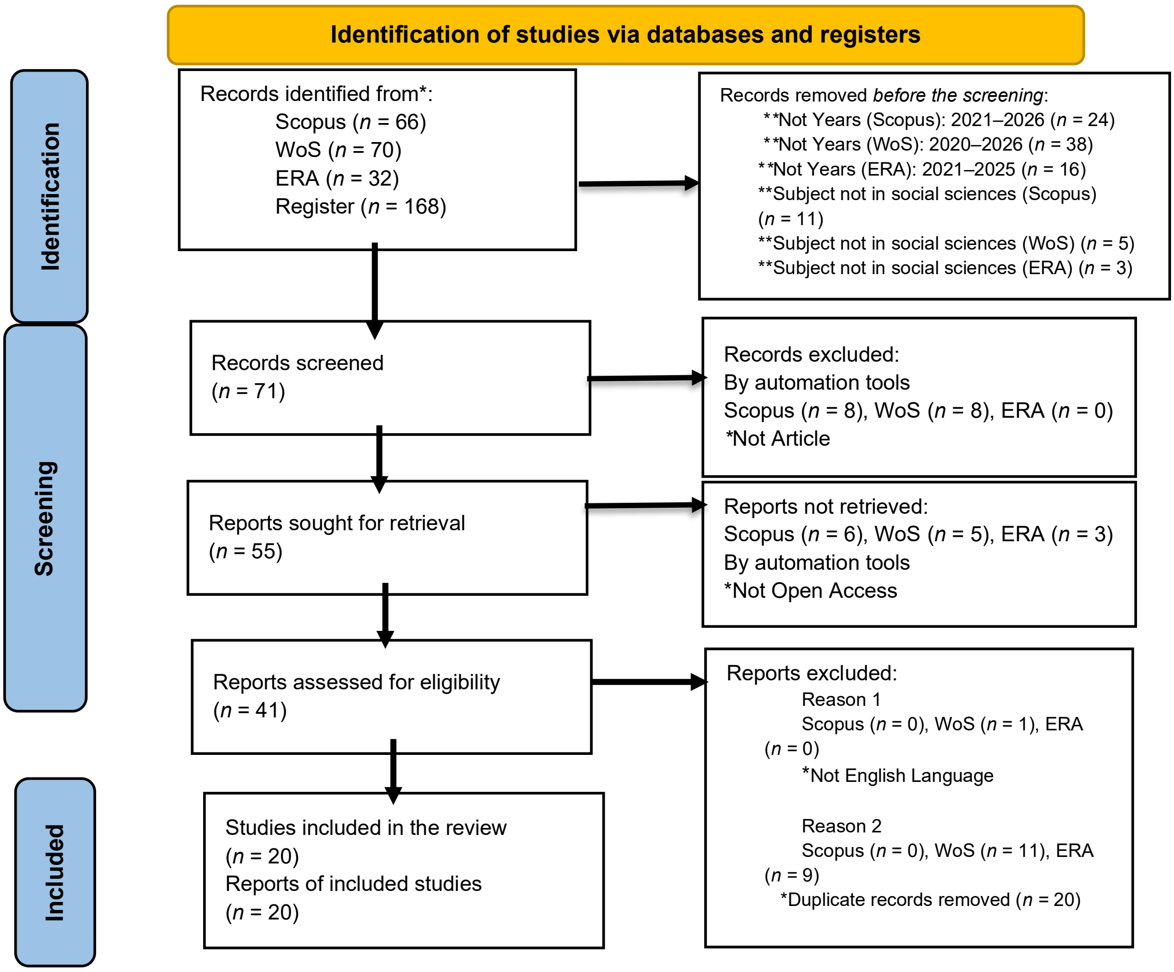

Figure 1: Flow diagram of the study

Note. Adapted from Page et al. (2021)
* Records were filtered manually by the researchers.
** Records were filtered using an automated screening tool.

3.5 Data Extraction

Data extraction was conducted in two stages. First, a descriptive analysis documented the bibliographic and methodological characteristics of each included study, covering publication year, educational level, sample characteristics, research design, subject domain, and educational context. Second, thematic analysis was employed to synthesise findings related to the implementation and effectiveness of spatial reasoning-based interventions. Relevant findings were systematically coded, categorised into recurring concepts, and organised into higher-order themes to support integrative interpretation.

3.6 Quality Assessment

Quality appraisal was conducted to evaluate the methodological rigour of all included studies, as this is a critical step in an SLR to ensure that conclusions drawn are based on credible and trustworthy evidence (Kitchenham & Charters, 2007). Each study was assessed using the quality appraisal instrument adapted from Abouzahra et al. (2020), which comprises six criteria: (C1) specificity of research objectives; (C2) applicability and value; (C3) methodological transparency; (C4) suitability of conceptual approach; (C5) comparison with existing literature; and (C6) adequacy in reporting limitations. Each criterion was scored on a three-point scale (Yes = 1.0, Partially = 0.5, No = 0), yielding a maximum total score of 6.0. Articles scoring above 3.0 were considered to meet the minimum quality threshold and classified as High (≥ 5.0), Moderate (3.5–4.5), or Low (< 3.5). Appraisal results are presented in Table 4.

Table 4: Article quality appraisal results

ID	C1	C2	C3	C4	C5	C6	Score	Quality Level
A1	1.0	1.0	1.0	1.0	0.5	1.0	5.5	High
A2	1.0	1.0	1.0	1.0	1.0	0	5.0	High
A3	1.0	1.0	1.0	1.0	1.0	0.5	5.5	High
A4	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High
A5	1.0	1.0	1.0	1.0	1.0	0.5	5.5	High
A6	1.0	1.0	1.0	1.0	0.5	0.5	5.0	High
A7	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High
A8	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High
A9	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High
A10	1.0	1.0	1.0	1.0	1.0	0.5	5.5	High
A11	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High
A12	1.0	1.0	1.0	1.0	1.0	0.5	5.5	High
A13	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High
A14	1.0	1.0	1.0	1.0	1.0	0.5	5.5	High
A15	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High
A16	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High
A17	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High
A18	1.0	1.0	1.0	1.0	1.0	0.5	5.5	High
A19	1.0	1.0	1.0	1.0	1.0	0.5	5.5	High
A20	1.0	1.0	1.0	1.0	1.0	1.0	6.0	High

All 20 articles demonstrated high methodological quality, with scores ranging from 5.0 to 6.0. Ten articles (A1, A2, A3, A5, A6, A10, A12, A14, A18, and A19) scored between 5.0 and 5.5, with marginally lower scores attributable to partial reporting of limitations (C6). The remaining ten (A4, A7, A8, A9, A11, A13, A15, A16, A17, and A20) achieved the maximum score of 6.0, demonstrating full compliance with all quality criteria. No articles fell below the minimum threshold; accordingly, all 20 studies were retained for synthesis.

3.7 Ethical Standards

Although this SLR does not involve primary data collection from human participants and, therefore, does not require formal ethical approval, ethical rigour was maintained throughout. Specifically, all sources were cited accurately in accordance with the conventions of the 7th edition of the APA Publication Manual; the findings and contributions of all cited authors were faithfully acknowledged; and the entire review process was documented transparently according to the PRISMA 2020 guidelines (Page et al., 2021). These measures ensured adherence to the principles of academic integrity, intellectual honesty, and scholarly transparency.

4. Results and Findings

4.1 Critical Analysis of Spatial Reasoning Intervention Studies

Table 5 presents a critical analysis of the studies included in this review, summarising their research objectives, methodological characteristics, sample profiles, key findings, and identified limitations or research gaps.

Table 5: Critical analysis of the studies

Author (Year)	Scope / Research Objective	Research Design	Sample	Findings	Limitations / Gaps
Moussa et al. (2025)	To examine the effectiveness of the Think-Pair-Share (TPS) strategy in developing sixth-grade students' spatial thinking in Cartesian coordinate tasks	Quasi-experimental design (pre-test and post-test with intervention)	32 sixth-grade students (aged 11–13 years) from Salalah Basic Education School, Oman; pilot sample of 100	TPS significantly improved spatial perception and visual-spatial reasoning ($p <$ .05), particularly in Cartesian coordinate representation tasks	Small purposive sample; limited generalisability; short intervention duration
Dos Santos et al. (2025)	To investigate how GeoGebra automatic feedback tasks enhance self-regulated learning, conceptual understanding, and computational thinking related to robotics	Literature review integrated with comparative empirical study	Four teachers from Brazil, Portugal, and Cape Verde in a continuous training programme	Increased engagement, improved problem solving, spatial visualisation, and algorithmic thinking; technical training challenges noted	Small participant group; teacher-focused rather than student outcome based; contextual limitations
Özçakır & Çakıroğlu (2022)	To foster middle-school students' spatial abilities using augmented reality (AR) and to examine students' spatial strategies	Educational design research with AR intervention	Eight seventh-grade students	AR supported invention and modification of spatial strategies; improved spatial understanding and reduced cognitive filter effect	Very small sample; exploratory nature limits generalisability
Fujita et al. (2022)	To identify 'core' spatial reasoning skills contributing to successful 3D geometry problem solving among Japanese students	Large-scale survey; 2-Parameter Logistic Model (2PLM) and correlational analyses	2 303 Japanese students (Grades 4–9)	Mental rotation and visualisation / drawing 3D shapes identified as core skills; property-based	Cross-sectional design; limited causal inference; context specific (Japan)

Author (Year)	Scope / Research Objective	Research Design	Sample	Findings	Limitations / Gaps
				reasoning crucial at secondary level	
Hasanah et al. (2024)	To investigate progression and challenges in primary students' spatial reasoning (mental rotation, orientation, visualisation)	Cross-sectional quantitative study using adapted Spatial Reasoning Instrument	135 Indonesian primary students (Years 2, 4, 6)	Below-average spatial reasoning overall; improvement with age; major challenges in 2D−3D transformations and multi-step reasoning	Cross-sectional only; no intervention tested; limited to Indonesian context
Gagnier et al. (2022)	To examine elementary teachers' beliefs, perceptions, anxiety, and self-efficacy regarding spatial thinking in STEM	Survey design with newly developed validated measures	Elementary school teachers (US context)	Teachers reported low spatial anxiety and strong belief in importance of spatial thinking but lower self-efficacy in teaching spatial skills	Self-reported data; no direct classroom observation; US-based sample
Dung et al. (2025)	To explore whether GeoGebra anaglyph (3D visualisation) improves students' understanding of relative positions of lines in space	Design-based research (four phases)	12th-grade Vietnamese students	Improved spatial visualisation and interpretation of skew vs intersecting lines after using anaglyph feature	Exploratory; limited sample size; no long-term retention analysis
Scippo et al. (2025)	To assess the effectiveness of a digitally supported tessellation program (GeoGebra + 3D printing) on primary geometry learning	Quasi-experimental (pre–post control group)	Grade 4 students (experimental vs control groups)	Experimental group showed significant improvement in geometric learning; high engagement reported	Short-term study; limited exploration of spatial sub-skills; context specific
McDougal et al. (2024)	To examine causal impact of physical vs digital LEGO construction training on spatial and mathematical skills	Randomised controlled intervention (6 weeks; pre–post measures)	198 children (7–9 years); physical LEGO (*n* = 59), digital LEGO (*n* = 64), control (*n* = 75)	Evidence of near transfer (LEGO ability) and limited far transfer (arithmetic); overall transfer modest	Limited transfer effects; short intervention; recommendations for improved integration
Zhang et al. (2025)	Examine questioning in Conceptual PlayWorld to support spatial reasoning	Five-month educational intervention	33 kindergarteners (China)	Dramatic questioning enhanced collaborative spatial reasoning	Small sample; context specific

Author (Year)	Scope / Research Objective	Research Design	Sample	Findings	Limitations / Gaps
Bower et al. (2025)	Test concrete vs digital spatial assembly interventions	Randomised controlled trial	331 preschoolers	Spatial skills improved; modest math transfer	Limited far transfer
Korkmaz & Yılmaz (2022)	Compare inquiry-based indoor vs outdoor geometry activities	Quasi-experimental	32 preschoolers	Significant gains in spatial and geometric thinking	Small sample; short duration
Bokhove & Redhead (2025)	Test digital cube-building tool on mental rotation skills	Field experiment (2 conditions)	85 Year-7 students (UK)	Significant gains in MRS accuracy; no speed effect	No long-term math outcome data
Gutiérrez de Ravé et al. (2025)	Compare Monge method with CADOP for descriptive geometry	Quasi-experimental	90 engineering undergraduates	CADOP significantly improved spatial reasoning and accuracy	Limited to engineering context
Habeeb (2025)	Integrate digital tools + origami to enhance geometry and creativity	Quasi-experimental (pre–post control)	60 kindergarteners (Kuwait)	Significant gains in geometric understanding and creative thinking	Short intervention; localised context
Yip et al. (2025)	Identify cognitive and math skill profiles predicting achievement levels	Latent profile analysis + regression	272 Grade 4 students (Hong Kong)	Spatial skills predict high achievement; fraction skills predict MLD	Cross-sectional; correlational
Möhring et al. (2024)	Test disruption vs reduced competency accounts of math anxiety	Correlational mediation study	163 children (6–8 yrs)	Math anxiety linked to reduced use of higher-level strategies	Correlational; limited spatial measures
Zhu et al. (2024)	Explore spatial thinking in children's open-ended design-by-analogy	Educational design-based research	16 children (Netherlands)	Identified unique spatial processes in divergent design tasks	Small sample; exploratory
Lin et al. (2025)	Analyse Swedish Technology & Craft curricula for spatial potential	Document analysis	National curriculum documents	Identified visual and epistemic dimensions for spatial development	No empirical validation
Hahn & Klein (2025)	Investigate students' coordination of vector field equations and diagrams using eye-tracking	Eye-tracking + cluster analysis	147 university students	Identified strategy clusters; spatial ability linked to successful coordination	Limited generalisability; topic specific

As shown in Table 5, the majority of studies (n = 14) employed quasi-experimental or randomised controlled designs. Interventions were predominantly technology-mediated, with GeoGebra, AR, digital construction tools, and 3D visualisation environments featuring prominently across multiple studies. Physical-manipulative and activity-based interventions—including LEGO construction, origami integration, and outdoor geometry—also appeared although less frequently. Overall, the findings indicate that spatial reasoning interventions have positive effects on students' geometric understanding, mental rotation, spatial visualisation, and spatial orientation, albeit with consistently reported limitations pertaining to small sample sizes, short intervention durations, and restricted generalisability. Several studies highlighted challenges in achieving far transfer of spatial gains to broader mathematical competencies. Collectively, these findings demonstrate that educational interventions aimed at developing spatial reasoning in school mathematics between 2021 and 2026 are diverse in method and context yet converge on a shared conclusion: structured, purposefully designed spatial experiences—whether digital or physical—can meaningfully enhance students' spatial reasoning.

4.2 Effects of Educational Interventions on Students' Spatial Reasoning Abilities and Mathematics Learning

Table 6 summarises the reported effects of the 20 reviewed educational interventions on students' spatial reasoning abilities and mathematics learning outcomes, categorised by intervention type, outcome domain, and the nature of the reported effect.

Table 6: Summary of the reported effects of educational interventions

Author (Year)	Type of Educational Intervention	Effect on Spatial Reasoning	Effect on Mathematics Learning	Nature of Effect
Moussa et al. (2025)	Think-Pair-Share (TPS) in Cartesian coordinates	Improved spatial perception and visual-spatial reasoning	Improved understanding of coordinate representation	Statistically significant ($p < .05$)
Dos Santos et al. (2025)	GeoGebra automatic feedback tasks	Enhanced spatial visualisation	Improved mathematical problem-solving performance	Positive performance gains
Özçakır & Çakıroğlu (2022)	Augmented Reality (AR)-based geometry tasks	Developed spatial strategies and visualisation	Better understanding of 3D geometry concepts	Qualitative improvement
Fujita et al. (2022)	3D geometry spatial reasoning tasks	Mental rotation strongly predicted performance	Strong association with 3D geometry achievement	Correlational (strong predictive link)
Hasanah et al. (2024)	Spatial reasoning assessment across grades	Developmental improvement; difficulty in 2D–3D tasks	Weak spatial skills linked to geometry difficulty	Diagnostic / developmental trend
Gagnier et al. (2022)	Teacher spatial self-efficacy study	Indirect improvement via spatial instruction quality	Improved STEM/math instructional effectiveness	Indirect contextual effect
Dung et al. (2025)	GeoGebra 3D anaglyph visualisation	Improved visualisation accuracy	Better understanding of spatial geometry	Measurable improvement
Scippo et al. (2025)	Digital tessellation (GeoGebra + 3D printing)	Strengthened spatial visualisation	Significant improvement in geometry scores	Statistically significant

Author (Year)	Type of Educational Intervention	Effect on Spatial Reasoning	Effect on Mathematics Learning	Nature of Effect
McDoug et al. (2024)	Physical vs digital LEGO spatial training	Near-transfer spatial gains	Limited arithmetic improvement	Strong near transfer; weak far transfer
Zhang et al. (2025)	Conceptual PlayWorld (play-based questioning)	Enhanced spatial visualisation and orientation	Improved mathematics concept learning	Significant qualitative gains
Bower et al. (2025)	Concrete and digital spatial assembly training	Significant improvement in 2D and 3D spatial skills	Minor improvement in overall math; stronger for low-SES students	Strong spatial gains; modest math transfer
Korkmaz & Yılmaz (2022)	Inquiry-based indoor/outdoor math activities	Improved geometric and spatial thinking skills	Significant preschool math improvement	Statistically significant
Bokhove & Redhead (2025)	Digital cube-building (mental rotation training)	Significant improvement in mental rotation accuracy	No direct math outcome measured	Significant spatial-only effect
Gutiérrez de Ravé et al. (2025)	CAD-integrated orthographic projection (CADOP)	Large improvement in spatial reasoning and visualisation	Higher performance in descriptive geometry	Very large effect size
Habeeb (2025)	Digital tools and origami integration	Enhanced spatial reasoning and visual manipulation	Significant improvement in geometric understanding	Large effect size (r = .78)
Yip et al. (2025)	Cognitive profiling of math learners	Strong spatial skills differentiate high achievers	Spatial ability predicts math achievement level	Strong predictive relationship
Möhring et al. (2024)	Study of math anxiety and strategy use	Mental rotation indirectly related	Math anxiety negatively affects arithmetic	Indirect effect
Zhu et al. (2024)	Open-ended design-by-analogy challenge	Developed unique spatial abstraction processes	Supports spatial application in STEM problem solving	Qualitative cognitive development
Lin et al. (2025)	Curriculum-embedded spatial development (Technology & Craft)	Identified strong potential for spatial ability development	Potential support for STEM/math achievement	Curriculum-level potential
Hahn & Klein (2025)	Eye-tracking study on vector field coordination	Spatial ability linked to representational coordination	Higher spatial ability associated with better task performance	Correlational evidence

As summarised in Table 6, educational interventions of diverse designs consistently produced measurable improvements in students' spatial reasoning, whereas their effects on mathematics learning outcomes were more variable. Technology-mediated interventions dominated the corpus, yielding the strongest and most frequently replicated gains in spatial visualisation and mental rotation.

Several studies reported statistically significant or large effects, particularly those combining digital visualisation with structured geometric tasks, while a smaller cluster of correlational and eye-tracking studies reinforced the predictive relationship between spatial ability and mathematics achievement. Transfer of spatial gains to mathematics performance was strongest for domain-proximal outcomes such as three-dimensional geometry, coordinate representation, and descriptive geometry and weakest for distal outcomes such as arithmetic.

Indirect pathways through teacher spatial self-efficacy, mathematics anxiety, and curriculum-level design were also identified as mediating or conditioning the spatial-mathematics relationship. In relation to the research question, the findings indicate consistent evidence that educational interventions enhance spatial reasoning abilities but mixed evidence regarding their effects on broader mathematics learning. The spatial visualisation-geometry achievement link received convergent support across experimental, correlational, and qualitative designs.

4.3 Thematic Trends, Research Focus, and Emerging Gaps

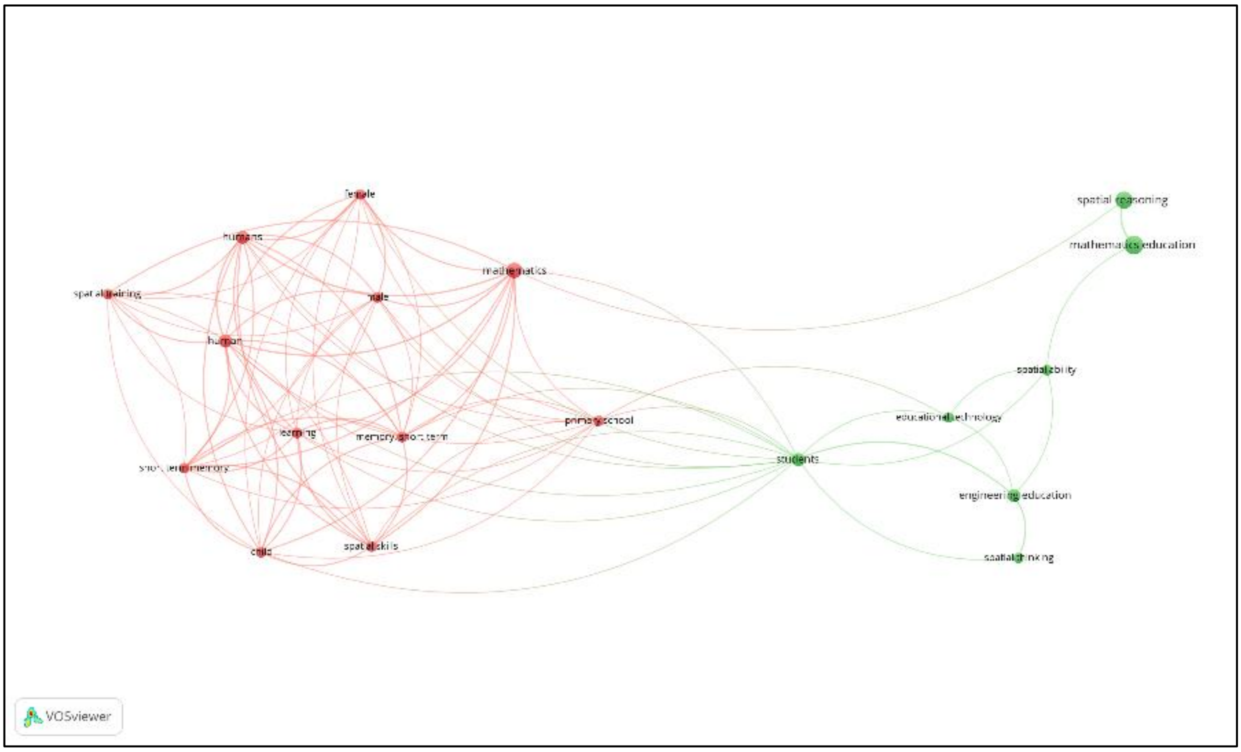

Figure 2: Keyword co-occurrence network analysis in spatial reasoning interventions in mathematics education

The VOSviewer keyword co-occurrence network (Figure 2) reveals the intellectual structure of research on educational interventions for developing spatial reasoning in school mathematics. By examining relationships among keywords, the network identifies major thematic trends, dominant research focuses, and underexplored areas within the field (Van Eck & Waltman, 2010).

4.3.1 Thematic Trends Emerging from the Keyword Clusters

The keyword network reveals two interconnected thematic clusters representing the field's dual foundations in cognitive-developmental research and mathematics education. The red cluster centres on the cognitive foundations of spatial development among young learners, while the green cluster reflects an educational orientation emphasising the integration of spatial reasoning into formal learning environments. The relationship between the two clusters is mediated through bridging nodes—mathematics, primary school, and students—indicating a partial but incomplete synthesis between cognitive and pedagogical perspectives. Overall, the network signals an evolving field moving from investigations of spatial ability to educational interventions that embed spatial reasoning within mathematics learning.

4.3.2 Dominant Research Focuses on Spatial Reasoning Interventions

Analysis of keyword prominence, node size, and connectivity reveals six dominant research focuses shaping the literature on spatial reasoning interventions in school mathematics. Spatial training interventions emerge as the most prominent focus, evidenced by the strong co-occurrence of spatial training, spatial skills, and mathematics within the red cluster. A closely related focus concerns the development of spatial skills and spatial ability, with sustained co-occurrence across both clusters, indicating recognition of spatial reasoning as a multidimensional construct. The network further highlights strong attention to cognitive mechanisms, reflected in the frequent association of memory, learning, and mathematics.

Technology-supported spatial learning features prominently within the green cluster, indicated by links among educational technology, spatial reasoning, and students. Student-centred approaches and primary-school interventions also appear consistently, with child, primary school, and learning co-occurring around the central node students. Across both clusters, the recurring association between spatial constructs and mathematics-related keywords reflects a broader focus on the spatial reasoning-mathematics achievement relationship. Overall, these focuses indicate a field transitioning from demonstrating the value of spatial reasoning to exploring its systematic integration into mathematics education.

4.3.3 Emerging Gaps, Underrepresented Areas, and Research Opportunities

Beyond dominant themes, the keyword co-occurrence network reveals several underrepresented areas through the absence of specific keywords. Secondary and upper-secondary education contexts are absent from the network despite the increasing spatial demands at higher grade levels. Keywords related to non-geometric mathematical domains such as algebra, statistics, and mathematical modelling are similarly absent, indicating a narrow disciplinary focus. Teacher-related terms, including pedagogy, professional development, and instructional design do not appear, suggesting limited attention to instructional practice.

Keywords associated with longitudinal or long-term effects are also absent, indicating that most studies address only immediate post-intervention outcomes. Terms related to diverse learner populations, including low-achieving students, learners with special educational needs, and culturally diverse groups are not represented. Emerging technologies such as AR, VR, and adaptive learning systems are likewise absent despite the presence of educational technology. Finally, connections between spatial reasoning and broader mathematical processes such as problem solving, modelling, and reasoning are not reflected in the network. Overall, the network indicates that the field has established a strong foundation in cognitive training and primary-school mathematics but remains characterised by notable thematic imbalances.

5. Discussion

5.1 Characteristics of Spatial Reasoning Intervention Studies

Three main patterns emerged from the reviewed studies. First, technology-based, manipulative-based, and activity-orientated interventions generally improved students' spatial abilities, including mental rotation, spatial visualisation, and spatial orientation. Second, technology-mediated approaches, particularly those involving GeoGebra, AR, and digital construction environments, were the most frequently investigated and consistently reported positive effects on spatial reasoning and geometric understanding. Third, although many interventions enhanced spatial skills, evidence of transfer to broader mathematics achievement remained limited and inconsistent.

These findings reinforce the view that spatial reasoning is a malleable component of mathematical learning that can be strengthened through purposeful instructional experiences (Fujita et al., 2022; Hasanah et al., 2024). The prominence of technology-enhanced interventions highlights the value of dynamic visualisation and interactive representations in supporting spatial cognition. Consistent with previous research, digital tools appear most effective when their representational features align with the cognitive demands of spatial tasks (Dung et al., 2025; Özçakır & Çakıroğlu, 2022).

While technology-based approaches dominated the literature, manipulative and activity-based interventions also produced meaningful improvements in spatial reasoning. However, evidence of transfer to broader mathematical achievement was generally modest, suggesting that explicit links between spatial activities and mathematical concepts are required to maximise learning outcomes (Bower et al., 2025; McDougal et al., 2024). The findings further indicate that intervention effectiveness depends not only on instructional tools but also on pedagogical practices. Teacher questioning, classroom discourse, and pedagogical scaffolding play important roles in supporting spatial reasoning development (Mahmud et al., 2020; Zhang et al., 2025). This highlights the need for professional development that strengthens teachers' capacity to integrate spatial reasoning into mathematics instruction, particularly in technology-enhanced environments (Saharuddin et al., 2025).

Although the reviewed studies spanned diverse educational levels and countries, they were concentrated primarily in East Asian, European, and Anglophone contexts. Greater representation of underexplored regions, including Southeast Asia, is needed to understand better how contextual factors influence intervention effectiveness. Overall, the findings indicate that spatial reasoning can be effectively developed through a range of instructional approaches. Future research should employ more diverse and longitudinal designs to examine the sustainability and transferability of intervention effects to broader mathematics learning outcomes.

5.2 Effects of Educational Interventions on Students' Spatial Reasoning Abilities and Mathematics Learning Outcomes

The reviewed studies consistently demonstrated that educational interventions improve students' spatial reasoning, although their effects on mathematics learning were more variable. Technology-mediated approaches, particularly digital visualisation and geometry tools, produced the most consistent gains in spatial visualisation and mental rotation, highlighting the value of dynamic representations in supporting spatial cognition (Dung et al., 2025; Habeeb, 2025; Scippo et al., 2025). A recurring finding was the stronger impact on near-transfer outcomes than on broader mathematical achievement. While improvements were commonly observed in geometry-related tasks and representational understanding, evidence of transfer to more distal mathematical domains remained limited (Bower et al., 2025; McDougal et al., 2024). This suggests that spatial and mathematical reasoning are closely related but not fully equivalent, requiring explicit instructional connections to facilitate transfer.

These findings support the integration of spatial reasoning within mathematics curricula and underscore the importance of teacher preparedness and affective factors in successful implementation (Gagnier et al., 2022; Möhring et al., 2024). Although many studies were limited by small samples and short intervention durations, the overall consistency of findings across diverse contexts indicates that well-designed spatial reasoning interventions can contribute meaningfully to mathematics learning. Future research should employ longitudinal designs, standardised assessment measures, and instructional approaches that explicitly connect spatial reasoning with mathematical concepts.

5.3 Thematic Trends, Research Focus, and Emerging Gaps in the Educational Interventions for Developing Spatial Reasoning in School Mathematics

The keyword co-occurrence analysis identified two dominant themes in the literature: a cognitive-developmental focus on spatial training, spatial skills, and learning processes, and an educational focus on technology-supported instruction and classroom implementation. The presence of bridging terms such as mathematics, students, and primary school suggests increasing integration between cognitive and pedagogical perspectives, although this connection remains limited. These findings indicate that research is gradually shifting from demonstrating the cognitive benefits of spatial reasoning to embedding spatial reasoning within mathematics education (Sinclair & Bruce, 2015; Uttal et al., 2013).

The prominence of technology-related keywords reflects the growing role of digital tools in supporting spatial learning, consistent with evidence highlighting the effectiveness of dynamic geometry environments and other technology-enhanced interventions (Dung et al., 2025; Özçakır & Çakıroğlu, 2022; Scippo et al., 2025). At the same time, several important gaps emerged. Research remains concentrated in primary-level and geometry-focused contexts, with limited attention given to secondary education, non-geometric mathematical domains, teacher pedagogy, longitudinal outcomes, and diverse learner populations. The absence of teacher-related themes is particularly notable, given the recognised importance of teacher expertise and professional development in supporting spatial reasoning instruction (Gagnier et al., 2022; Johari et al., 2022; Saharuddin et al., 2025).

These findings suggest that the field has established a strong foundation regarding the cognitive benefits of spatial reasoning interventions but requires greater emphasis on pedagogical implementation and contextual diversity. Future research should investigate secondary-level settings, teacher professional development, emerging technologies, and the long-term impact of spatial reasoning interventions across different educational contexts. Although keyword co-occurrence analysis reflects associative rather than causal relationships, the systematic application of VOSviewer and PRISMA 2020 procedures provides a robust basis for identifying current research trends and priorities.

6. Conclusion

This SLR addressed a recognised gap in the evidence base by synthesising empirical research published between 2021 and 2026 on educational interventions for developing spatial reasoning in school mathematics. Twenty peer-reviewed studies were analysed across three dimensions: intervention characteristics, effects on spatial reasoning and mathematics learning outcomes, and thematic trends emerging from keyword co-occurrence analysis. The findings demonstrate that purposefully designed spatial interventions, particularly those employing dynamic digital environments, manipulative-based activities, and inquiry-orientated pedagogies, consistently strengthen students' spatial visualisation, mental rotation, and spatial orientation. Transfer to mathematics learning was most evident in domain-proximate outcomes such as three-dimensional geometry and coordinate representation, although gains were more limited for distal outcomes such as arithmetic.

These findings carry clear implications for practice, policy, and research. Educators and curriculum developers should prioritise the deliberate integration of spatial reasoning tasks into geometry instruction, particularly at secondary level; this remains critically underrepresented in the literature. Teacher professional development programmes addressing spatial self-efficacy warrant urgent attention. Future research should employ longitudinal designs, standardised spatial measures, and explicit instructional bridging to generate more transferable evidence, particularly in non-Western contexts such as Malaysia where localised, empirically grounded frameworks for spatial reasoning instruction are still needed.

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8. References

Abouzahra, A., Sabraoui, A., & Afdel, K. (2020**).** Model composition in model driven engineering: A systematic literature review. *Information and Software Technology*, *125*, 106316. https://doi.org/10.1016/j.infsof.2020.106316

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

Almubarak, M., Maat, S. M., & Mahmud, M. S. (2025). Evolving three decades of geometry learning strategies: A combination of bibliometric analysis and systematic review. *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(6), em2654. https://doi.org/10.29333/ejmste/16515

Alves, F. R. V., de Sousa, R. T., & Fontenele, F. C. F. (2022). Three-dimensional geometric perceptions in ENEM: A contribution from GeoGebra for mathematics teachers in Brazil. *Acta Didactica Napocensia*, *15*(1), 114–123. https://doi.org/10.24193/adn.15.1.10

Anwar, R., Rahmawati, D., & Wulandari, A. (2025). Trends in research on mathematical representation in mathematics learning: A systematic literature review. *International Journal of Education in Mathematics, Science and Technology*, *13*(3), 698–714. https://doi.org/10.46328/ijemst.4848

Bansil, A. G., & Yabut, E. V. (2025). Educational intervention involving physical manipulatives for improving Grade 7 learners' spatial reasoning skills. *Journal of Practical Studies in Education*, *6*(3), 1–9. https://doi.org/10.46809/jpse.v6i3.99

Bokhove, C., & Redhead, E. S. (2025). Building digital cube houses to improve mental rotation skills. *International Journal of Mathematical Education in Science and Technology*, *57*(3), 393–412. https://doi.org/10.1080/0020739X.2024.2441889

Booth, A., Sutton, A., & Papaioannou, D. (2016). *Systematic approaches to a successful literature review* (2nd ed.). SAGE Publications.

Borboeva, G., Sooronbaeva, K., Kalbekova, M., Seiitkazyeva, G., & Sarygulova, N. (2025). Evaluating the effectiveness of interactive learning technologies in enhancing spatial thinking among mathematics students. *Jurnal Ilmiah Ilmu Terapan Universitas Jambi*, *9*(3), 981–994. https://doi.org/10.22437/jiituj.v9i3.42557

Bower, C. A., Zimmermann, L., Verdine, B. N., Spiewak Toub, T., Hirsh-Pasek, K., & Michnick Golinkoff, R. (2025). What does play have to do with it? A concrete and digital spatial intervention with 3-year-olds predicts spatial and math learning. *Developmental Psychology*, *61*(3), 461-481. https://doi.org/10.1037/dev0001904

Chivai, C. H., Soares, A. A., & Catarino, P. (2022). Application of GeoGebra in the teaching of descriptive geometry: Sections of solids. *Mathematics*, *10*(17), 3034. https://doi.org/10.3390/math10173034

Cooke, A., Smith, D., & Booth, A. (2012). Beyond PICO: The SPIDER tool for qualitative evidence synthesis. *Qualitative Health Research*, *22*(10), 1435–1443. https://doi.org/10.1177/1049732312452938

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

Crompton, H., & Ferguson, S. (2024). An analysis of the essential understandings in elementary geometry and a comparison to the common core standards with teaching implications. *European Journal of Science and Mathematics Education*, *12*(2), 258–275. https://doi.org/10.30935/scimath/14361

Dung, T. M., Trung, L. T. B. T., & Nga, N. T. (2025). Visualizing relative position of two straight lines in space: An exploratory study of the anaglyph in GeoGebra. *Journal of Pedagogical Research*, *9*(1), 203–219. https://doi.org/10.33902/JPR.202527952

Dos Santos, J. M., Pereira Abar, C. A. A., D'Azevedo Breda, A. M., & Lavicza, Z. (2025). Automatic feedback in mathematics education: A pathway to robotics and computational thinking. *Acta Scientiae*, *27*(2). https://doi.org/10.17648/acta.scientiae.8240

Etikan, I., Musa, S. A., & Alkassim, R. S. (2016). Comparison of convenience sampling and purposive sampling. *American Journal of Theoretical and Applied Statistics*, *5*(1), 1–4. https://doi.org/10.11648/j.ajtas.20160501.11

Fitriyana, N., Luthfiana, M., & Purwasi, L. A. (2025). Profiling junior high school students' spatial ability in geometry transformations based on five spatial indicators. *Mimbar Sekolah Dasar*, *12*(4), 920–932. https://doi.org/10.53400/mimbar-sd.v12i4.95235

Fitriawan, D., Siregar, N., Hartoyo, A., & Sulistyowati, E. (2026). Developing STEM integrated analysis geometry learning materials through digital visualization and e-learning platforms. *Al-Jabar: Jurnal Pendidikan Matematika*, *17*(1), 89–105. https://doi.org/10.24042/ajpm.v17i1.29388

Fujita, T., Kondo, Y., Kumakura, H., Miyawaki, S., Kunimune, S., & Shojima, K. (2022). Identifying Japanese students' core spatial reasoning skills by solving 3D geometry problems: An exploration. *Asian Journal for Mathematics Education*, *1*(4), 437–454. https://doi.org/10.1177/27527263221142345

Gagnier, K. M., Holochwost, S. J., & Fisher, K. R. (2022). Spatial thinking in science, technology, engineering, and mathematics: Elementary teachers' beliefs, perceptions, and self-efficacy. *Journal of Research in Science Teaching*, *59*(1), 95–126. https://doi.org/10.1002/tea.21722

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), Article 10. https://doi.org/10.1038/s41539-022-00128-9

Gusenbauer, M., & Haddaway, N. R. (2020). Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources. *Research Synthesis Methods*, *11*(2), 181–217. https://doi.org/10.1002/jrsm.1378

Gutiérrez de Ravé, S., Gutiérrez de Ravé, E., & Jiménez-Hornero, F. J. (2025). Integrating CAD and orthographic projection in descriptive geometry education: A comparative analysis with Monge's system. *Education Sciences*, *15*(11), 1492. https://doi.org/10.3390/educsci15111492

Habeeb, K. M. (2025). Integrating digital tools with origami activities to enhance geometric concepts and creative thinking in kindergarten education. *Education Sciences*, *15*(7), 924. https://doi.org/10.3390/educsci15070924

Hahn, L., & Klein, P. (2025). Clustering eye-movement data uncovers students' strategies for coordinating equations and diagrams of vector fields. *Educational Studies in Mathematics*, *118*, 359–385. https://doi.org/10.1007/s10649-023-10243-y

Hanid, M. F. A., Mohamad Said, M. N. H., Yahaya, N., & Abdullah, Z. (2022). Effects of augmented reality application integration with computational thinking in geometry topics. *Education and Information Technologies*, *27*(7), 9485–9521. https://doi.org/10.1007/s10639-022-10994-w

Haqq, A. A., Handoko, H., & Al Farizi, R. (2025). Developing pedagogically aligned AR media for teaching polyhedra in junior secondary education. *Information Technology Engineering Journals (ITEJ)*, *10*(1), 174–192. https://doi.org/10.24235/itej.v10i1.260

Harris, D. (2023). Spatial reasoning in context: Bridging cognitive and educational perspectives of spatial-mathematics relations. *Frontiers in Education*, *8*, 1302099. https://doi.org/10.3389/feduc.2023.1302099

Harris, D., Logan, T., & Lowrie, T. (2021). Unpacking mathematical-spatial relations: Problem-solving in static and interactive tasks. *Mathematics Education Research Journal*, *33*(3), 495–511. https://doi.org/10.1007/s13394-020-00316-z

Hasanah, U., Putrawangsa, S., Purwanta, E., Setiawati, F. A., & Purnomo, W. P. (2024). Primary student spatial reasoning abilities: Progression and challenges. *Jurnal Pendidikan Matematika*, *18*(3), 329–348. https://doi.org/10.22342/jpm.v18i3.pp329-348

Hawes, Z. C. K., Gilligan-Lee, K. A., & Mix, K. S. (2022). Effects of spatial training on mathematics performance: A meta-analysis. *Developmental Psychology*, *58*(1), 112–137. https://doi.org/10.1037/dev0001281

Ikhsan, M., Rochaminah, S., & Mastura, A. (2024). Development of Geo-Math application by integrating Geo-Gebra applets to improve students' spatial ability. *Jurnal Ilmiah Peuradeun*, *12*(3), 1129–1154. https://doi.org/10.26811/peuradeun.v12i3.1492

Johari, M. I., Rosli, R., Maat, S. M., Mahmud, M. S., Capraro, M. M., & Capraro, R. M. (2022). Integrated professional development for mathematics teachers: A systematic review. *Pegem Journal of Education and Instruction*, *12*(4), 226–234. https://doi.org/10.47750/pegegog.12.04.23

Juman, Z. A. M. S., Mathavan, M., Ambegedara, A. S., & Udagedara, I. G. K. (2022). Difficulties in learning geometry component in mathematics and active-based learning methods to overcome the difficulties. *Shanlax International Journal of Education*, *10*(2), 41–58. https://doi.org/10.34293/education.v10i2.4299

Kitchenham, B. (2004). *Procedures for performing systematic reviews.* Keele University Technical Report TR/SE-0401; NICTA Technical Report 0400011T.1. Department of Computer Science, Keele University & National ICT Australia. https://www.inf.ufsc.br/~aldo.vw/kitchenham.pdf

Kitchenham, B., & Charters, S. (2007). *Guidelines for performing systematic literature reviews in software engineering.* Version 2.3, EBSE Technical Report No. EBSE-2007-01. Keele University & Durham University. https://www.scirp.org/reference/ReferencesPapers?ReferenceID=1555797

Korkmaz, H. İ., & Yılmaz, A. (2022). Inquiry-based mathematics activities to improve children's geometric and spatial thinking skills. *Turkish Journal of Education*, *11*(3), 143–161. https://doi.org/10.19128/turje.949930

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

Lin, T. J., Buckley, J., Gumaelius, L., & Ampadu, E. (2025). The potential for spatial ability development through the Swedish technology and craft compulsory curricula. *International Journal of Technology and Design Education*, *35*(4), 1409–1427. https://doi.org/10.1007/s10798-024-09958-7

Lowrie, T., & Logan, T. (2023). Spatial visualization supports students' math: Mechanisms for spatial transfer. *Journal of Intelligence*, *11*(6), 127. https://doi.org/10.3390/jintelligence11060127

Mahmud, M. S., Yunus, A. S. Md., Ayub, A. F. M., & Sulaiman, T. (2020). The use of oral questioning in inculcating values in mathematics for primary school students. *Universal Journal of Educational Research*, *8*(3C), 1–8. https://doi.org/10.13189/ujer.2020.081601

McDougal, E., Silverstein, P., Treleaven, O., Jerrom, L., Gilligan-Lee, K., Gilmore, C., & Farran, E. K. (2024). Assessing the impact of LEGO® construction training on spatial and mathematical skills. *Developmental Science*, *27*(2), e13432. https://doi.org/10.1111/desc.13432

Möhring, W., Moll, L., & Szubielska, M. (2024). Unpacking associations among children's spatial skills, mathematics, and arithmetic strategies: Decomposition matters. *Psychological Research*, *88*(5), 1550–1564. https://doi.org/10.1007/s00426-024-01952-x

Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of Web of Science and Scopus: A comparative analysis. *Scientometrics*, *106*(1), 213–228. https://doi.org/10.1007/s11192-015-1765-5

Moussa, M. A., Ahmed, S. A., & Al-Adamat, O. A. (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

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

Nathan, M. J., Schenck, K. E., Vinsonhaler, R., Michaelis, J. E., Swart, M. I., & Walkington, C. (2021). Embodied geometric reasoning: Dynamic gestures during intuition, insight, and proof. *Journal of Educational Psychology*, *113*(5), 929–948. https://doi.org/10.1037/edu0000638

Özçakır, B., & Çakıroğlu, E. (2022). Fostering spatial abilities of middle school students through augmented reality: Spatial strategies. *Education and Information Technologies*, *27*(3), 2977–3010. https://doi.org/10.1007/s10639-021-10729-3

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

Palatnik, A., Abrahamson, D., & Lomos, C. (2025, February 4–8). I see what you're thinking: Embodied collaborative argumentation. In *Proceedings of the Fourteenth Congress of the European Society for Research in Mathematics Education (CERME14)* (No. 16). https://hal.science/hal-05199688

Patton, M. Q. (2015). *Qualitative research & evaluation methods: Integrating theory and practice* (4th ed.). SAGE Publications.

Petticrew, M., & Roberts, H. (2006). *Systematic reviews in the social sciences: A practical guide*. Blackwell Publishing. https://doi.org/10.1002/9780470754887

Ridgley, L. M., Geary, D. C., Li, Y., Myers, P., Ottinger, R., Silvaggio, D. N., Ünal, Z., & Popov, V. (2025). The language of folding: Increasing spatial language and decreasing mathematics anxiety through origami. *Frontiers in Education*, *10*, 1613317. https://doi.org/10.3389/feduc.2025.1613317

Saharuddin, M. H., Nasir, M. K. M., & Mahmud, M. S. (2025). Exploring teachers' technological pedagogical content knowledge in utilising artificial intelligence (AI) for teaching. *International Journal of Learning, Teaching and Educational Research*, *24*(1), 136–151. https://doi.org/10.26803/ijlter.24.1.7

Sarkis-Onofre, R., Catalá-López, F., Aromataris, E., & Lockwood, C. (2021). How to properly use the PRISMA Statement. *Systematic Reviews*, *10*(1), 117. https://doi.org/10.1186/s13643-021-01671-z

Schenck, K. E., & Nathan, M. J. (2024). Navigating spatial ability for mathematics education: A review and roadmap. *Educational Psychology Review*, *36*(3), Article 90.https://doi.org/10.1007/s10648-024-09935-5

Scippo, S., Madiai, S., & Cuomo, S. (2025). Digital tessellation for geometry learning in primary school: A quasi-experimental study. *Journal of Information Technology Education: Research*, *24*, 009. https://doi.org/10.28945/5473

Sinclair, N., & Bruce, C. D. (2015). New opportunities in geometry education at the primary school. *ZDM Mathematics Education*, *47*(3), 319–329. https://doi.org/10.1007/s11858-015-0693-4

Sunzuma, G., & Maharaj, A. (2020). In-service secondary teachers' teaching approaches and views towards integrating ethnomathematics approaches into geometry teaching. *Bolema: Boletim de Educação Matemática*, *34*(66), 22–39. https://doi.org/10.1590/1980-4415v34n66a02

Suparman, S., Marasabessy, R., & Helsa, Y. (2024). Fostering spatial visualization in GeoGebra-assisted geometry lesson: A systematic review and meta-analysis. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(9), em2509. https://doi.org/10.29333/ejmste/15170

Thom, J. S., McGarvey, L. M., & Markle, J. (2024). Projective geometry and spatial reasoning for STEM learning. *Frontiers in Education*, *9*, 1312845. https://doi.org/10.3389/feduc.2024.1312845

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402. https://doi.org/10.1037/a0028446

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Wahyuni, S., Noviani, J., & Saleha, D. (2024). Profile of spatial ability of high school students when solving geometry problems. *Southeast Asian Mathematics Education Journal*, *14*(1), 47–68. https://doi.org/10.46517/seamej.v14i1.288

Weigand, H.-G., Hollebrands, K., & Maschietto, M. (2025). Geometry education at secondary level – a systematic literature review. *ZDM – Mathematics Education*, *57*, 829–843. https://doi.org/10.1007/s11858-025-01703-1

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, Y., Du, W., Mavrikis, M., & Geraniou, E. (2025). Spatial skill development through augmented reality in mathematics education: A scoping review. *Digital Experiences in Mathematics Education*, *12*, 277–310. https://doi.org/10.1007/s40751-025-00187-8

Yip, C. C. H., Ouyang, X., Yip, E. S.-K., Tong, C. K.-Y., & Wong, T. T.-Y. (2025). Distinct roles of cognitive and mathematics skills in different levels of mathematics development. *Learning and Individual Differences*, *119*, 102645. https://doi.org/10.1016/j.lindif.2025.102645

Zhang, W., Li, L., & Disney, L. (2025). "Asking questions is the key": Chinese kindergarten teachers support children's mathematics concept learning and spatial reasoning through a Conceptual PlayWorld approach. *Mathematics Education Research Journal*, *38*(2), 323–352. https://doi.org/10.1007/s13394-025-00530-7

Zhu, C., Klapwijk, R., Silva-Ordaz, M., Spandaw, J., & de Vries, M. J. (2024). Investigating the role of spatial thinking in children's design ideation through an open-ended design-by-analogy challenge. *International Journal of Technology and Design Education*, *34*(5), 1733–1762. https://doi.org/10.1007/s10798-024-09877-7