International Electronic Journal of Mathematics Education
2026, 21(4), em0913
e-ISSN: 1306-3030
https://www.iejme.com

MODESTUM

Review Article

OPEN ACCESS

Geometry-based and technology-enhanced instructional interventions for developing students' spatial thinking: A meta-analysis (2020–2025)

Akmaral Rysbayeva [1], Yessenkeldi Tuyakov [2], Gulzhan Zhetpisbayeva [3], Adkhamzhan Issakov [4*], Zhanar Akhmedova [5], Kimberly Sirin Budak [6]

[1] Kazakh National Women's Teacher Training University, Almaty, KAZAKHSTAN
[2] Kazakh National Pedagogical University named by Abai, Almaty, KAZAKHSTAN
[3] Zhanibekov University, Shymkent, KAZAKHSTAN
[4] Zhetysu State University Named After Ilyas Zhansugurov, Taldykorgan, KAZAKHSTAN
[5] Abai Kazakh National Pedagogical University Methodology of Teaching Mathematics, Physics, and Informatics, Almaty, KAZAKHSTAN
[6] University of Wisconsin, UNITED STATES
***Corresponding Author:** issakovadkhamzhan@gmail.com

Citation: Rysbayeva, A., Tuyakov, Y., Zhetpisbayeva, G., Issakov, A., Akhmedova, Z., & Budak, K. S. (2026). Geometry-based and technology-enhanced instructional interventions for developing students' spatial thinking: A meta-analysis (2020–2025). *International Electronic Journal of Mathematics Education, 21*(4), em0913. https://doi.org/10.29333/iejme/19973

ARTICLE INFO

Received: 20 Aug. 2026
Accepted: 04 Oct. 2026

ABSTRACT

Spatial thinking is a foundational cognitive skill for geometry learning and broader mathematics and STEM achievement, yet it remains insufficiently emphasized in many instructional contexts. Recent advances in digital technology have expanded the ways in which geometry instruction can support spatial reasoning through dynamic, interactive, and immersive learning environments. This meta-analysis synthesizes empirical evidence on the effectiveness of geometry-based instructional interventions designed to enhance students' spatial thinking. Following PRISMA 2020 guidelines, studies published between 2020 and 2025 were systematically identified through major academic databases. The final analysis included 15 studies. Using a random-effects model with Restricted Maximum Likelihood estimation, the results revealed a statistically significant and educationally meaningful overall effect of geometry-based interventions on spatial thinking (Hedges' $g = 0.81$, 95% CI [0.53, 1.08], $p < .001$), although substantial between-study heterogeneity was observed ($I^2 = 89.90\%$). Moderator analyses indicated that intervention type significantly influenced effect sizes, with particularly strong effects for augmented and virtual reality interventions and 3D modeling/visualization approaches. Educational level also significantly moderated intervention effects, with a larger pooled effect for secondary students than for primary students. These findings suggest that spatial thinking can be deliberately cultivated through geometry instruction, particularly when learning environments emphasize active manipulation, visualization, three-dimensional representation, and spatial transformation.

Keywords: spatial thinking, geometry education, technology-enhanced learning, spatial reasoning, geometry instruction, meta-analysis

INTRODUCTION

Spatial thinking has emerged as a vital component of mathematical cognition, particularly within geometry, where students must visualize shapes, mentally rotate figures, and interpret spatial relationships. Recent studies demonstrate that spatial reasoning predicts success in geometry and also plays a foundational role in broader mathematics and STEM learning (Gilligan-Lee et al., 2022). Despite this importance, many school geometry curricula still stress procedural knowledge and symbolic manipulation, giving less attention to the development of spatial reasoning skills that support conceptual understanding.

Research confirms that spatial thinking is highly malleable. Targeted instruction, whether through geometry tasks, spatial visualization exercises, or technology-enhanced learning environments, can substantially increase students' spatial skills (Hawes et al., 2022; Yang et al., 2026). For instance, spatial training interventions have been shown to transfer positively to mathematics performance, particularly in measurement and geometry domains (Adams et al., 2023). This has led to increased interest in designing geometry-based instructional interventions aimed at increasing spatial reasoning in secondary and high-school learners.

Parallel to this, rapid developments in educational technology have introduced new ways to support spatial learning. Virtual and augmented reality, dynamic geometry software, 3-D modeling environments, and spatial visualization tools present

Copyright © 2026 by Author/s and Licensed by Modestum Open DOO, Serbia. This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

immersive, interactive experiences that may increase spatial thinking more effectively than traditional methods. Recent empirical studies report improvements in spatial reasoning when students engage with VR environments (Wang et al., 2024), 3-D sketching systems (Tung & Chang, 2024), and AR-supported geometry applications (Beisenbayeva et al., 2024). Systematic reviews also indicate that dynamic geometry environments such as GeoGebra can meaningfully increase spatial visualization, although results differ widely across grade levels and study designs (Suparman et al., 2024).

While prior meta-analyses have established a general link between spatial ability and mathematics achievement (Xie et al., 2020) and demonstrated that spatial training improves mathematical performance (Hawes et al., 2022), no comprehensive meta-analysis has specifically combined geometry-based instructional interventions targeting spatial thinking. Moreover, the field lacks clarity on which types of geometric interventions, traditional, digital, or immersive, produce the largest gains, and how factors such as educational level, intervention duration, and assessment instruments moderate effects. Addressing these gaps is important for informing curriculum design, teacher practice, and policy decisions regarding spatial reasoning instruction in geometry education.

The purpose of this meta-analysis is to synthesize empirical evidence from 2020–2025 (November) on geometry-based interventions designed to improve students' spatial thinking.

Research Questions

RQ1 What is the overall effectiveness of geometry-based instructional interventions in improving students' spatial thinking?

RQ2 How do intervention type, and educational level moderate the effects of geometry-based interventions on spatial thinking?

LITERATURE REVIEW

Definition and Components of Spatial Thinking

Spatial thinking is a multidimensional cognitive system that enables individuals to perceive, encode, manipulate, and reason about objects and their relationships in space. It is usually recognized as a foundational component of mathematics and STEM learning (Gilligan-Lee et al., 2022; Newcombe, 2017; Pinilla, 2024; Taylor et al., 2023). Spatial thinking comprises several separate but interrelated components; spatial visualization, mental rotation, spatial orientation, and spatial relations, each contributing uniquely to learners' ability to understand and work with geometric and spatial information.

Spatial visualization examines the ability to interpret, transform, and handle complex two- and three-dimensional configurations. This ability is about tasks such as imagining a geometric net becoming a 3D object, interpreting cross-sections, or decomposing and recomposing shapes. Spatial visualization is often targeted in geometry interventions, and research demonstrates that technological tools can significantly increase this skill (Dere & Kalelioglu, 2020; Suparman et al., 2024). Visualization also plays an important role in students' interpretation of geometrical figures and their ability to generate multiple solution strategies, highlighting the close relationship between spatial processes and creative geometry problem solving (Geitona et al., 2022)

Mental rotation involves rotating objects mentally along one or more axes to understand if two shapes are congruent or represent the same figure from different viewpoints. This form of spatial processing is mainly in geometry topics such as transformations and symmetry. Meta-analytic evidence shows that mental-rotation ability is strongly related to mathematical and geometry performance (Atit et al., 2022; Xie et al., 2020), and that targeted interventions can reliably improve this skill (Hawes et al., 2022; Uttal et al., 2013).

Spatial orientation shows the ability to understand an object's position relative to oneself or to other objects. This includes interpreting diagrams from several perspectives, navigating coordinate systems, and mentally adjusting viewpoints. Spatial orientation supports many geometry tasks, having students imagine viewing a shape from a different angle or aligning objects in space.

Spatial relations (also referred to as spatial scaling or proportional spatial reasoning) pertain to understanding the relational structure among objects; such as distance, alignment, directionality, and proportional differences. These skills are mainly in geometry for interpreting diagrams, understanding similarity and scale, and reasoning about compound figures (Gilligan-Lee et al., 2022; Taylor et al., 2023).

Across these sections, research consistently supports the idea that spatial thinking is strongly connected to mathematics performance. Large-scale meta-analyses confirm robust correlations between spatial skills and mathematical achievement (Atit et al., 2022; Xie et al., 2020), while experimental and training studies show that spatial skills are highly flexible across age groups (Hawes et al., 2022; Uttal et al., 2013). Moreover, because different components of spatial thinking respond differently to intervention, examining spatial thinking as a multidimensional construct is essential for understanding how geometry instruction produces learning gains.

This multidimensionality is particularly appropriate in school-based geometry, where instructional approaches engage in spatial skills in different ways. For example, augmented reality supports spatial visualization and orientation (Beisenbayeva et al., 2024); web-based 3D modeling enhances mental rotation (Dere & Kalelioglu, 2020); and dynamic geometry environments strengthen spatial relations and visualization (Suparman et al., 2024). Thus, recognizing spatial thinking as a composite construct provides the theoretical foundation for analyzing the varied effects of geometry-based instructional interventions in the present meta-analysis.

How Spatial Thinking Supports Geometry Learning

Geometry is naturally spatial; it involves reasoning shapes, positions, transformations, and the structure of space itself. As Clements and Battista (1992) observed in their foundational synthesis, geometry learning is inseparable from spatial reasoning because geometric ideas are expressed, understood, and manipulated through spatial representations. Spatial thinking provides the cognitive resources that led students to construct mental images, coordinate multiple representations, and understand spatial relations that underlie all geometric concepts.

Empirical evidence demonstrates that spatial thinking strongly predicts mathematical performance, with particularly strong associations in geometry. Meta-analytic studies by Xie et al. (2020) and Atit et al. (2022) show that spatial skills account for unique variance in mathematical achievement, and that their predictive power is strongest for geometry due to its visual/spatial nature. Developmental research similarly indicates that spatial reasoning plays a significant role in children's and adolescents' growth in geometry and measurement understanding (Newcombe, 2017; Newcombe & Stieff, 2012). Evidence from upper-primary students (aged 8–12) further shows that mental rotation and perspective-taking both predict mathematics performance, with fluid reasoning partially mediating these relations (Harris et al., 2025).

Contemporary educational research expands this understanding by showing that students with stronger spatial skills are better able to use visual models and external representations to reason geometrically. Lowrie et al. (2021) says that flexible visualization improves performance on transformational geometry tasks, including symmetry, dilation, and composite figures. Taylor et al. (2023) additionally argue that diagrams, dynamic visualizations, and spatial models act as "external spatial tools" that increase students' internal cognitive processes; thus, geometry learning effectiveness depends partly on learners' spatial capacities.

Why Do Geometry Interventions Improve Spatial Thinking?

Geometry-based instructional interventions improve students' spatial thinking because they engage in cognitive, perceptual, and representational mechanisms that cover spatial reasoning. Spatial skills are known to be highly malleable, and decades of meta-analytic and experimental research have shown that targeted spatial instruction produces substantial gains across age groups (Newcombe, 2017; Uttal et al., 2013). Geometry learning environments activate a set of mechanisms; including embodied interaction, external visualization, dynamic manipulation, and representational scaffolding, that help both the acquisition and internalization of spatial processes such as mental rotation, spatial visualization, and spatial orientation.

Embodied cognition perspectives propose that spatial thinking develops through sensorimotor engagement with objects and space. When learners gesture, drag shapes, rotate models, or manipulate geometric representations, their physical actions help them encode spatial relationships more deeply (DeSutter & Stieff, 2017). Embodied actions strengthen internal spatial representations by mapping motor feedback onto visual transformations, helping students to reason more flexibly about shape, position, and orientation (Clifton et al., 2016; Weisberg & Newcombe, 2017). A systematic review of 36 empirical studies likewise identified embodied-interaction features that help to develop spatial skills (Lee-Cultura & Giannakos, 2020). In geometry, embodied interactions such as rotating polygons on a touchscreen, using 3D solids, or walking around augmented reality objects help learners coordinate multiple perspectives, enhancing mental rotation and spatial orientation skills.

Geometry interventions often provide external spatial representations that support learners in doing transformations and visualizations that might be difficult to complete mentally. When students interact with diagrams, nets, or 3D renderings, they receive immediate perceptual feedback that guides attention to critical spatial relations such as adjacency, symmetry, proportionality, and alignment (Newcombe, 2017). These representational supports help learners to build correct mental models, finally promoting more precise spatial reasoning.

Dynamic geometry software (DGS) supports spatial development by letting real-time manipulation of geometric figures, allowing students to drag, rotate, reflect, and transform objects while observing continuous motion. The dynamic nature of these tools externalizes spatial transformations, showing how shapes behave under rotation, translation, and reflection, thereby increasing students' abilities to guess and mentally simulate such operations. Research shows that DGS environments improve spatial visualization and mental rotation because learners repeatedly do and observe spatial transformations, receiving immediate feedback that reinforces spatial representations (Güven & Kosa, 2008; Suparman et al., 2024). Classroom implementations show that dynamic manipulation promotes inductive reasoning, multiple-representation coordination, and the development of flexible spatial strategies (Fiangga, 2024).

Virtual and augmented reality environments increase spatial learning by providing immersive, interactive, and 3D contexts in which learners can explore geometric structures from multiple viewpoints. VR supports spatial reasoning by posing rich depth clues, realistic perspective changes, and embodied interaction with virtual objects (Wang et al., 2024). AR transfers digital geometric objects onto real space, letting students walk around, rotate, and examine shapes in ways that blend physical and virtual affordances (Ozcakir & Cakiroglu, 2021). These immersive environments increase mental rotation, spatial orientation, and perspective taking by enabling continuous exploration of complex spatial scenes (Yang et al., 2026). AR-based geometry tools combined with intelligent tutoring have also been reported to improve middle school students' learning gains and motivation in geometry (Uriarte-Portillo et al., 2023). Mechanistically, VR/AR tools leverage multisensory feedback, increased presence, and interactive manipulation to strengthen learners' spatial view and accepting of geometric structures (Shah et al., 2024).

Effective geometry interventions share design features that directly affect spatial skill development. Meta-analyses show that interventions are more successful when they provide varied practice, progressive increases in difficulty, and explicit attention to spatial strategies, such as identifying axes of rotation or dividing figures into simpler components (Uttal et al., 2013; İleri et al., 2023). Instructions that integrates spatial language, for example, describing symmetry, direction, or alignment, additionally

support learners by helping them program spatial relations verbally and visually (Newcombe & Stieff, 2012). Feedback-rich environments, whether through dynamic geometry tools or immersive platforms, help students upgrade their spatial strategies and transfer gains to new tasks.

Conceptual Model

Geometry-based instructional interventions are theorized to increase students' spatial thinking by engaging cognitive, perceptual, and representational processes that support the development of spatial skills. In turn, spatial thinking is strongly linked to mathematics and geometry achievement across childhood, adolescence, and adulthood (Resnick et al., 2020; Young et al., 2018; Xie et al., 2020). The conceptual model for this meta-analysis therefore situates spatial thinking as the central mediating mechanism through which geometry interventions apply their effects. This model is situated in converging evidence from developmental psychology, cognitive science, and mathematics education research.

Geometry instruction inherently inserts spatial content, including reasoning about shapes, transformations, spatial relations, and 2D–3D structure. When instructional interventions, such as dynamic geometry software, augmented and virtual reality, 3D modeling, manipulatives, or guided inquiry, are done, they provide structured opportunities for learners to do spatial transformations, play with geometric objects, and use external representations. These experiences are thought to directly activate subskills within spatial thinking, such as mental rotation, spatial visualization, spatial orientation, and spatial relational reasoning (Kyaw & Vidákovich , 2025; Lowrie & Logan, 2023).

Furthermore, modern technology-enhanced geometry environments make highly interactive and multisensory learning conditions. Dynamic geometry software expresses geometric transformations in ways that reduce cognitive load and promote internalization of spatial strategies (Walkington et al., 2024). Augmented and virtual reality tools provide immersive three-dimensional contexts, rich deep cues, and embodied interactions, all of which are theorized to increase spatial reasoning (Kaźmierczak et al., 2025; Ozcakir & Cakiroglu, 2021; Wang et al., 2024; Yang et al., 2026). Thus, the model assumes that geometry-based interventions affect specific spatial processes depending on the modality, intensity, and nature of the instructional design.

The model proposes that geometry interventions produce gains in one or more spatial components, which in turn support improvements in geometric reasoning, geometric problem-solving, and broader mathematical understanding. This mediational pathway aligns with theoretical perspectives identifying spatial reasoning as a foundational cognitive resource for mathematics learning (Newcombe, 2017; Uttal & Cohen, 2012; Uttal & Newcombe, 2013). It also fits with experimental evidence showing that interventions that increase spatial thinking tend to give gains in geometry performance (Resnick et al., 2020).

The outcome domain in the model includes performance in geometry, spatially rich mathematics topics, and related conceptual understanding. Geometry tasks often require coordinating visual and symbolic representations, interpreting diagrams, and performing mental transformations. Studies of teachers and students show that spatial reasoning is closely related to geometric reasoning ability, including the ability to generalize patterns, identify invariant properties, and reason about transformations (Kyaw & Vidákovich, 2025).

The model hypothesizes that improvements in spatial thinking serve as key drivers of gains observed in geometry learning outcomes. This reflects broader theories of positioning spatial thinking as a fundamental cognitive foundation for STEM achievement and problem-solving (Newcombe, 2017; Uttal et al., 2013).

METHOD

Research Design

This study used a meta-analysis design to synthesize empirical evidence on the effectiveness of geometry-based instructional interventions in improving students' spatial thinking skills. The procedures followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020; Page et al., 2021) guidelines to ensure transparency, rigor, and replicability.

Literature Search Strategy

A comprehensive literature search was done to identify relevant empirical studies published between 2020 and 2025. The following electronic databases were systematically searched: ERIC, Scopus, Web of Science, PsycINFO, and Google Scholar. These databases were selected to make sure wide coverage of educational, psychological, and interdisciplinary research on spatial thinking and geometry instruction. The search strategy combined keywords related to spatial thinking, geometry, and instructional interventions using Boolean operators:

("spatial thinking" OR "spatial ability" OR "spatial reasoning" OR "mental rotation" OR "spatial visualization") AND ("geometry" OR "geometric reasoning" OR "geometry learning") AND ("intervention" OR "teaching" OR "instruction" OR "training")

Searches were conducted in ERIC, Scopus, Web of Science, PsycINFO, and Google Scholar between September 2025 and November 2025. Search syntax was adapted to the requirements of each database. Searches were limited to studies published from 2020 to 2025 and to English language. Title, abstract, and keyword fields were searched where available. Reference lists of eligible studies and relevant reviews were also manually searched. Duplicate records were identified and removed before screening. In addition to database searches, manual searches were done by reviewing reference lists of key articles and relevant reviews.

Inclusion and Exclusion Criteria

Studies were included in the meta-analysis if they met the following criteria: (1) Employed experimental or quasi-experimental research designs. (2) Reported quantitative outcomes related to spatial thinking (e.g., spatial visualization, mental rotation, spatial orientation). (3) Included at least one geometry-related instructional intervention, such as dynamic geometry software, geometric transformations, 3D modeling, drawing, or technology-enhanced visualization tools. (4) Provided sufficient statistical information (e.g., means and standard deviations, *t* or *F* values, or pre–post correlations) to calculate an effect size. (5) Were published in peer-reviewed journals or dissertations between 2020 and 2025. (6) Included participants from elementary, or secondary education levels.

Studies were excluded if they (a) were only qualitative or theoretical, (b) focused on non-geometric domains or (c) lacked adequate quantitative data for effect size computation.

These criteria were selected to ensure that included studies provided empirical evidence directly addressing the effects of geometry-related instructional interventions on measurable spatial-thinking outcomes. Restricting inclusion to experimental and quasi-experimental studies with sufficient quantitative data enabled the calculation of comparable effect sizes.

Study Selection Process

All identified records were screened in two stages. First, titles and abstracts were reviewed to remove clearly irrelevant studies. Second, full texts of potentially eligible studies were examined against the inclusion criteria. The screening process was conducted independently by two reviewers, and disagreements were resolved through discussion. Duplicate records were removed before screening. Two reviewers independently conducted title/abstract and full-text screening using the predefined eligibility criteria. The overall selection process is reported using a PRISMA flow diagram. The complete list of the studies included in the meta-analysis is presented in **Table A1** in the **Appendix**.

Data Extraction and Coding

A standardized data extraction form was used to systematically code information from each included study. Extracted variables included: Study information: author(s), year of publication, country, and publication type; Sample characteristics: sample size, age or grade level, gender distribution, and educational level; Intervention characteristics: type of intervention (e.g., dynamic geometry software, 3D modeling, drawing-based visualization, AR/VR), duration, and instructional setting; Research design: experimental or quasi-experimental design, presence of control group, and pre–post structure; Measurement instruments: spatial thinking assessments used or researcher-developed instruments; Statistical data: means, standard deviations, test statistics, and reported reliability coefficients; Moderator variables: intervention type, and educational level. All extracted data were double-checked for accuracy, and coding discrepancies were resolved by consensus. Both reviewers independently coded the included studies using a predefined coding form and coding guide. The coded variables and category definitions were established before analysis, and discrepancies were discussed until consensus was reached.

Effect Size Calculation

The main effect size metric was Hedges' g, selected due to its correction for small-sample bias and common use in educational meta-analyses. Hedges' g was calculated from standardized mean differences and corrected for small-sample bias. For independent-group studies, post-test means, standard deviations, and sample sizes were used. For single-group pre–post studies, standardized mean change was calculated. When multiple eligible spatial-thinking outcomes were reported within one study, they were combined into a single composite effect to avoid violating the assumption of statistical independence.

Data Analyses

All statistical analyses were done using a meta-analytic framework. Meta-analytic methods have been widely used to synthesize intervention effects across heterogeneous educational contexts and participant groups (Balta et al., 2023). The primary effect size metric was Hedges' *g*, which gives a bias-corrected standardized mean difference and is suitable for studies with small and unequal sample sizes. If studies employed post-test-only designs with intervention and comparison groups, effect sizes were calculated using post-test means and standard deviations. For studies using pre–post designs without a control group, standardized mean change effect sizes were calculated. When multiple spatial-thinking outcomes were reported within a single study, these were combined into a single effect size to preserve statistical independence.

Overall effects were synthesized using a random-effects meta-analysis, acknowledging that true effect sizes were expected to vary across studies due to differences in participants, instructional contexts, intervention types, and measurement instruments. Between-study variance (τ^2) was estimated using the Restricted Maximum Likelihood (REML) method, which provides unbiased estimates of heterogeneity and is recommended for educational meta-analyses. Statistical significance was evaluated using *z* tests, and 95% confidence intervals were calculated for all pooled estimates.

Heterogeneity among effect sizes was assessed using Cochran's *Q* statistic, the between-study variance estimate (τ^2), and the I^2 index, which represents the proportion of total variability attributable to between-study heterogeneity rather than sampling error. Model fit was further evaluated using log-likelihood, deviance, Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and corrected AIC (AICc) values to confirm the suitability of the selected estimation approach.

To examine the robustness of the findings, sensitivity analyses were conducted by excluding studies with extremely large effect sizes. Random-effects models were re-estimated after exclusion to evaluate changes in the magnitude and stability of the pooled effect size. In addition, influence diagnostics were performed using Cook's distance to identify whether any individual study exerted disproportionate influence on the overall results.

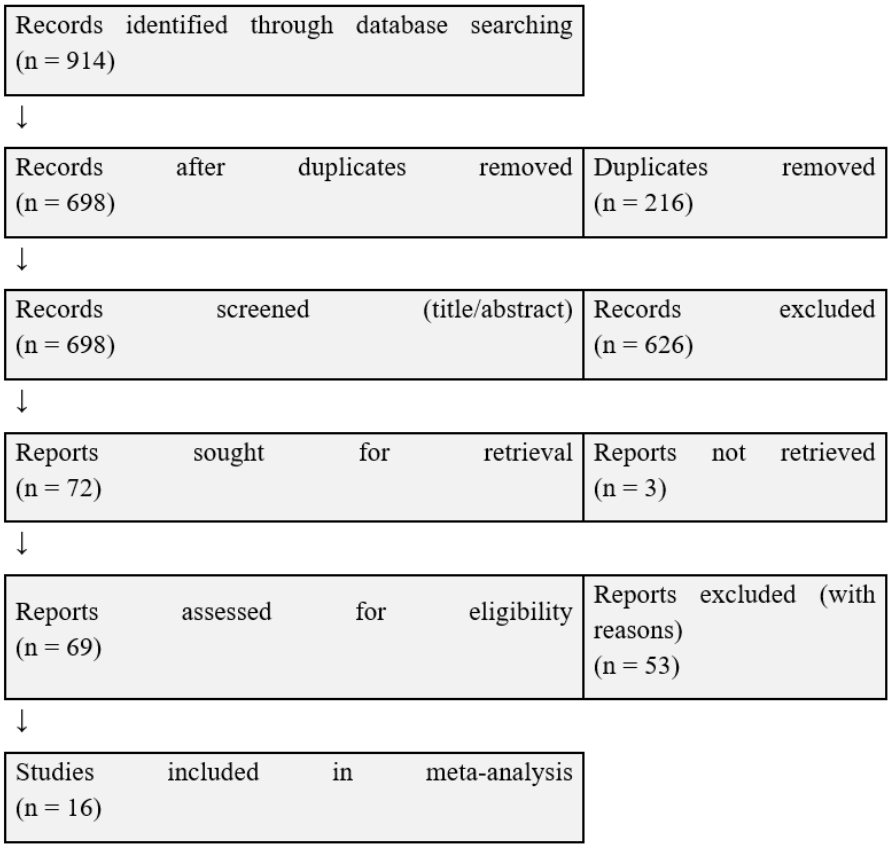


Figure 1. PRISMA flow diagram of the selection process (Note: Example reasons for full-text exclusion: not spatial thinking outcome, not geometry-focused, non-empirical design, insufficient quantitative data, duplicate sample) (Source: Authors' own elaboration, based on PRISMA 2020 flow diagram template, Page et al., 2021)

Publication bias was assessed using a combination of visual and statistical approaches. Funnel plots were inspected for asymmetry, and formal tests included Rosenthal's Fail-Safe *N*, Kendall's rank correlation test, and Egger's regression test. Furthermore, Two One-Sided Tests (TOST) equivalence testing was conducted to determine whether the overall effect could be considered statistically equivalent within predefined bounds, complementing traditional null-hypothesis significance testing.

The study selection process followed the PRISMA 2020 guidelines and is presented in **Figure 1**. The initial search identified 914 records; after removing 216 duplicates, 698 records were screened by title and abstract, 72 reports were sought for retrieval, 69 were assessed for eligibility, and 15 studies were included in the meta-analysis.

Moderator analyses were conducted using random-effects subgroup models to examine whether effect sizes differed as a function of intervention type, and educational level. Differences between subgroups were evaluated using the between-group heterogeneity statistic. All moderator analyses were conducted after excluding studies with extreme effect sizes to ensure conservative and stable estimates. Finally, model assumptions were examined using diagnostic plots, including a normal quantile–quantile (Q–Q) plot of standardized residuals, to assess the normality assumption underlying the random-effects model.

RESULTS

Study Selection

The systematic literature search and screening process resulted in the identification of 15 empirical studies that met all inclusion criteria and were included in the final meta-analysis. Following the removal of duplicate records, titles and abstracts were screened to assess relevance to geometry-based interventions pointing to spatial thinking outcomes. Studies that did not focus on spatial thinking, lacked a geometry-related instructional component, employed non-empirical designs, or failed to report enough quantitative data were removed at this stage.

Full-text versions of the remaining articles were then analyzed in detail for eligibility. Studies were excluded if they did not report enough statistical information for effect size calculation or if the intervention was not clearly related to geometry instruction. After the full-text screening process, 15 studies published between 2020 and 2025 satisfied all inclusion criteria and were retained for quantitative synthesis.

Table 1. Study-by-study characteristics of included studies

Author(s) & Year	Country	Educational Level	Sample Size	Intervention Type	Hedges' g
Lowrie et al. (2021)	Australia	Secondary	641	Spatial intervention program integrating geometry tasks	0.39
İbili et al. (2020)	Türkiye	Secondary	103	Augmented reality–supported geometry instruction	0.64
Šafhalter et al. (2022)	Slovenia	Secondary	166	3D modeling–based geometry learning	0.84
Ng et al. (2020)	Hong Kong	Primary	166	Dynamic geometry and 3D printing–based geometry instruction	0.28
Schoevers et al. (2020)	Netherlands	Primary	2,909	Integrated visual arts and geometry (MACE) intervention	0.43
Dere et al. (2020)	Türkiye	Secondary	63	Web-based 3D design (Tinkercad) spatial training	0.51
Srivastava et al. (2024)	India	Secondary	90	AR-enhanced inquiry learning for spatial perspective-taking	0.77
Nadzeri et al. (2024)	Malaysia	Primary	61	Augmented reality–supported geometry learning (LearnGeoAR)	0.7
Mandala et al. (2025)	Indonesia	Secondary	18	Mobile AR geometry learning game (GEMBI AR) for spatial reasoning	1.32
Putri et al. (2025)	Indonesia	Secondary	75	AR geometry intervention	1.21
Saputra et al. (2025)	Indonesia	Secondary	60	Augmented reality–supported 3D geometry instruction	1.76
Mjenda et al. (2023)	Tanzania	Secondary	267	Computer simulation and animation–supported 3D geometry spatial visualization instruction	1.73
Crissey (2023)	USA	Secondary	65	Desmos/GeoGebra-based spatial visualization activities vs. concrete manipulatives	-0.21
del Cerro Velázquez and Morales Méndez (2021)	Spain	Secondary	48	GeoGebra AR–supported mathematical functions instruction for spatial visualization and rotation	0.82
Abdul Hanid et al. (2022)	Malaysia	Secondary	124	AR + computational thinking–supported geometry instruction	1.30

Characteristics of Included Studies

The final sample contained 16 empirical studies published between 2020 and 2025 that examined the effects of geometry-based instructional interventions on students' spatial thinking. The studies were conducted across a broad range of geographical contexts, including Europe, Asia, Australia, and North America, showing the international scope of current research on spatial thinking in mathematics education.

The included studies involved learners from primary and secondary. The majority focused on secondary school students, consistent with the vital role of geometry instruction at this level. Sample sizes ranged from small classroom-based interventions to large-scale school implementations, with total participant numbers varying substantially across studies.

In terms of instructional methodology, the interventions represented different pedagogical and technological designs. These included dynamic geometry software, augmented and virtual reality (AR/VR) applications, 3D modeling and visualization environments, and technology-supported drawing or manipulation tasks. Intervention durations changed from short-term instructional units to extended programs spanning multiple weeks. Most studies employed experimental or quasi-experimental designs, typically comparing intervention and control groups using pre- and post-test measures. The characteristics of the 15 included studies, including country, educational level, sample size, intervention type, and Hedges' g effect sizes, are presented in **Table 1**. The full references of the 15 included studies are provided in **Table A1** in **Appendix**.

Methodological Quality of the Included Studies

The methodological quality of the included studies was evaluated using the Joanna Briggs Institute (JBI) critical appraisal checklists appropriate to each research design (Tufanaru et al., 2020). JBI critical appraisal tools are designed to assess the methodological rigor, trustworthiness, and potential risk of bias of studies according to their specific research designs (Barker et al., 2023, 2024). Quasi-experimental studies were assessed using the nine-item JBI Critical Appraisal Checklist for Quasi-Experimental Studies, whereas the randomized experimental study was assessed using the 13-item JBI Critical Appraisal Checklist for Randomized Controlled Trials (JBI, 2017a, 2017b). Rather than applying arbitrary quality cut-off scores, the number of criteria satisfied was reported for each study.

The methodological quality varied across the included studies. Among the quasi-experimental studies, the number of JBI criteria satisfied ranged from 4/9 to 7/9. Several studies met 7/9 criteria, including Lowrie et al., Schoevers et al., Crissey, del Cerro Velázquez and Morales Méndez, and Abdul Hanid et al. Other studies satisfied between 5/9 and 6/9 criteria, while Dere and Kalelioglu satisfied 4/9. The randomized study by Srivastava et al. satisfied 8/13 criteria.

Common methodological limitations included non-random allocation, small or non-probability samples, lack of a true control group in some studies, unclear reporting of attrition, possible teacher- or school-level confounding, and limited follow-up measurement. In contrast, common strengths included the use of pretest–posttest designs, comparison groups, established spatial-ability instruments, clearly described interventions, and appropriate statistical analyses in several studies. These variations in methodological quality should be considered when interpreting the pooled effect estimates and the substantial heterogeneity observed across studies.

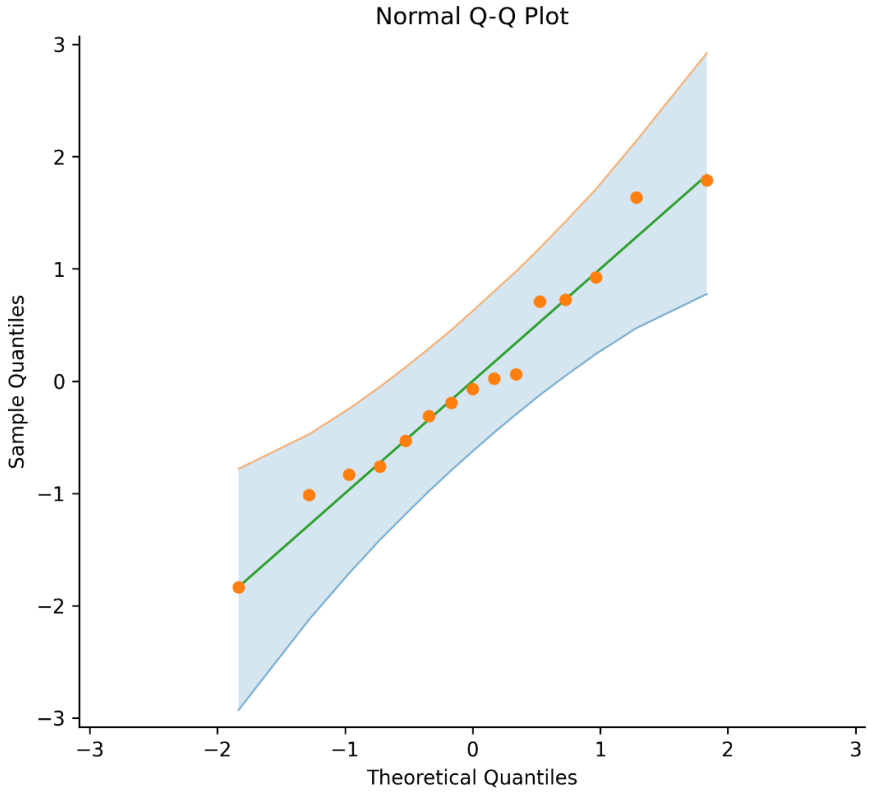


Figure 2. Normal Q–Q plot of standardized residuals from the random-effects (Source: Authors' own elaboration)

Table 2. Overall effect size estimated using random-effects

	Estimate	SE	Z	p	CI Lower Bound	CI Upper Bound
Intercept	0.807	0.141	5.73	< .001	0.531	1.084

Note. Tau^2 estimator: Restricted Maximum Likelihood (REML)

Sensitivity Analysis

In the full random-effects model including all 15 studies, geometry-based instructional interventions demonstrated a large positive effect on students' spatial thinking (g = 1.03), accompanied by substantial heterogeneity (I^2 = 94%). After removing one study with extreme effect sizes, the recalculated random-effects model based on 15 studies yielded a reduced but still statistically significant pooled effect (g = 0.807, 95% CI [0.531, 1.084], p < .001).

This section presents the results of the random-effects meta-analysis synthesizing effect sizes from the 15 studies. First, the overall pooled effect size and statistical significance are reported. Next, between-study heterogeneity is examined using multiple heterogeneity indices. Model fit statistics and information criteria are then shown to justify the selected estimation approach. Publication bias is assessed using both visual and statistical methods, followed by equivalence testing to additionally evaluate the robustness of the findings. Finally, diagnostic plots are used to examine main model assumptions.

Figure 2 presents a normal quantile–quantile (Q–Q) plot used to assess the normality assumption underlying the random-effects meta-analysis.

As shown in **Figure 2**, the standardized residuals are plotted against the theoretical quantiles of a normal distribution. The points generally follow the reference diagonal line and remain largely within the confidence envelope, suggesting that the residuals are approximately normally distributed. Some deviations are visible, particularly at the tails, but they do not indicate a severe departure from normality. The Q–Q plot supports the adequacy of the random-effects model with respect to the normality assumption for the residuals.

Table 2 presents the results of the random-effects meta-analysis, summarizing the overall effect across included separate studies. The model was estimated using the Restricted Maximum Likelihood method, accounting for between-study heterogeneity.

As shown in **Table 2**, the random-effects model produced a statistically significant overall effect size of Hedges' g = 0.807 (SE = 0.141), with a Z value of 5.73, p < .001. The 95% confidence interval ranged from 0.531 to 1.084, indicating a moderate-to-large positive overall effect of the interventions on students' spatial thinking. The estimated τ^2 = 0.245.

Table 3 summarizes the heterogeneity statistics used to evaluate the variability of effect sizes across the studies used.

Table 3. Heterogeneity statistics for the random-effects model

Tau	Tau²	I²	H²	df	Q	p
0.495	0.245 (SE = 0.111)	89.90%	9.903	14	138.64	< .001

Table 4. Model fit statistics and information criteria for the random-effects model

Estimation method	Log-likelihood	Deviance	AIC	BIC	AICc
Maximum Likelihood	-11.719	45.193	27.437	28.853	28.437
Restricted Maximum Likelihood	-12.777	25.553	29.553	30.831	30.644

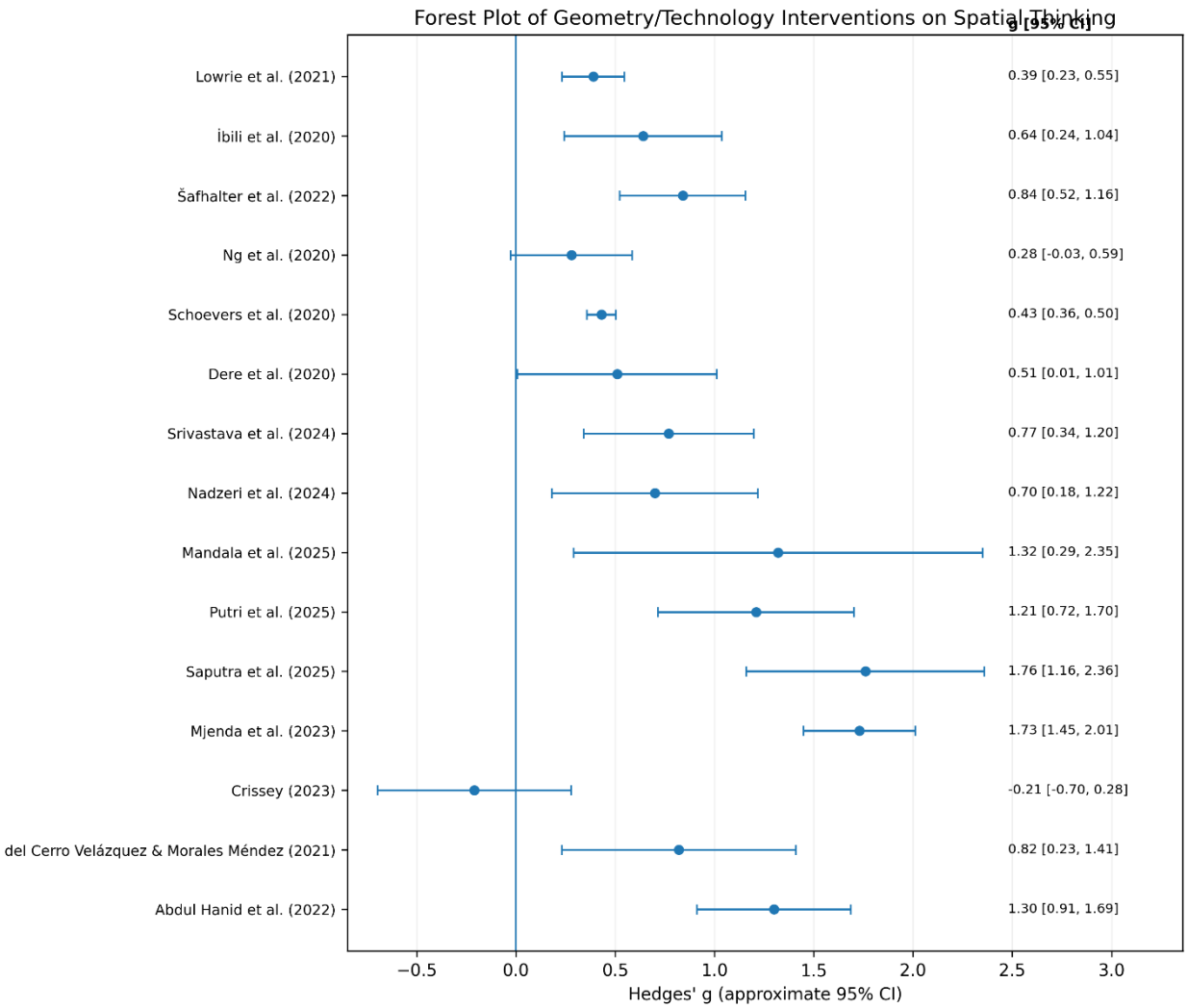


Figure 3. Forest plot of individual study effect sizes and overall random-effects estimate (Source: Authors' own elaboration)

As shown in **Table 3**, the estimated between-study standard deviation was $\tau = 0.495$, with a corresponding variance of $\tau^2 = 0.245$ (SE = 0.111). The I^2 value of 89.90% indicates substantial heterogeneity among the 15 studies. Similarly, $H^2 = 9.903$ shows that the observed variability was considerably greater than would be expected from sampling error alone. Cochran's Q test was statistically significant, $Q(14) = 138.64$, $p < .001$, confirming substantial between-study heterogeneity and supporting the use of a random-effects model.

Table 4 reports the model fit indices and information criteria used to evaluate and compare estimation approaches for the random-effects meta-analysis.

As shown in **Table 4**, the ML and REML approaches produced broadly comparable model-fit statistics. The ML model yielded lower AIC, BIC, and AICc values than the REML model. However, REML was retained as the primary estimation method because it generally provides less biased estimates of between-study variance, particularly when the number of studies is relatively small.

Figure 3 presents a forest plot summarizing the individual study effect sizes included in the meta-analysis and the pooled effect estimated using a random-effects model.

As shown in the forest plot, the 15 studies vary considerably in both effect magnitude and precision. Most studies report positive effects of geometry- and technology-enhanced interventions on students' spatial thinking. The largest effects are

Table 5. Publication bias assessment results

Test Name	Value	p
Fail-Safe N	1,705	< .001
Kendall's Tau	0.257	.202
Egger's Regression	1.113	.266

Note. Fail-safe N calculated using the Rosenthal approach.

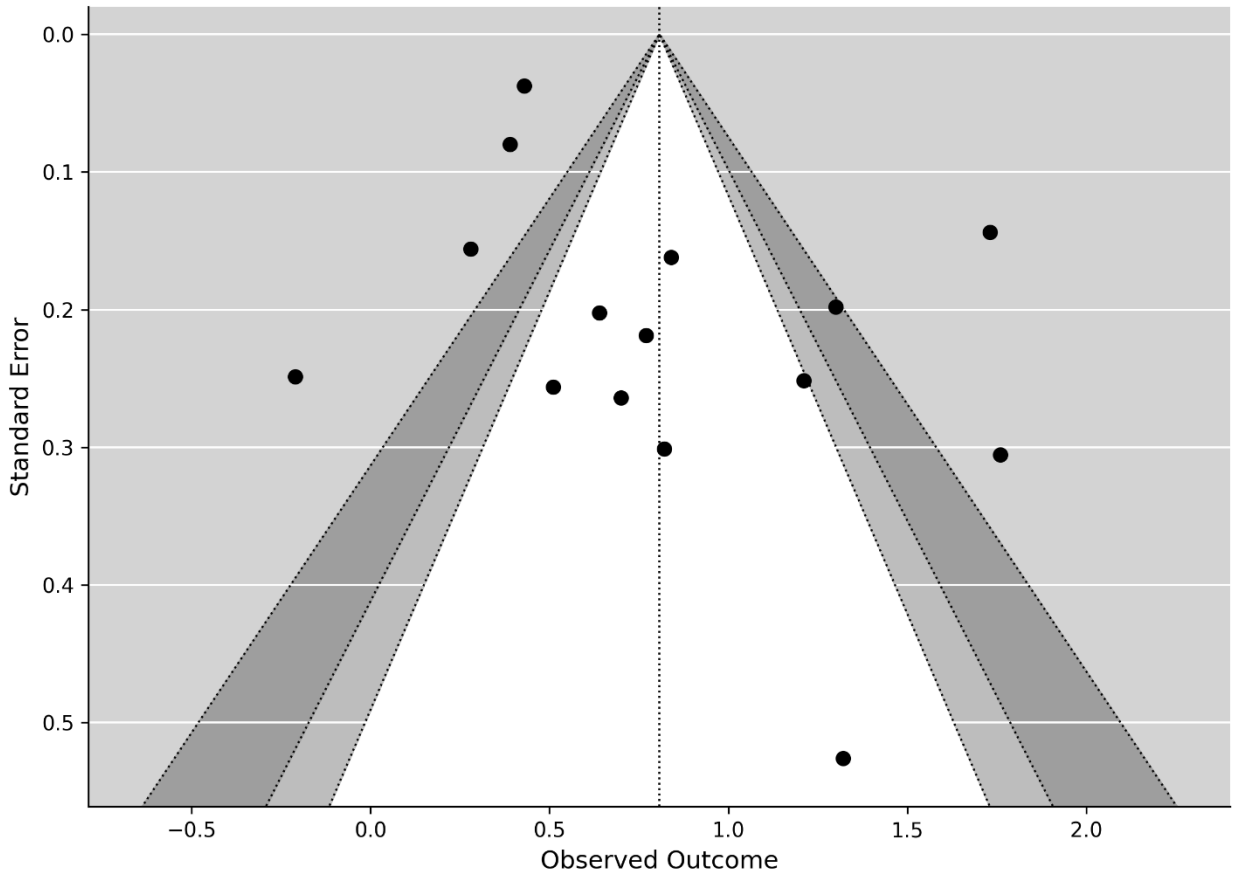


Figure 4. Funnel plot for assessing publication bias (Source: Authors' own elaboration)

observed for Saputra et al. (2025), Mjenda et al. (2023), Mandala et al. (2025), and Abdul Hanid et al. (2022). Several studies, including Lowrie et al. (2021), Schoevers et al. (2020), and Ng et al. (2020), show smaller positive effects.

The confidence intervals also differ substantially across studies, reflecting differences in sample size and study-level variability. Large-sample studies such as Schoevers et al. (2020) have relatively narrow confidence intervals, whereas smaller studies such as Mandala et al. (2025) show much wider intervals. Most confidence intervals remain above zero, indicating statistically significant positive effects, although some studies, including Ng et al. (2020) and Crissey (2023), have confidence intervals that cross zero. Crissey (2023) is the only study with a negative point estimate. The forest plot indicates a generally positive pattern of intervention effects, but the substantial variation in effect sizes and confidence intervals suggests considerable between-study heterogeneity.

Table 5 presents the statistical tests used to evaluate the presence of publication bias in the meta-analysis.

As shown in **Table 5**, Rosenthal's Fail-Safe N indicated that approximately 1,705 null-effect studies would be required to reduce the overall result to non-significance. Kendall's rank correlation test was not statistically significant, $\tau = 0.257$, $p = .202$, and Egger's regression test was also non-significant, $z = 1.113$, $p = .266$. Overall, these tests provide no statistically significant evidence of publication bias or small-study effects in the 15-study dataset.

Figure 4 displays a funnel plot used to visually assess potential publication bias and small-study effects in the meta-analysis.

As shown in **Figure 4**, the contour-enhanced funnel plot displays the 15 study effect sizes against their standard errors. The studies are distributed on both sides of the pooled effect estimate, although the pattern is not perfectly symmetrical. Several studies with larger standard errors are located farther from the center, while the more precise studies tend to cluster closer to the pooled effect. Most studies fall within the central and adjacent contour regions, and there is no clear concentration of studies exclusively on one side of the funnel. Although some asymmetry is visible, the overall pattern does not suggest a strong or systematic publication-bias effect. This interpretation is consistent with the non-significant Kendall's tau and Egger's regression results.

Table 6. Two One-Sided Tests (TOST) equivalence testing results

Z-Value Lower Bound	P-Value Lower Bound	Z-Value Upper Bound	P-Value Upper Bound	LL_CI_TOST	UL_CI_TOST	LL_CI_ZTEST	UL_CI_ZTEST
9.274	< .001	2.180	.985	0.575	1.039	0.531	1.084

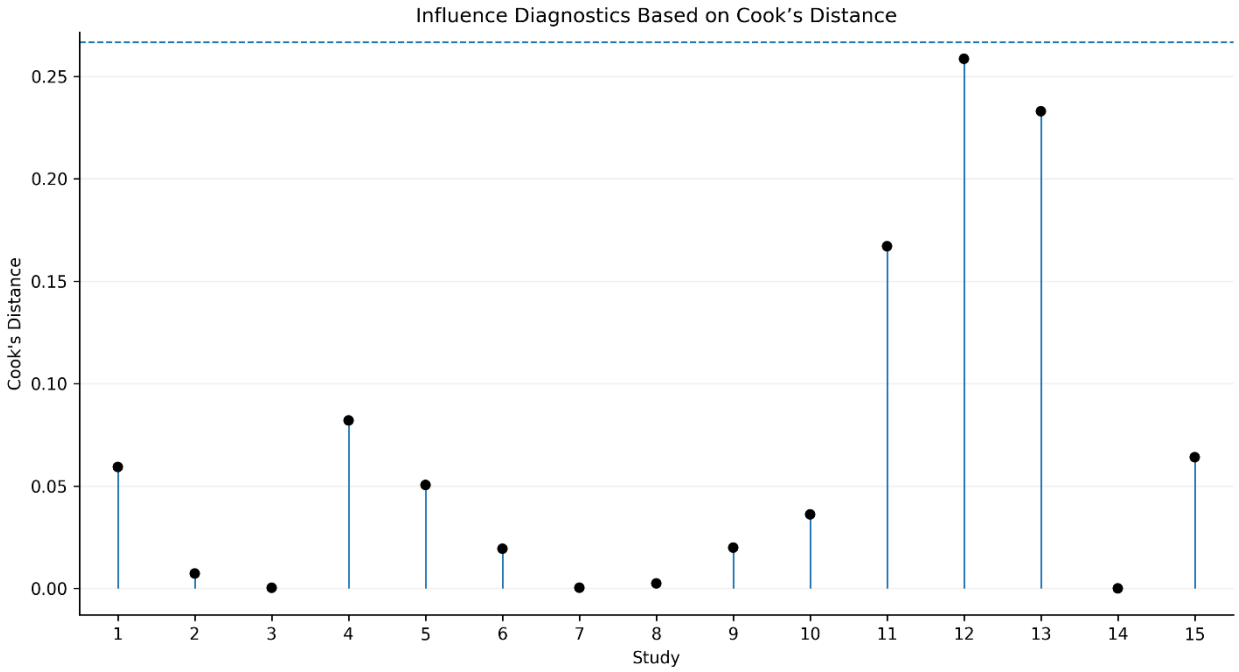


Figure 5. Influence diagnostics based on Cook's distance (Source: Authors' own elaboration)

Table 6 presents the results of the Two One-Sided Tests (TOST) procedure used to evaluate if the overall meta-analytic effect can be judged statistically equivalent within predefined equivalence bounds.

As shown in **Table 6**, the lower-bound TOST was statistically significant, $Z = 9.274$, $p < .001$, whereas the upper-bound test was not statistically significant, $Z = 2.180$, $p = .985$. The 90% TOST confidence interval ranged from 0.575 to 1.039, while the conventional 95% confidence interval ranged from 0.531 to 1.084. Because the TOST confidence interval does not fall entirely within the predefined equivalence bounds of −0.50 to 0.50, statistical equivalence cannot be established. However, the conventional confidence interval excludes zero, confirming a statistically significant positive overall effect.

Figure 5 presents the Cook's distance influence plot used to calculate whether any individual study applied disproportionate influence on the overall meta-analytic effect size.

As shown in **Figure 5**, Cook's distance values were generally low across the 15 studies, indicating that no single study exerted a disproportionate influence on the overall random-effects estimate. All values remained below the conventional influence threshold, suggesting that the pooled effect size was not driven by any one individual study. These results support the stability and robustness of the meta-analytic findings.

Moderator Analyses

To test if intervention effects changed across key moderators under a conservative model, subgroup analyses were done after excluding studies with extreme effect sizes. Random-effects models were estimated within each subgroup, and differences between subgroups were evaluated using $Q_{between}$.

Table 7 shows statistically significant differences in effect sizes across intervention types, AR/VR interventions produced the largest pooled effect, followed by 3D modeling and visualization interventions. Non-immersive visualization interventions produced a smaller but statistically significant pooled effect. The Dynamic Geometry Software category contained only one study and showed a small negative, non-significant effect; therefore, this subgroup should not be interpreted as a reliable estimate of the effectiveness of dynamic geometry software. Substantial heterogeneity remained within the 3D modeling/visualization subgroup, whereas heterogeneity was moderate within the AR/VR subgroup and negligible within the non-immersive visualization subgroup.

Table 7. Random-effects subgroup analysis by intervention type

Intervention type	k	g	SE	95% CI	z	p	Qwithin (df)	p(Q)	I^2 (%)
3D Modeling / Visualization	4	0.85	0.32	[0.21, 1.49]	2.62	.009	51.35 (3)	< .001	94.16
AR/VR	8	1.03	0.14	[0.76, 1.30]	7.42	< .001	15.47 (7)	.030	54.76
Dynamic Geometry Software	1	-0.21	0.25	[-0.70, 0.28]	-0.84	.399	—	—	—
Non-immersive Visualization	2	0.42	0.03	[0.36, 0.49]	12.44	< .001	0.21 (1)	.650	0.00

Between-group difference: $Q_{between}(3) = 71.61$, $p < .001$

Table 8. Random-effects subgroup analysis by educational level

Educational level	k	g	SE	95% CI	z	p	Qwithin (df)	p(Q)	I^2 (%)
Primary	3	0.43	0.04	[0.36, 0.50]	11.81	< .001	1.96 (2)	.375	0.00
Secondary	12	0.91	0.17	[0.58, 1.23]	5.42	< .001	106.37 (11)	< .001	89.66

Between-group difference: $Q_{between}(1) = 30.31$, $p < .001$

Table 8 shows positive and statistically significant pooled effects at both educational levels. The pooled effect was larger for secondary students (g = 0.91, 95% CI [0.58, 1.23], $p < .001$) than for primary students (g = 0.43, 95% CI [0.36, 0.50], $p < .001$). Heterogeneity was negligible among the three primary-level studies (I^2 = 0.00%) but substantial among the 12 secondary-level studies (I^2 = 89.66%), indicating considerable variation in intervention effects within secondary education.

DISCUSSION

This meta-analysis combined recent empirical evidence on the effectiveness of digital technology-supported geometry-based instructional interventions in improving students' spatial thinking. Across studies published between 2020 and 2025, the findings show that geometry-focused interventions produce moderate-to-large and educationally meaningful gains in spatial thinking. The pooled random-effects estimate was Hedges' g = 0.81, 95% CI [0.53, 1.08], p < .001, indicating a substantial positive overall effect. These results confirm that spatial thinking is a cognitive outcome that can be deliberately developed through instructional design, rather than an incidental byproduct of geometry instruction.

The magnitude of the pooled effect indicates the instructional sensitivity and malleability of spatial thinking. Effect sizes of this scale are notable in educational research, particularly given the diversity of participants, instructional formats, and assessment instruments included in the analysis. The results align with earlier meta-analytic evidence demonstrating that spatial skills are trainable and predictive of mathematics achievement (Atit et al., 2022; Hawes et al., 2022; Uttal et al., 2013), while extending this literature by showing that geometry-based instruction provides a particularly powerful context for spatial development. Geometry learning inherently requires learners to visualize, transform, and reason about spatial relationships, positioning it as a natural vehicle for strengthening spatial cognition (Clements & Battista, 1992; Newcombe, 2017).

Substantial heterogeneity was observed across studies (I^2 = 89.90%), indicating meaningful differences in instructional design, duration, technological affordances, participant characteristics, and measurement approaches. Such variability is common in educational meta-analyses and highlights the importance of examining moderators rather than assuming uniform effects. The significant heterogeneity also supports the use of a random-effects framework and reinforces the value of moderator analyses for understanding when and how geometry-based interventions are most effective. This substantial heterogeneity may reflect differences in intervention design and duration, participant characteristics, instructional settings, and the spatial-thinking assessment instruments used across studies. These methodological and contextual differences may have contributed to variation in the magnitude of observed effects and should therefore be considered when interpreting the pooled estimate.

Moderator analyses showed that intervention type played a significant role in shaping outcomes, with significant between-group differences. AR/VR interventions produced the largest pooled effect (g = 1.03), followed by 3D modeling and visualization interventions (g = 0.85). Non-immersive visualization approaches produced a smaller but still positive effect (g = 0.42). The Dynamic Geometry Software category contained only one study and therefore should not be interpreted as providing a reliable subgroup estimate. These findings support theoretical accounts emphasizing embodied cognition and the role of external representations in spatial learning (DeSutter & Stieff, 2017; Weisberg & Newcombe, 2017). Interactive and immersive environments allow learners to manipulate geometric objects, coordinate multiple perspectives, and experience continuous transformations, thereby externalizing spatial processes and potentially reducing cognitive demands (Newcombe, 2017; Shah et al., 2024).

Subgroup differences were statistically significant for both intervention type, $Q_{between}(3) = 71.61$, $p < .001$, and educational level, $Q_{between}(1) = 30.31$, $p < .001$. However, these findings should be interpreted cautiously because several subgroups contained very few studies, particularly Dynamic Geometry Software (k = 1), Non-immersive Visualization (k = 2), and primary education (k = 3). Moreover, Egger's test and Kendall's rank correlation test did not indicate statistically significant publication bias; however, these findings should be interpreted cautiously given the relatively small number of included studies (k = 15).

Educational level showed a different pattern. The pooled effect was significantly larger for secondary students (g = 0.91) than for primary students (g = 0.43), Qbetween(1) = 30.31, p < .001. Educational level significantly moderated intervention effects, with a larger pooled effect for secondary students than for primary students. This difference may reflect the increasing abstraction and spatial demands of secondary geometry, including transformations, coordinate reasoning, and 2D–3D relationships. Older students may also be better positioned to benefit from spatially rich instructional environments because of more developed

cognitive and metacognitive capacities (Newcombe & Stieff, 2012). However, this finding should be interpreted cautiously because only three primary-level studies were included.

The findings have important theoretical, practical, and policy implications. The results provide strong empirical support for conceptual models positioning spatial thinking as a mediating mechanism through which geometry instruction enhances learning (Uttal & Cohen, 2012; Resnick et al., 2020). From a practical perspective, geometry instruction should explicitly target spatial reasoning through tasks emphasizing visualization, manipulation, and transformation, supported by appropriate use of technology. Teacher education and professional development programs should equip educators with strategies for embedding spatial thinking into geometry instruction and for effectively integrating technology-supported pedagogies (Davor et al., 2026; Wekullo, 2026). At the policy level, the findings support the inclusion of spatial thinking as a core curricular objective within mathematics education and justify investment in instructional resources that promote spatial engagement.

Several limitations should be acknowledged. The operationalization of spatial thinking varied across studies, limiting fine-grained conclusions about specific spatial components. The literature was unevenly distributed across educational levels and geographic regions, with a greater concentration of studies at the secondary level. In addition, many interventions were short in duration and relied on immediate post-test outcomes. As a result, the long-term durability and transfer of spatial gains remain unclear. The substantial between-study heterogeneity also suggests that intervention effects are sensitive to differences in instructional design, participants, and measurement approaches. Although publication-bias analyses did not provide statistically significant evidence of substantial bias, the possibility of selective reporting cannot be entirely excluded. Future research should prioritize component-specific spatial assessments, expanded primary-level investigations, longer-term follow-up measures, and comparative studies examining instructional design features across low- and high-technology contexts. Attention to equity and access is also needed to ensure that spatial-thinking instruction benefits diverse learners.

CONCLUSIONS, IMPLICATIONS, AND LIMITATIONS

This meta-analysis provides strong and consistent evidence that geometry-based, technology-enhanced instructional interventions significantly increase students' spatial thinking. Combining findings from empirical studies published between 2020 and 2025, the results show that geometry instruction, particularly when designed to engage learners in visualization, manipulation, and transformation of spatial representations, functions as an effective means of developing spatial reasoning. The calculated moderate-to-large overall effect size (Hedges' $g = 0.81$, 95% CI [0.53, 1.08]), which remained robust across influence and publication-bias analyses, confirms that spatial thinking is associated with geometry learning and can be deliberately cultivated through instructional design. However, the substantial between-study heterogeneity ($I^2 = 89.90\%$) indicates considerable variation in the magnitude of intervention effects.

From a theoretical perspective, the findings support models that position spatial thinking as a main cognitive mechanism underlying geometry and mathematics learning. The stronger effects observed for interactive and immersive interventions reinforce theoretical accounts grounded in embodied cognition and external representation, which stress that spatial knowledge develops through active engagement with spatial transformations and representations. These results extend prior meta-analytic work on spatial training by showing that geometry-based instruction provides a particularly powerful and authentic context for spatial skill development.

The findings also have important implications for educational practice. Geometry instruction should explicitly target spatial thinking as a learning outcome rather than assuming that spatial skills will develop incidentally. Instructional approaches that emphasize dynamic manipulation, multiple perspectives, and three-dimensional reasoning are especially promising for increasing spatial reasoning. In particular, the moderator analysis showed that intervention type significantly influenced effect sizes, with strong effects observed for augmented and virtual reality and 3D modeling/visualization approaches. Teacher education and professional development programs should therefore equip educators with pedagogical strategies for integrating spatial thinking into geometry instruction, including the use of spatial language, representational scaffolding, and tasks that promote mental rotation and visualization.

At the policy level, the results show the need to recognize spatial thinking as a core component of mathematics education. Current curricula and standards often prioritize procedural fluency and symbolic reasoning while giving limited attention to spatial competencies. The evidence synthesized in this study provides an empirical basis for embedding explicit spatial-thinking objectives within geometry curricula and assessment frameworks. Investment in instructional resources that support spatial exploration at both primary and secondary levels may contribute to stronger mathematics learning and broader STEM readiness. Educational level significantly moderated intervention effects, although this finding should be interpreted cautiously because only three primary-level studies were included.

Despite these contributions, several limitations should be acknowledged. The included studies varied widely in their operationalization of spatial thinking, limiting the ability to draw fine-grained conclusions about specific spatial components. The literature was unevenly distributed across educational levels and geographic regions, with a concentration of studies at the secondary level and in certain national contexts. In addition, many interventions were short in duration and relied on immediate post-test measures, preventing conclusions about the long-term durability and transfer of spatial gains. Consequently, the evidence is insufficient to determine whether improvements in spatial thinking are sustained over time or transfer to other mathematics or STEM contexts. The substantial heterogeneity across studies also indicates that intervention effects depend considerably on instructional design, participant characteristics, and measurement approaches. Although publication-bias analyses suggested no substantial bias, the possibility of selective reporting cannot be entirely excluded.

In conclusion, this meta-analysis establishes digital technology-enhanced, geometry-based instructional interventions as a reliable and powerful means of enhancing students' spatial thinking. By clarifying the instructional conditions associated with stronger spatial gains, the study adds to theory, informs educational practice, and supports policy efforts aimed at strengthening geometry education and spatial reasoning as foundational components of mathematical learning.

Author contributions: AR: conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing – original draft, writing – review & editing; **YT:** supervision, validation, writing – review & editing; **GZ:** validation, writing – review & editing; **AI:** project administration, writing – review & editing; **ZA:** investigation, visualization; **KSB:** writing – review & editing. All authors have agreed with the results and conclusions.

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that ethical approval and informed consent were not required for this study, as it is a meta-analysis based exclusively on previously published studies and did not involve the recruitment of human participants or the collection of new personal data.

AI statement: The authors stated that, during the preparation of this work, the authors used GPT-6.1 (OpenAI) and Claude Sonnet 5.5 (Anthropic) for language editing, academic proofreading, improving the clarity and readability of the English text, and assisting with the processing and organization of information. After using these tools, the authors thoroughly reviewed, validated, and edited the content as necessary and take full responsibility for the overall content and integrity of the publication.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

REFERENCES

Abdul Hanid, M. F., 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

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

Atit, K., Power, J. R., Pigott, T., Lee, J., Geer, E. A., Uttal, D. H., Ganley, C. M., & Sorby, S. A. (2022). Examining the relations between spatial skills and mathematical performance: A meta-analysis. *Psychonomic Bulletin & Review, 29*(3), 699–720. https://doi.org/10.3758/s13423-021-02012-w

Balta, N., Fukkink, R., & Amendum, S. J. (2023). The effect of job-embedded professional development on teacher and student outcomes: A multi-level meta-analysis. *International Educational Review, 1*(1), 1–23.

Barker, T. H., Stone, J. C., Sears, K., Klugar, M., Tufanaru, C., Leonardi-Bee, J., Aromataris, E., & Munn, Z. (2023). The revised JBI critical appraisal tool for the assessment of risk of bias for randomized controlled trials. *JBI Evidence Synthesis, 21*(3), 494–506. https://doi.org/10.11124/JBIES-22-00430

Barker, T. H., Habibi, N., Aromataris, E., Stone, J. C., Leonardi-Bee, J., Sears, K., Hasanoff, S., Klugar, M., Tufanaru, C., Moola, S., & Munn, Z. (2024). The revised JBI critical appraisal tool for the assessment of risk of bias for quasi-experimental studies. *JBI Evidence Synthesis, 22*(3), 378–388. https://doi.org/10.11124/JBIES-23-00268

Beisenbayeva, G. K., Mubarakov, A. M., Seylova, Z. T., Zhadrayeva, L. U., & Artymbayeva, B. N. (2024). Evaluating the impact of an augmented reality app on geometry learning in Kazakh secondary schools. *Journal of Information Technology Education: Research, 23*, Article 22. https://doi.org/10.28945/5355

Clements, D. H., & Battista, M. T. (1992). Geometry and spatial reasoning. In D. A. Grouws (Ed.), *Handbook of research on mathematics teaching and learning* (pp. 420–464). Macmillan.

Clifton, P. G., Chang, J. S.-K., Yeboah, G., Doucette, A., Chandrasekharan, S., Nitsche, M., Welsh, T., & Mazalek, A. (2016). Design of embodied interfaces for engaging spatial cognition. *Cognitive Research: Principles and Implications, 1*, Article 24. https://doi.org/10.1186/s41235-016-0032-5

Crissey, J. (2023). *Spatial visualization of high school geometry students* [Doctoral dissertation, The University of Southern Mississippi]. Aquila Digital Community.

Davor, I., Boateng, F. O., Asare, C., & Benewaah, A. (2026). The influence of teachers' digital pedagogical content knowledge on perceived student learning outcomes in mathematics: The mediating role of instructional quality. *The European Educational Researcher, 9*(2), 39–63. https://doi.org/10.31757/euer.923

Dere, H. E., & Kalelioğlu, F. (2020). The effects of using web-based 3D design environment on spatial visualisation and mental rotation abilities of secondary school students. *Informatics in Education, 19*(3), 399–424. https://doi.org/10.15388/infedu.2020.18

DeSutter, D., & Stieff, M. (2017). Teaching students to think spatially through embodied actions: Design principles for learning environments in science, technology, engineering, and mathematics. *Cognitive Research: Principles and Implications, 2*, Article 22. https://doi.org/10.1186/s41235-016-0039-y

Fiangga, S. (2024). Interactive activities using dynamic geometry software to improve students' spatial reasoning. *Journal of Mathematics Education, 15*(1), 45–60.

Geitona, Z., Gagatsis, A., Elia, I., Deliyianni, E., & Gridos, P. (2022). How could the presentation of a geometrical task influence student creativity? *Journal of Research in Science, Mathematics and Technology Education, 5*(1), 93–116. https://doi.org/10.31756/jrsmte.514

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

Güven, B., & Kosa, T. (2008). The effect of dynamic geometry software on student mathematics teachers' spatial visualization skills. *Turkish Online Journal of Educational Technology, 7*(4), 100–107.

Harris, D., Resnick, I., Logan, T., & Lowrie, T. (2025). Pathways from spatial skills to mathematics: The roles of gender and fluid reasoning. *Developmental Science, 28*(2), Article e13602. https://doi.org/10.1111/desc.13602

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

İbili, E., Çat, M., Resnyansky, D., Şahin, S., & Billinghurst, M. (2020). An assessment of geometry teaching supported with augmented reality teaching materials to enhance students' 3D geometry thinking skills. *International Journal of Mathematical Education in Science and Technology, 51*(2), 224–246. https://doi.org/10.1080/0020739X.2019.1583382

İleri, Ç. İ., Erşan, M., Kalaça, D., Coşkun, A., Göksun, T., & Küntay, A. C. (2023). Malleability of spatial skills: Bridging developmental psychology and toy design for joyful STEAM development. *Frontiers in Psychology, 14*, Article 1137003. https://doi.org/10.3389/fpsyg.2023.1137003

Joanna Briggs Institute [JBI]. (2017a). *JBI critical appraisal checklist for quasi-experimental studies (non-randomized experimental studies).* Joanna Briggs Institute.

Joanna Briggs Institute [JBI]. (2017b). *JBI critical appraisal checklist for randomized controlled trials.* Joanna Briggs Institute.

Kaźmierczak, R., Leszek, S., & Wójtowicz, A. (2025). Augmented reality tools for mathematics and geoscience education. *Scientific Reports, 15*, Article 2090. https://doi.org/10.1038/s41598-025-02090-z

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), Article em2684. https://doi.org/10.29333/ejmste/16718

Lee-Cultura, S., & Giannakos, M. (2020). Embodied interaction and spatial skills: A systematic review of empirical studies. *Interacting with Computers, 32*(4), 331–366. https://doi.org/10.1093/iwcomp/iwaa023

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

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

Mandala, A. S., Anwar, L., Sa'dijah, C., & Zulnaidi, H. (2025). Development of mobile augmented reality-based geometry learning games to facilitate spatial reasoning. *Infinity Journal, 14*(2), 323–348. https://doi.org/10.22460/infinity.v14i2.p323-348

Mjenda, M., Mutarutinya, V., & Owiti, D. (2023). Assessing the effectiveness of computer-aided instructional techniques in enhancing students' 3D geometry spatial visualization skills among secondary school students in Tanzania. *International Journal of Learning, Teaching and Educational Research, 22*(6), 613–637. https://doi.org/10.26803/ijlter.22.6.31

Nadzeri, M. B., Musa, M., Meng, C. C., & Ismail, I. M. (2024). The effects of augmented reality geometry learning applications on spatial visualization ability for lower primary school pupils. *International Journal of Interactive Mobile Technologies, 18*(16), 104–118. https://doi.org/10.3991/ijim.v18i16.47079

Newcombe, N. S. (2017). Harnessing spatial thinking to support STEM learning. *OECD Education Working Papers* (No. 161). OECD Publishing. https://doi.org/10.1787/7d5dcae6-en

Newcombe, N. S., & Stieff, M. (2012). Six myths about spatial thinking. *International Journal of Science Education, 34*(6), 955–971. https://doi.org/10.1080/09500693.2011.588728

Ng, O.-L., Shi, L., & Ting, F. (2020). Exploring differences in primary students' geometry learning outcomes in two technology-enhanced environments: Dynamic geometry and 3D printing. *International Journal of STEM Education, 7*, Article 50. https://doi.org/10.1186/s40594-020-00244-1

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*, Article n71. https://doi.org/10.1136/bmj.n71

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

Pinilla, R. K. (2024). Defining spatial reasoning: A content analysis to explicate spatial reasoning skills for early childhood educators' use. *Journal of Research in Science, Mathematics and Technology Education, 7*(SI), 141–176. https://doi.org/10.31756/jrsmte.317SI

Putri, D. A. P., Fatmawati, A., Haryanti, Y., Maryam, Minalloh, A. N., & Wijaya, P. P. (2025). Development of an augmented reality mobile application for interactive geometry learning in children. In *2025 22nd International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)* (pp. 1–6). IEEE. https://doi.org/10.1109/ECTI-CON64996.2025.11101056

Resnick, I., Harris, D., Logan, T., & Lowrie, T. (2020). The relation between mathematics achievement and spatial reasoning. *Mathematics Education Research Journal, 32*. https://doi.org/10.1007/s13394-020-00338-7

Šafhalter, A., Glodež, S., Šorgo, A., & Ploj Virtič, M. (2022). Development of spatial thinking abilities in engineering 3D modeling course aimed at lower secondary students. *International Journal of Technology and Design Education, 32*(1), 167–184. https://doi.org/10.1007/s10798-020-09597-8

Saputra, M. P. A., Hidayana, R. A., & Azahra, A. S. (2025). Utilizing augmented reality media to enhance students' motivation and spatial thinking in 3D geometry learning. *International Journal of Ethno-Sciences and Education Research, 5*(3), 94–100.

Schoevers, E. M., Leseman, P. P. M., & Kroesbergen, E. H. (2020). Enriching mathematics education with visual arts: Effects on elementary school students' ability in geometry and visual arts. *International Journal of Science and Mathematics Education, 18*, 1613–1634. https://doi.org/10.1007/s10763-019-10018-z

Shah, S. F. A., Mazhar, T., Shahzad, T., Ghadi, Y. Y., & Hamam, H. (2024). Integrating educational theories with virtual reality: Enhancing engineering education and VR laboratories. *Social Sciences & Humanities Open, 10*, Article 101207. https://doi.org/10.1016/j.ssaho.2024.101207

Srivastava, A., Vaidya, V., Murthy, S., & Dasgupta, C. (2024). GeoSolvAR: Scaffolding spatial perspective-taking ability of middle-school students using AR-enhanced inquiry learning environment. *British Journal of Educational Technology, 55*(6), 2617–2638. https://doi.org/10.1111/bjet.13456

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

Taylor, H. A., Burte, H., & Renshaw, K. T. (2023). Connecting spatial thinking to STEM learning through visualizations. *Nature Reviews Psychology, 2*, 637–653. https://doi.org/10.1038/s44159-023-00224-6

Tufanaru, C., Munn, Z., Aromataris, E., Campbell, J., & Hopp, L. (2020). Chapter 3: Systematic reviews of effectiveness. In E. Aromataris & Z. Munn (Eds.), *JBI manual for evidence synthesis*. JBI. https://doi.org/10.46658/JBIMES-20-04

Tung, Y.-H., & Chang, C.-Y. (2024). How three-dimensional sketching environments affect spatial thinking: An fMRI study using virtual reality. *PLOS ONE, 19*(3), Article e0294451. https://doi.org/10.1371/journal.pone.0294451

Uriarte-Portillo, A., Zatarain-Cabada, R., Barrón-Estrada, M. L., Ibáñez, M. B., & González-Barrón, L. M. (2023). Intelligent augmented reality for learning geometry. *Information, 14*(4), Article 245. https://doi.org/10.3390/info14040245

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: When, why, and how. In B. H. Ross (Ed.), *Psychology of learning and motivation* (Vol. 57, pp. 147–181). Academic Press. https://doi.org/10.1016/B978-0-12-394293-7.00004-2

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

Uttal, D. H., & Newcombe, N. S. (2013). Exploring and enhancing spatial thinking: Links to achievement in science, technology, engineering, and mathematics. *Current Directions in Psychological Science, 22*(5), 367–373. https://doi.org/10.1177/0963721413484756

Walkington, C., Nathan, M. J., Hunnicutt, J., Washington, J., & Zhou, M. (2024). New kinds of embodied interactions that arise in augmented reality dynamic geometry software. *The Journal of Mathematical Behavior, 75*, Article 101175. https://doi.org/10.1016/j.jmathb.2024.101175

Wang, S.-M., Yaqin, M. A., & Lan, V. H. (2024). Enhancing spatial-reasoning perception using virtual reality immersive experience. *IEEE Transactions on Education, 67*(5), 648–659. https://doi.org/10.1109/TE.2024.3401839

Weisberg, S. M., & Newcombe, N. S. (2017). Embodied cognition and STEM learning: Overview of a topical collection in CR:PI. *Cognitive Research: Principles and Implications, 2*, Article 38. https://doi.org/10.1186/s41235-017-0071-6

Wekullo, B. J. (2026). Professional development for K–12 mathematics teachers: A systematic literature review of technology, pedagogy, and equity. *International Educational Review, 4*(1), 5–23. https://doi.org/10.58693/ier.412

Xie, F., Zhang, L., Chen, X., & Xin, Z. (2020). Is spatial ability related to mathematical ability? A meta-analysis. *Educational Psychology Review, 32*, 113–155. https://doi.org/10.1007/s10648-019-09496-y

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, 12*, 277–310. https://doi.org/10.1007/s40751-025-00187-8

Young, C. J., Levine, S. C., & Mix, K. S. (2018). The connection between spatial and mathematical ability across development. *Cognitive Processing, 19*(2), 167–186. https://doi.org/10.1007/s10339-018-0867-2

APPENDIX

Table A1. Studies included in the meta-analysis

Abdul Hanid, M. F., 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
del Cerro Velázquez, F., & Morales Méndez, G. (2021). Application in augmented reality for learning mathematical functions: A study for the development of spatial intelligence in secondary education students. *Mathematics, 9*(4), 369. https://doi.org/10.3390/math9040369
Dere, H. E., & Kalelioğlu, F. (2020). The effects of using web-based 3D design environment on spatial visualisation and mental rotation abilities of secondary school students. *Informatics in Education, 19*(3), 399–424. https://doi.org/10.15388/infedu.2020.18
İbili, E., Çat, M., Resnyansky, D., Şahin, S., & Billinghurst, M. (2020). An assessment of geometry teaching supported with augmented reality teaching materials to enhance students' 3D geometry thinking skills. *International Journal of Mathematical Education in Science and Technology, 51*(2), 224–246. https://doi.org/10.1080/0020739X.2019.1583382
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
Mandala, A. S., Anwar, L., Sa'dijah, C., & Zulnaidi, H. (2025). Development of mobile augmented reality-based geometry learning games to facilitate spatial reasoning. *Infinity Journal, 14*(2), 323–348. https://doi.org/10.22460/infinity.v14i2.p323-348
Mjenda, M., Mutarutinya, V., & Owiti, D. (2023). Assessing the effectiveness of computer-aided instructional techniques in enhancing students' 3D geometry spatial visualization skills among secondary school students in Tanzania. *International Journal of Learning, Teaching and Educational Research, 22*(6), 613–637. https://doi.org/10.26803/ijlter.22.6.31
Nadzeri, M. B., Musa, M., Meng, C. C., & Ismail, I. M. (2024). The effects of augmented reality geometry learning applications on spatial visualization ability for lower primary school pupils. *International Journal of Interactive Mobile Technologies, 18*(16), 104–118. https://doi.org/10.3991/ijim.v18i16.47079
Ng, O.-L., Shi, L., & Ting, F. (2020). Exploring differences in primary students' geometry learning outcomes in two technology-enhanced environments: Dynamic geometry and 3D printing. *International Journal of STEM Education, 7*, Article 50. https://doi.org/10.1186/s40594-020-00244-1
Šafhalter, A., Glodež, S., Šorgo, A., & Ploj Virtič, M. (2022). Development of spatial thinking abilities in engineering 3D modeling course aimed at lower secondary students. *International Journal of Technology and Design Education, 32*(1), 167–184. https://doi.org/10.1007/s10798-020-09597-8
Saputra, M. P. A., Hidayana, R. A., & Azahra, A. S. (2025). Utilizing augmented reality media to enhance students' motivation and spatial thinking in 3D geometry learning. *International Journal of Ethno-Sciences and Education Research, 5*(3), 94–100.
Schoevers, E. M., Leseman, P. P. M., & Kroesbergen, E. H. (2020). Enriching mathematics education with visual arts: Effects on elementary school students' ability in geometry and visual arts. *International Journal of Science and Mathematics Education, 18*, 1613–1634. https://doi.org/10.1007/s10763-019-10018-z
Srivastava, A., Vaidya, V., Murthy, S., & Dasgupta, C. (2024). GeoSolvAR: Scaffolding spatial perspective-taking ability of middle-school students using AR-enhanced inquiry learning environment. *British Journal of Educational Technology, 55*(6), 2617–2638. https://doi.org/10.1111/bjet.13456