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Teaching Geometry in Mathematics Education (2016-2025): A Systematic Review and Bibliometric Analysis

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Abstract. Geometry plays a central role in mathematics education, yet research on effective teaching strategies remains fragmented, particularly in integrating theoretical, cognitive and technology driven perspectives. A combination of bibliometric and systematic review methods was employed to analyse 1196 articles published between 2016 and 2025, retrieved from the Web of Science database. Data were analysed using bibliometric techniques, including co-citation analysis and network visualization with VOSviewer, alongside thematic synthesis. The findings reveal three major thematic clusters: (1) theoretical and pedagogical foundations, (2) cognitive development and spatial reasoning and (3) applied and empirical studies on early spatial learning. The findings highlight the growing integration of spatial reasoning and digital technologies in shaping effective instructional approaches, alongside the continued influence of established pedagogical frameworks. However, several research gaps remain, including limited representation from certain regions, underexplored interdisciplinary collaborations and the need for more evidence on the long-term impact of innovative teaching methods such as Artificial Intelligence, Virtual Reality and adaptive learning technologies. Theoretically, this study contributes by providing a structured understanding of the intellectual landscape of geometry teaching research. Practically, the findings offer guidance for educators and policymakers in designing more effective, evidence-based instructional strategies. Overall, this study provides a comprehensive synthesis to inform future research and practice in mathematics education.

Keywords: bibliometric analysis; systematic literature review; teaching geometry; geometry knowledge

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1. Introduction

Geometry is fast becoming a key component in mathematics education, serving as a foundation for developing spatial reasoning, logical deduction, visualization and problem-solving abilities (Crompton & Ferguson, 2024; Jones, 2012). A substantial body of research has established that its importance extends beyond mathematics classrooms as spatial reasoning is consistently linked to achievement in science, technology, engineering and mathematics (STEM) disciplines (Uttal & Cohen, 2012; Wai et al., 2009). Historically, geometry has also been regarded as a gateway to higher-order mathematical thinking, laying the groundwork for abstraction, proof and reasoning (Jablonski & Ludwig, 2023). For this reason, the quality of geometry instruction is widely acknowledged as a critical factor in preparing learners for advanced study as well as real-life applications requiring logical and visual analysis.

Research in geometry education has explored diverse approaches to strengthen students' understanding, drawing attention to the cognitive, developmental and technological dimensions of learning. Scholars have long emphasized that geometry cultivates not only visualization but also intuition, deductive reasoning, argumentation and proof, all of which are essential for knowledge advancement in STEM fields (Liu et al., 2025). From a cognitive perspective, studies demonstrate that working memory and visual spatial ability significantly affect learners' capacity to solve geometric problems, especially when reasoning about abstract relationships or manipulating spatial configurations (Cragg et al., 2017; Rivella et al., 2024). Despite these insights, many students continue to struggle with visualization, proportional reasoning and the transfer of acquired skills to new contexts (Barut & Retnawati, 2020; Dooren, 2014). Such persistent difficulties underscore the importance of instructional designs that scaffold both conceptual understanding and cognitive processes.

Parallel to these cognitive perspectives, technological innovations have reshaped the landscape of geometry instruction. Tools such as dynamic geometry software (DGS), augmented reality (AR) and immersive virtual environments offer new opportunities for interactive visualization and engagement (Bujak et al., 2013; Ibáñez & Delgado-Kloos, 2018). Evidence suggests that these technologies can deepen conceptual understanding, improve retention and enhance learners' motivation, especially when carefully aligned with developmental needs (Arvanitaki & Zaranis, 2020; Demetriou et al., 2020)).

Furthermore, technology has the potential to reduce cognitive overload by presenting complex geometric concepts in more manageable visual formats (Surbakti et al., 2024) . However, challenges remain. Many teachers face difficulties in adapting traditional lessons into technology-enhanced environments, often due to limited training, resources or confidence in using digital tools effectively (Mayantao & Tantiado, 2024). These barriers highlight the need for ongoing professional development and equitable access to technological infrastructure to fully realize the promise of digital geometry instruction.

At the same time, emerging innovations are pushing the boundaries of how geometry is conceptualized and taught. Advances in artificial intelligence are now supporting mathematical discovery by identifying patterns, generating conjectures and facilitating adaptive learning experiences (Davies et al., 2021). Similarly, the integration of embodied learning and computational thinking has provided multidimensional frameworks for engaging learners in ways that connect abstract concepts with concrete and sensory experiences (Angeli & Valanides, 2020; Città et al., 2019). These frontiers expand the possibilities of geometry education, yet their adoption across diverse contexts is uneven and often shaped by educational policy, socio-cultural environments and resource allocation.

Despite these advances, several important gaps remain in the literature. Given the growing complexity of this field, a comprehensive synthesis of global research remains essential. Existing studies, while valuable, are often fragmented by region, school level or specific instructional strategies, making it difficult to identify consistent patterns and research priorities. Areas such as equitable access to digital resources, culturally responsive pedagogy and personalized learning progressions remain insufficiently addressed (Chigeza & Halbert, 2014; Ndlovu & Mji, 2012). While previous review studies have examined specific aspects of geometry education, such as cognitive development, spatial reasoning or technology integration, they tend to focus on isolated dimensions rather than providing an integrated, global perspective of the field. In addition, limited studies have combined bibliometric analysis with systematic review to map both the intellectual structure and thematic development of teaching geometry research over time.

This integrated approach provides a more comprehensive understanding of the field. The systematic review provides depth by synthesizing theoretical and pedagogical insights, while the bibliometric analysis offers breadth by quantifying global publication trends, research networks and thematic developments (Aria & Cuccurullo, 2017; Donthu et al., 2021). By focusing on a decade of research (2016–2025), this study captures recent developments shaped by technological advancements and evolving pedagogical practices, offering a timely and globally relevant contribution. By integrating these perspectives, the study situates geometry education within ongoing technological and pedagogical innovations, while also addressing persistent challenges related to cognition, access and equity. In doing so, it not only identifies influential contributions and emerging priorities but also provides critical insights to guide future research and practice in the teaching and learning of geometry.

2. International Evidence on Teaching Geometry

Research on geometry education reflects diverse global contexts, highlighting how cultural, curricular and technological differences shape teaching practices. In high-income countries such as the United States, Canada and several European nations, there has been a strong emphasis on technology-enhanced and inquiry-based approaches. Meanwhile, East Asian education systems such as those in Japan, South Korea and Singapore strike a balance between visual reasoning and procedural fluency, often structured through the concrete–pictorial–abstract progression (Shafiee & Meng, 2023; Takayama, 2017). In contrast, low- and middle-income regions face infrastructural limitations that restrict the integration of advanced technologies, despite growing interest in innovative, low-cost interventions (Aderibigbe et al., 2023). These comparisons highlight the uneven but evolving landscape of geometry teaching worldwide.

Technological tools have been at the heart of recent advances, especially Dynamic Geometry Software (DGS) such as GeoGebra, which has become widely adopted to promote visualization, exploration and problem-solving. Systematic reviews indicate that its impact is most effective when paired with inquiry-based or collaborative pedagogies, suggesting that technology alone is insufficient without meaningful instructional design (Abuhassna et al., 2024; Sam, 2024). Building on these developments, AR has recently emerged as a promising frontier in geometry education, allowing learners to manipulate three-dimensional objects within authentic contexts. Evidence across educational levels shows that AR enhances spatial reasoning, engagement and conceptual understanding, although its long-term effectiveness depends on embedding the technology within well-structured pedagogical frameworks (Fowler et al., 2022; Chaudhari et al., 2025).

Beyond technology, spatial reasoning itself has gained international recognition as a key predictor of geometry achievement and overall mathematical proficiency. Interventions in countries such as Australia, Canada and Singapore demonstrate that structured training in skills like mental rotation, isometric drawing and spatial visualization supports both immediate learning and transfer to broader mathematical domains (Lowrie & Logan, 2023; Zhu et al., 2023). These findings are further reinforced by large-scale international assessments such as TIMSS and PISA, which consistently show that education systems that prioritizing visualization, reasoning and problem-solving outperform those relying heavily on rote memorization (IEA, 2020; OECD, 2019). Taken together, this body of research suggests that future directions in geometry education will likely depend on combining technological innovation with systematic development of spatial reasoning, ensuring both conceptual depth and long-term mathematical readiness.

In summary, international evidence on geometry education highlights a shared recognition that both technological innovation and cognitive skill development are essential for meaningful learning. While tools such as GeoGebra and Augmented Reality offer powerful means to enhance visualization and engagement, their effectiveness relies on being embedded within sound pedagogical frameworks that emphasize inquiry and collaboration. At the same time, strengthening spatial reasoning skills remains fundamental, not only for immediate success in geometry but also for long-term readiness in mathematics and STEM. Future work may focus on integrating digital tools with spatial reasoning training to advance twenty-first century learning (Choudhary et al., 2025; Lowrie & Logan, 2023; OECD, 2019).

3. Objectives of the Study

The primary objective of this study is to explore the current landscape of studies focusing on teaching geometry. The outlined questions will help defining the extent of this exploration:

RQ1: What patterns and developments can be observed in teaching geometry research publications when analyzed by publication year, leading authors and most productive affiliations?

RQ2: How are publications on teaching geometry strategies distributed across different countries and research domains?

RQ3: What do the patterns of keyword co-occurrence, co-citation networks and thematic cluster analysis reveal about emerging trends in research on teaching geometry?

Importantly, this study addresses a clear methodological and conceptual gap in the literature, namely the lack of integrated analyses that combine bibliometric mapping with systematic review to provide a holistic understanding of teaching geometry research. In addition, there remains a practical gap in translating emerging insights especially in spatial reasoning and digital technologies into coherent instructional strategies.

4. Methodology

4.1 Data Collection Methodology and Search Strategy

This study employs a combination of systematic review and bibliometric analysis to examine research trends in the teaching of geometry. Data were retrieved from the Web of Science Core Collection databases, focusing on articles published between 2016 and 2025. The Web of Science was selected due to its rigorous indexing standards, comprehensive coverage of high-impact journals in education and STEM fields and widespread acceptance as a reliable source for bibliometric research.

The time frame of 2016 to 2025 was chosen to capture contemporary developments in geometry education, especially the emergence of digital learning technologies and renewed emphasis on spatial reasoning within mathematics curricula. Keywords related to geometry education were used to retrieve relevant publications. Inclusion criteria encompassed peer-reviewed journal articles, conference papers and reviews. In conducting bibliometric research, several scholars and reviewers advocate for the use of multiple databases, such as WoS and Scopus, to ensure comprehensive coverage of the literature.

However, this strategy is not without limitations. Combining multiple databases often results in overlapping or duplicate records, which can complicate the data cleaning process and potentially compromise the reliability of the findings (Lim et al., 2024). Moreover, a significant proportion of journals are co-indexed in both Scopus and WoS, particularly within established research domains, suggesting that using multiple databases may add limited value. To preserve the data integrity, minimize redundancy and streamline the analysis process, this study relies exclusively on the WoS database as a single and comprehensive source for bibliometric data.

To ensure methodological rigor, a quality appraisal process was applied through clearly defined inclusion and exclusion criteria. Articles were systematically screened based on publication type, time frame, language, subject relevance and educational context. Abstracts were first reviewed, followed by full-text screening where necessary to confirm relevance. Only studies directly addressing teaching geometry, including instructional strategies, conceptual understanding and intervention outcomes were retained. This process ensured the inclusion of high-quality and relevant studies for subsequent bibliometric and content analysis. Inclusion and exclusion criteria were systematically applied to ensure the relevance and quality of selected studies as seen in Table 1.

Table 1: Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Publication type	Peer-reviewed journal articles, conference papers, review articles	Books, book chapters, theses, editorials, non-peer-reviewed sources
Time frame	Published between 2016 and 2025	Published before 2016
Language	English	Non-English publications
Subject focus	Studies related to teaching geometry, including concepts, instructional strategies and learning outcomes	Studies not related to geometry teaching (e.g., pure mathematics, unrelated STEM topics)
Educational context	Studies within mathematics education (including primary, elementary and related levels)	Studies outside educational context or not focused on teaching/learning
Relevance	Empirical or review studies addressing geometry teaching or interventions	Studies lacking clear relevance to teaching geometry

The search covered the period from 2016 to 2025, and the data were analyzed accordingly. Search string of suitable keywords ("geometry" OR "geometric" OR "shape" OR "spatial") AND ("teaching" OR "instruction" OR "education" OR "pedagogy") AND ("primary school" OR "elementary school" OR "grade school" OR "early education") was used. The initial search across titles, abstracts or keywords generated 1,196 results. This number was narrowed down to 862 after filtering articles published within 10 years from 2016 to 2025.

Then, the search was further narrowed to the elimination based on English language, limiting the records to 602 papers. The remaining articles were screened by reading the abstracts and in cases where there was uncertainty about relevance, full papers were reviewed. To ensure only relevant articles were included, the final section focused on those discussing teaching geometry (concepts, strategies and outcomes) and interventions aimed at improving teaching geometry. Following the elimination based on these, the final dataset consisted of 436 papers, which were included in the bibliometric analysis to identify publication trends, influential authors and thematic structures. From this dataset, a subset of 30 articles was purposefully selected for in-depth content analysis. These articles were identified based on their prominence within co-citation clusters, representing key themes and influential works in the field. The entire process of data extraction is illustrated in Figure 1.

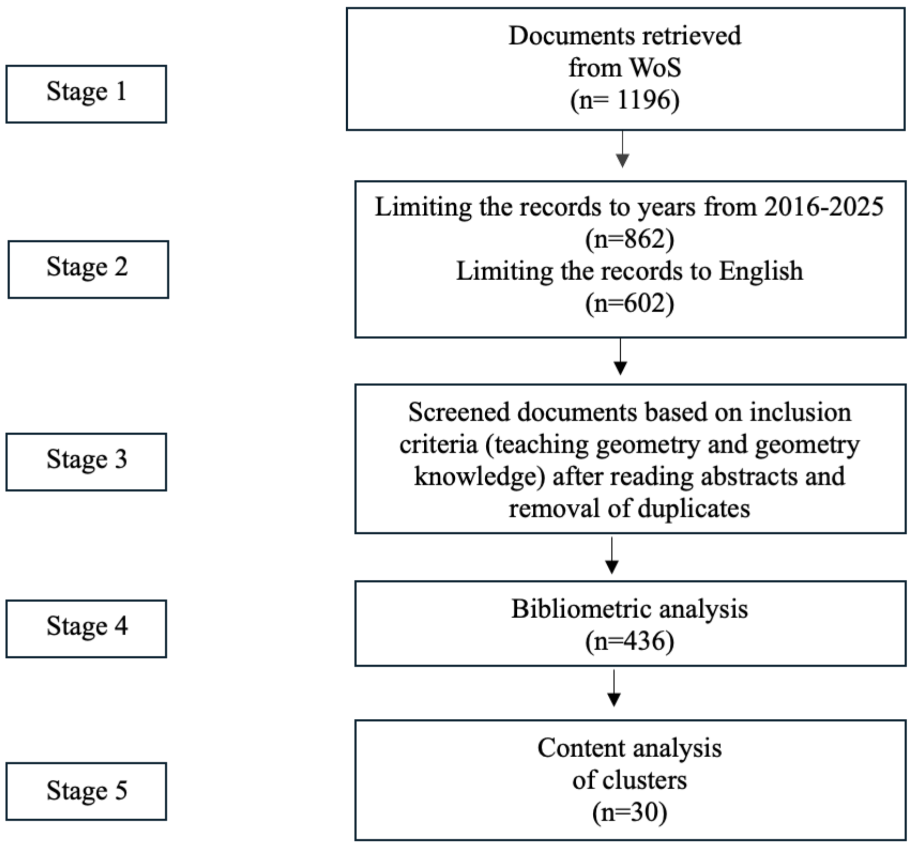

Figure 1: Data extraction process (Ismail et al., 2024)

5. Data Analysis

This study employs an integrated methodological framework that combines bibliometric analysis with a systematic review to examine the evolution of geometry education research over the past decade. The collected data were analyzed using both quantitative bibliometric techniques and qualitative thematic analysis. Bibliometric analysis was conducted using specialized software, VOSviewer to systematically map publication trends, visualize co-citation networks and analyze keyword co-occurrence patterns and content structures within the field. These techniques enabled the identification of research clusters, influential publications and thematic relationships across the dataset. This quantitative mapping is complemented by a systematic review, which provides qualitative insights into thematic developments and research path.

As highlighted in previous methodological literature, systematic reviews can take multiple forms ranging from narrative reviews that apply theoretical frameworks to propose future research directions (Migliavaca et al., 2020), scoping reviews that chart key concepts and evidence types (Munn et al., 2022), meta-analyses synthesizing statistical outcomes (Knoll & Matthes, 2017), bibliometric reviews that map scholarly landscapes (Donthu et al., 2021) to umbrella reviews that consolidate evidence on broad research questions (Nayak et al., 2025).

This study employs a combined bibliometric and systematic literature review (SLR) design, a methodology that enables both macro-level mapping of the research landscape and micro-level thematic interpretation. This dual approach is well-suited for comprehensive field analysis and has been effectively implemented in prior studies (Ang et al., 2025; Sengodan et al., 2025). Bibliometric techniques are widely recognized for their capacity to represent the intellectual structure of academic fields (Ismail et al., 2025) and to identify emerging thematic clusters (Blanco-Mesa et al., 2017). Systematic reviews, on the other hand, are crucial for synthesizing accumulated knowledge, minimizing bias (Tranfield et al., 2003) and identifying underexplored areas that warrant further investigation (Talan & Sharma, 2019).

In this study, bibliometric analysis is first applied to investigate structural and thematic patterns across the literature, followed by content analysis to explore dominant research themes in depth (Baker et al., 2020). While the primary dataset was restricted to publications between 2016 and 2025, the co-citation analysis inherently incorporates earlier studies that are cited within these documents. As a result, the temporal span of the co-citation network extends beyond the defined study period. This allows the identification of foundational and highly influential works that continue to shape current research in geometry education. Consequently, some clusters include publications dating back to earlier years, such as 1971, reflecting the historical development of the field rather than inconsistencies in data selection.

Specifically, co-citation analysis was used to examine relationships between frequently cited documents, while keyword co-occurrence analysis was applied to identify dominant research topics and emerging trends. Following the methodological principles outlined by Boyack & Klavans (2010), co-citation and content analyses are employed to examine the interconnections between scholarly documents, thereby uncovering the intellectual structure of the field. Building upon this foundation, the analysis investigates publication trends, citation networks, co-citation clusters, keyword co-occurrence patterns and both local and global citation impacts. This is complemented by a qualitative thematic interpretation, consistent with the recommendations of Donthu et al. (2021) and methodological frameworks in bibliometric research (Aria & Cuccurullo, 2017; Zupic & Čater, 2015).

The bibliometric mapping was carried out using VOSviewer, which applies the "visualization of similarities" (VOS) technique to generate spatial maps that position items according to their relational strength (van Eck & Waltman, 2010).

Its sturdy clustering algorithms and intuitive visualization features make it specifically effective for conducting co-citation and keyword analyses (Perianes-Rodriguez et al., 2016). The qualitative content analysis was conducted using a thematic approach, where recurring patterns across selected studies were identified, categorized and interpreted. A total of 436 articles were included in the bibliometric analysis, providing a comprehensive overview of the research landscape on geometry education during the studied period.

5.1 Findings

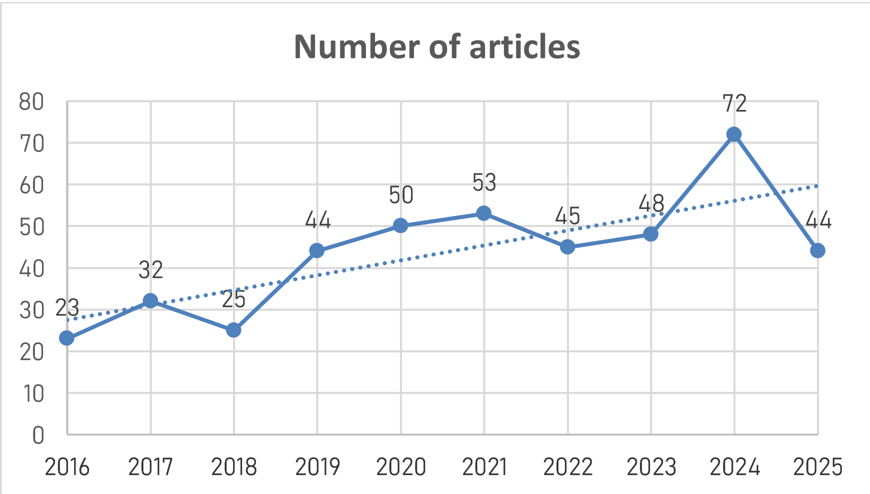

Figure 2: Yearly distributions trends for publishing 436 articles from 2016 through 2025 (Source: Author's own elaboration)

5.2 Publication Trends and Development of Teaching Geometry (RQ1)

To address Research Question 1, this section examines the publication trends and development of research on teaching geometry from 2016 to 2025. Figure 2 shows the yearly trend of publication on teaching geometry from 2016 to 2025. Overall, the number of studies has steadily increased over the past ten years, with only small changes in some years. The number of publications grew from 23 in 2016 to a peak of 72 in 2024, reflecting a significant rise in scholarly engagement with this topic.

The early phase from 2016 to 2018 showed modest growth followed by a dip, potentially due to shifting research agendas or limited international collaboration. However, from 2019 onwards, the trend accelerated with notable increases in 2020 and 2024. This surge may be attributed to the global emphasis on innovative pedagogies and technology-enhanced learning, mainly in response to challenges posed by the COVID-19 pandemic which prompted greater exploration of digital tools for geometry instruction (Cahyono & Ludwig, 2019; Lai & Bower, 2020).

The decline to 44 articles in 2025 is likely due to incomplete database indexing for the current year rather than a true decrease in scholarly interest. The dotted trendline in Figure 2 confirms a positive long-term progression which indicating that geometry education remains a vibrant research domain. These findings align with bibliometric observations in other STEM education fields where technological integration and competency-based learning continue to drive research momentum (Talan & Sharma, 2019). In fact, recent bibliometric studies of STEM fields show consistent growth and diversification, especially in how new tools, data-driven pedagogy and cross-disciplinary themes become focal points (Abdi et al., 2024; Khalil et al., 2024). Thus, the observed decline in 2025 is probably because of some papers have not been fully indexed, not because the interest in geometry has been decreased.

5.2.1 Distribution of Publications, Authors and Research Landscape (RQ2)
To address Research Question 2, this section presents the distribution of publications, key contributors, research areas and geographical trends in teaching geometry research.

Table 2: Leading Authors and Affiliations

Leading Authors	Numbers of Publications	Top Affiliations	Numbers of Publications
Ayub, Ahmad Fauzi Mohd	3	Beijing Normal University	8
Davis, Brent	3	University of London	8
Farran, Emily K.	3	University of California System	7
Hwang, Wu-Yuin	3	University of North Carolina	7
Lavicza, Zsolt	3	University of Belgrade	6
Lennon-Maslin Michelle	3	Utrecht University	6
Liu, Jia	3	Autonomous University of Madrid	5
Mulligan, Joanne	3	State University System of Florida	5
Andersson, Johanna	2	University of Melbourne	5

Table 2 presents the most active authors and institutional affiliations contributing to research on teaching geometry. Several scholars emerge as key contributors to the field, with Ayub Ahmad Fauzi Mohd, Davis Brent, Farran Emily K., Hwang Wu-Yuin, Lavicza Zsolt, Lennon-Maslin Michelle, Liu Jia and Mulligan Joanne each authoring three publications. Their consistent output reflects sustained engagement with research themes related to teaching geometry, highlighting their influence in shaping the discourse and advancing the field. Additionally, Anderson Johanna has contributed two publications, further enriching the breadth of scholarship in this area.

Institutional analysis reveals the leading research hubs in teaching geometry. Beijing Normal University and the University of London each recorded eight publications, positioning them as central institutions driving research activity in this domain. The University of California System and the University of North Carolina follow closely with seven publications each, demonstrating strong institutional investment in geometry education. Other notable contributors include the University of Belgrade and Utrecht University with six publications each, as well as the Autonomous University of Madrid, State University System of Florida and the University of Melbourne, each with five publications. This distribution underscores a diverse yet concentrated network of research activity with significant contributions stemming from both individual universities and larger university systems. This concentration of contributions within specific institutions suggests that research in teaching geometry is influenced by established academic networks and research capacity. This may limit the diversity of pedagogical perspectives and highlights the need for broader international collaboration to ensure more contextually responsive teaching practices.

5.2.2 Publication by Academic Landscape

Figure 3: Primary research areas in teaching geometry across 436 papers

Figure 3 illustrates the research areas contributing to the 436 publications on teaching geometry. The distribution highlights the interdisciplinary nature of this field, showing how different domains support the advancement of teaching in geometry. The largest share comes from Education and Educational Research with 330 publications, which clearly demonstrate that most studies are directed towards improving classroom practices, instructional methods, curriculum design, teacher training and the integration of digital tools in mathematics education (Jablonski & Ludwig, 2023).

Psychology ranks second with 77 publications, emphasizing the importance of cognitive, developmental and motivational factors in teaching geometry. Following this, Computer Science accounts for 23 publications, reflecting the rising role of technology such as dynamic geometry environments, artificial intelligence and digital platforms in supporting geometry instruction. Smaller yet notable contributions come from fields such as Social Sciences with 20 contributions and Engineering with 14 contributions. Moving to Linguistics with 13 contributions and Mathematics with 12 contributions. These indicate cross-disciplinary perspectives where geometry research intersects with problem-solving approaches, spatial language, engineering simulations and mathematical reasoning. Additional fields of research areas such as Rehabilitation and

Telecommunications with number of five contributions and Life Sciences with 4 contributions suggest niche applications such as in special education and accessibility or visualization technologies.

While education and psychology remain the predominant domains within the teaching geometry research landscape, the active participation of fields such as computer science, engineering, linguistics and the social sciences indicates that teaching geometry extends beyond pedagogical concerns. It increasingly intersects with technological innovation, cognitive science and applied research, reflecting a broader interdisciplinary shift. This convergence offers a stronger foundation for addressing persistent challenges in geometry teaching and fosters opportunities for the development of innovative, technology-enhanced and learner-centered instructional approaches (Almubarak et al., 2025; van den Heuvel-Panhuizen & Elia, 2012).

5.3 Global scale of distributions of teaching geometry in different countries

Table 3: Teaching geometry contributions based on countries

Countries	Contributions
USA	86
Germany	34
Australia	31
China	25
Spain	23
England	21
Canada	17
Italy	16
Netherlands	16
Taiwan	14

Table 3 presents the leading countries contributing to research on teaching geometry. The United States leads the field with 86 publications, reflecting its strong research infrastructure, sustained investment in STEM education and emphasis on developing innovative pedagogical approaches. This dominance also indicates active collaboration between universities and educational research centres in advancing geometry teaching practices.

Next is Germany, ranks second with 34 publications and Australia with 31 publications have vibrant research communities that actively contribute to both theoretical and classroom-based development in geometry teaching. European countries such as Spain with 23 publications, England with 21, showing same numbers of publications from Italy and the Netherlands with 16 publications also show significant engagement, highlighting Europe’s collective role in promoting technological integration and learner-centered methods in teaching geometry.

In Asia, China with 25 publications and Taiwan with 14 publications are emerging as notable contributors, reflecting their increasing involvement in international research collaborations and their focus on embedding digital tools and visualization techniques in mathematics instruction. Canada with 17 publications further reinforces North America's strong representation in the global research landscape.

Figure 4 illustrates a geographically diverse research landscape, reflecting how the study of teaching geometry has expanded beyond traditional academic hubs. While Western countries remain at the forefront, especially the USA that shown in dark purple along with several European countries, there is a clear rise in contributions from Asian countries, indicating active involvement in advancing teaching geometry. This uneven distribution suggests that access to research funding and technological infrastructure significantly influences knowledge production in geometry education. Consequently, teaching practices in underrepresented regions may not fully benefit from current research advancements, reinforcing the need for more inclusive global research efforts.

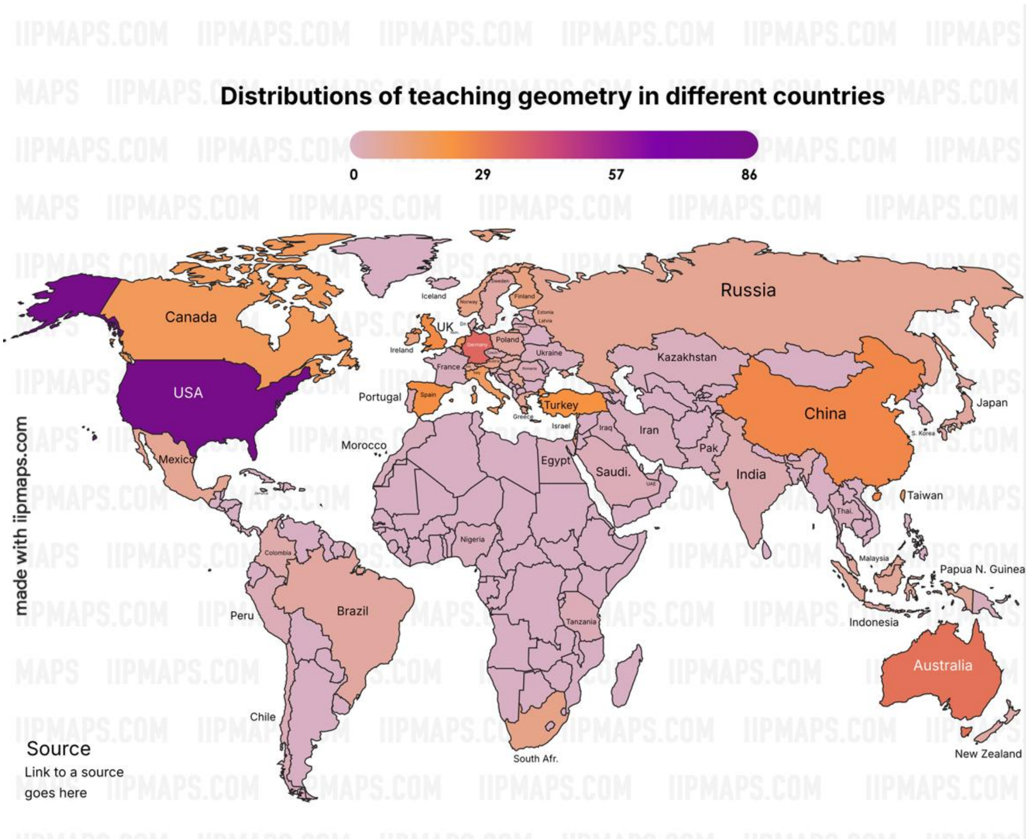

Figure 4: Distributions of teaching geometry in different countries

5.4 Thematic Structure and Emerging Research Trends (RQ3)

To address Research Question 3, this section analyzes keyword co-occurrence patterns, co-citation networks and thematic clusters to identify emerging research trends in teaching geometry.

Table 4: Keyword occurrences

Keywords	Occurrences
mathematics	157
primary school	67
children	48
geometry	42
students	38
teachers	37
knowledge	33
preschool	32
performance	31
skills	29

Table 4 provides keyword analysis that reveals the central themes and research focus areas across the dataset. The most frequent keyword is mathematics with 157 occurrences, indicating that most of the studies are broadly situated within the field of mathematics education. This confirms that the research primarily investigates mathematical learning processes and pedagogical strategies. The second most common keyword, primary school with 67 occurrences, suggests that a large proportion of the research is concentrated on the elementary level, where foundational mathematical and spatial concepts are developed. Closely related are the keyword children with 48 occurrences, emphasizing the importance of early learning stages and the introduction of geometry to young learners.

Geometry appears 42 times, positioning it as a central theme but not the sole focus, suggesting that geometry is often studied in connection with broader aspects of mathematics learning. The keywords students with 38 occurrences and teachers with 37 occurrences reflect the dual focus of research which are understanding how learners acquire knowledge and how educators design and deliver instruction. Meanwhile, knowledge with 33 occurrences underscores the attention given to conceptual understanding and the role of teacher or student knowledge in learning outcomes. The appearance of preschool with 32 occurrences highlights the growing recognition of introducing spatial reasoning and geometry concepts at very early stages of education.

Next, keywords such as performance with 31 occurrences and skills with 29 occurrences indicate a strong research interest in measuring outcomes, both in terms of students' achievement and the development of cognitive and spatial skills. These suggest that beyond teaching methods, researchers are also concerned with evaluating the effectiveness of instructional practices in geometry education. The strong emphasis on early education and performance-related keywords suggests that current research prioritizes foundational learning and measurable outcomes. This may influence teaching practices to focus more on skill acquisition and assessment, potentially at the expense of deeper conceptual exploration if not carefully balanced.

5.5 Co-Citation Analysis

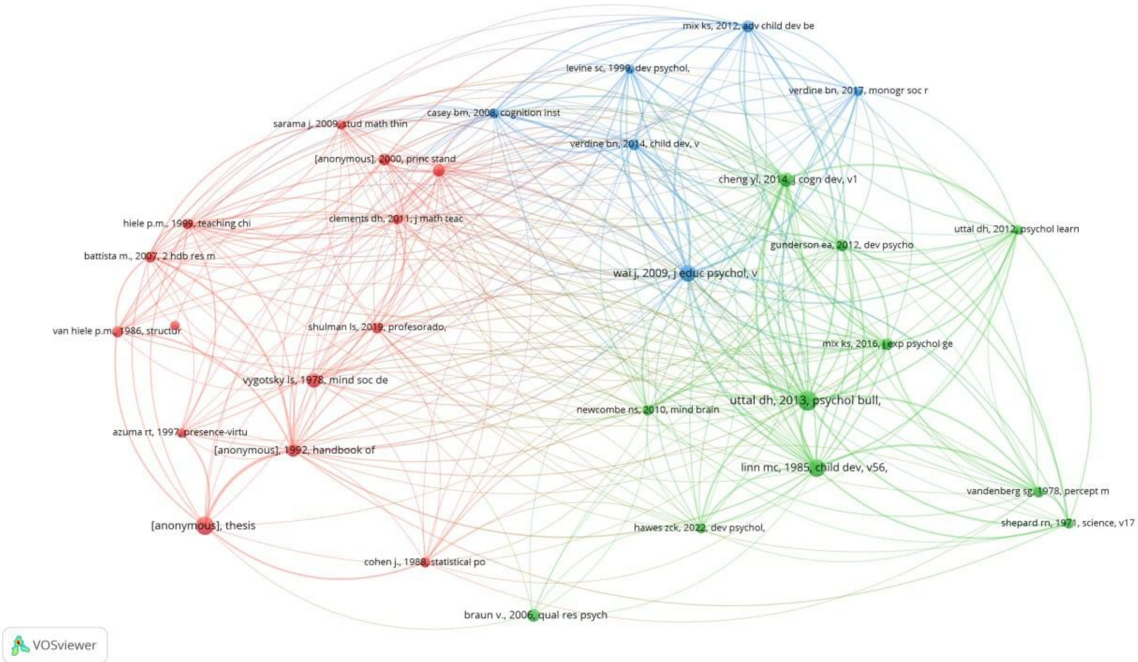

Figure 5: Co-citation network analysis on teaching geometry research (created using Vosviewer, with a minimum citation threshold of 10)

According to Garfield et al. (2017) and van Eck and Waltman (2010), a co-citation network enables the organization of articles into clusters based on the intensity of their interconnectedness, where stronger linkages are typically observed within clusters rather than between them. Articles that fall within the same cluster tend to share common themes and exhibit closer intellectual relationships compared to those in other clusters. Co-citation analysis examines how frequently pairs of documents are cited together within the scholarly literature, allowing the identification of intellectual linkages and influential works that shape the field.

By mapping these co-citation patterns, clusters of related studies emerge, revealing underlying research traditions, theoretical foundations and evolving scholarly conversations. This clustering approach provides a systematic means of identifying thematic groupings and intellectual structures within the co-citation network (Mora et al., 2019). The co-citation analysis visualized through VOSviewer revealed that the emergence of three distinct yet interconnected clusters, each representing a core dimension within the research landscape of geometry teaching from 2016 to 2025.

Cluster 1, comprising 13 documents, encapsulates works that establish the theoretical and pedagogical foundations of geometry instruction. This cluster is characterized by seminal contributions on mathematical thinking models, pedagogical content knowledge and sociocultural approaches to learning, all of which collectively frame the conceptual and instructional bases of geometry education. Cluster 2, consisting of 11 documents, centers on cognitive development and spatial reasoning, gathering studies that examine the psychological and developmental processes underpinning spatial ability and its role in supporting learners' understanding of geometric concepts.

Cluster 3, contains 6 documents, encompasses applied and empirical studies on early spatial learning, with a particular emphasis on research exploring instructional interventions, experimental designs and technology integration aimed at enhancing spatial reasoning in early geometry education. It should be clarified that the cluster analysis in Table 5 is based on co-cited references from the selected articles published between 2016 and 2025. The documents in the clusters are not limited to the reviewed articles but include influential works cited by them. This is a common approach in co-citation analysis, which aims to identify the key theoretical foundations of a research field.

Table 5: Leading articles in each cluster based on total link strength

Cluster 1 (Theoretical and Pedagogical Foundations)	Cluster 2 (Cognitive Development and Spatial Reasoning)	Cluster 3 (Applied and Empirical Studies on Early Spatial Learning)
Handbook of Research on Mathematics Teaching (1992)	Braun (2006)	Casey et al. (2008)
NCTM (2000)	Cheng & Mix (2014)	Levine et al. (1999)
Azuma (1997)	Gunderson et al. (2012)	Mix (2012)
Battista (2007)	Hawes et al. (2022)	Verdine et al. (2014)
Clements (2011)	Lin & Petersen (1985)	Verdine et al. (2017)
Cohen (1988)	Mix (2016)	Wai et al. (2009)
Duncan et al. (2007)	Newcombe & Frick (2010)	
Van Hiele (1999)	Shepard & Metzler (1971)	
Miles & Huberman (1994)	Uttal et al. (2012)	
Sarama & Clements (2009)	Uttal et al. (2013)	
Shulman (2019)	Vanderberg & Kuse (1978)	
Van Hiele (1986)		
Vygotsky (1978)		

Building on the co-citation analysis, the following content analysis further explores the thematic dimensions identified in RQ3.

5.6 Content Analysis

Following the co-citation analysis, an in-depth review of 30 selected articles was conducted and categorized into three groups. The detailed examination of each group highlighted a prevailing theme emerging within them. In parallel, content analysis is used to qualitatively and thematically examine the focus of the selected studies, capturing the key pedagogical themes, instructional strategies and conceptual frameworks that characterize current research.

5.6.1 Cluster 1: Theoretical and Pedagogical Foundations

This cluster encapsulates the seminal theories and pedagogical frameworks that form the foundation of mathematics education, particularly in the teaching and learning of geometry and spatial reasoning. The works collectively illustrate the evolution of thought from cognitive developmental theories to instructional standards and teacher knowledge frameworks.

Early cognitive and sociocultural theories such as Vygotsky (1980) and Van Hiele (1986) established the conceptual underpinnings for understanding how learners progress through levels of mathematical and geometric thinking. Vygotsky's sociocultural theory foregrounded the role of social interaction and mediated learning in cognitive development, while Van Hiele's five hierarchical levels which are visualization, analysis, abstraction, formal deduction and rigor that outlined how learners' geometric reasoning matures through structured instruction and language development. Later, Van Hiele (1999) extended these ideas by emphasizing the role of play and hands-on activities such as mosaics and tangrams in developing geometric thinking among children.

Building on this foundation, the pedagogical implications of these theories are further elaborated in Battista (2007) who refined and contextualized the Van Hiele model, highlighting the importance of instructional strategies that nurture both geometric and spatial reasoning. Similarly, documents from Clements and Sarama (2009, 2011) focused on early childhood mathematics education, demonstrating how young learners construct spatial understanding through creative, play-based and hands-on exploration. Their research underscores that well-designed professional development and learning trajectories can transform teachers' beliefs and practices, enhancing early geometry learning outcomes.

Extending beyond classroom-level implementation, the NCTM (2000) provided a broad policy framework, outlining a national vision for excellence in mathematics education. It emphasized teacher preparation, systematic assessment and shared responsibility among educational stakeholders to ensure equitable learning opportunities for all students. Complementing this, Grouws (1992) consolidated empirical and theoretical insights for mathematics education researchers, establishing the discipline's scholarly foundation. In parallel and enriching this discourse, theoretical discussions on teacher knowledge are advanced through Shulman (2019), whose conceptualization of pedagogical content knowledge (PCK) explains how teachers integrate content expertise with pedagogical reasoning. This construct bridges theory and practice, informing how teachers design and enact instruction that aligns with learners' cognitive development.

In a similar vein, Cohen (1988) contributes methodological rigor to educational research through his foundational work on statistical power analysis, influencing the design and interpretation of quantitative studies in mathematics education.
Further linking theory to developmental outcomes, Duncan et al. (2007) provide longitudinal evidence showing that early mathematical and attentional skills are strong predictors of later academic achievement, underscoring the long-term

significance of early geometry and spatial learning. Finally, Azuma (1997) offers a technological dimension by reviewing frameworks and tools for developing educational applications using augmented reality setting the stage for future pedagogical innovation that bridges foundational learning theories with digital implementation.

5.6.2 Cluster 2: Cognitive Development and Spatial Reasoning

This cluster brings together foundational, experimental and meta-analytic works that collectively trace the development, structure and trainability of spatial reasoning and its relationship to mathematical cognition. The studies show that spatial thinking is not only central to early cognitive development but also functions as a crucial predictor and enhancer of mathematical and STEM-related achievement. Early experimental research by Shepard and Metzler (1971) established the concept of mental rotation, demonstrating that the time required to recognize two objects as identical is linearly related to the angular disparity between them. This discovery laid the groundwork for understanding spatial visualization as one of measurable cognitive process.

Building on this, Vandenberg and Kuse (1978) developed a group-based paper-and-pencil test for assessing three-dimensional spatial visualization, validating its reliability and identifying consistent sex differences, thereby extending spatial cognition research into scalable educational and psychometric applications. Whereas this work focused on psychometric instrument development, Linn and Petersen (1985) conducted a meta-analysis on sex differences in spatial ability, concluding that significant disparities appear primarily in mental rotation tasks and can be detected across the lifespan. These findings contextualized the study of spatial cognition within developmental and gender-based frameworks, later motivating research into the malleability of such abilities.

In refining the conceptual understanding of spatial growth, Newcombe and Frick (2010) emphasized the developmental trajectory of spatial intelligence from infancy to early schooling, noting both its evolutionary significance and its educational implications. She argued that spatial thinking develops through everyday play and experience and that intentional early interventions could enhance these abilities while reducing gender and socioeconomic gaps. Similarly, Gunderson et al. (2012) revealed that spatial skills specifically mental transformation, predict children's understanding of the linear number line, which in turn mediates their later numerical reasoning. This longitudinal evidence situates spatial cognition as a cognitive bridge linking perceptual understanding to abstract mathematical concepts.

In response, empirical work has increasingly focused on intervention-based approaches, with several studies examining the causal relationship between spatial training and mathematical achievement. Cheng and Mix (2014) demonstrated that even a single session of mental rotation training can significantly improve young children's calculation skills, particularly in tasks requiring relational reasoning. Hawes et al. (2022) identified moderating variables such as age, use of manipulatives and the proximity of transfer tasks, emphasizing that concrete, hands-on spatial training is most effective in fostering mathematical understanding.

Reinforcing these conclusions, complementary meta-analytic evidence from Uttal et al. (2013) further confirmed that training effects generalize to untrained spatial tasks and persist over time, suggesting enduring cognitive change. A typology was introduced that differentiates between intrinsic and extrinsic as well as static and dynamic spatial skills, emphasizing the importance of adopting instructional approaches tailored to these distinct dimensions of spatial reasoning. In a related synthesis, Uttal and Uttal and Cohen (2012) explored when and why spatial skills influence STEM success, proposing that they act as gateways to participation in these fields. They argued that spatial training could reduce early barriers to STEM learning, particularly for novices whose limited visualization capacities hinder conceptual understanding.

Moving from intervention to cognitive structure, cross-sectional and developmental insights from Mix et al. (2016) offered a nuanced view of the structural relationship between space and mathematics. Their analyses revealed that spatial and mathematical abilities, though distinct, are highly correlated across childhood, with specific cognitive components such as mental rotation and visual-spatial working memory, predicting mathematical performance at different ages. This supports the idea of domain-specific development with dynamic cross-domain interaction.

Broadening the analytical toolkit for exploring these patterns, Braun and Clarke (2006) provided a qualitative analytic lens through thematic analysis, emphasizing theoretical flexibility and rigor in identifying cognitive and behavioral patterns within complex psychological data. This contribution complements the empirical studies by offering a solid interpretive framework for analyzing developmental trajectories and cognitive mechanisms in spatial reasoning research.

5.6.3 Cluster 3: Applied and Empirical Studies on Early Spatial Learning

A key theme in this cluster is the effectiveness of early, experience-based spatial learning in supporting mathematical development. The studies collectively trace how spatial reasoning especially through play-based and constructive activities such as block building that develops in early childhood and predicts later mathematical and STEM achievement. They also highlight the influence of contextual variables such as socioeconomic status, gender and executive functioning on spatial–mathematical relations.

Early empirical work by Levine et al. (1999) provided foundational evidence for the emergence of sex differences in spatial skills among preschool-aged children. Using a spatial transformation task, the study identified a clear male advantage by age four and a half, which was not limited to rotation tasks but also extended to translation items. This finding distinguished early childhood patterns from those seen in older populations, where differences are typically strongest in mental rotation. Importantly, boys and girls performed comparably on vocabulary measures, indicating that the observed spatial differences were not due to general cognitive disparities. The findings foregrounded biological and experiential factors in early spatial development and laid groundwork for understanding individual differences in spatial cognition.

Building upon this, Casey et al. (2008) examined whether structured interventions could enhance young children's spatial reasoning through block-building activities. The study compared two intervention groups with and without a storytelling context and a control group. Both intervention types of significantly improved children's spatial visualization, while the story-integrated condition yielded the highest performance in block building. These results underscored the pedagogical value of embedding spatial learning within narrative and play-based contexts, showing that meaningful engagement through stories supports deeper spatial understanding. Moreover, consistent with earlier findings, boys outperformed girls in three-dimensional mental rotation, reinforcing early sex-based performance trends.

Extending the empirical evidence to broader educational contexts, Mix and Cheng (2012) reviewed the developmental and educational implications of the relationship between space and mathematics. The analysis reaffirmed that spatial ability correlates strongly with mathematical performance across the lifespan but noted that this relationship in early development remains underexplored. Mix identified a critical need for mechanistic explanations and longitudinal studies that trace how spatial experiences in early childhood contribute to later mathematical cognition. This synthesis illuminated both the potential of spatial interventions for mathematics education and the current gaps in understanding developmental causality.

A major advance in this domain came from Verdine et al. (2014) who systematically analyzed preschoolers' spatial assembly performance using interlocking block tasks. Their detailed scoring system revealed fine-grained variations in spatial processing beyond simple accuracy metrics. Spatial assembly was found to be a significant independent predictor of concurrent mathematical skills, demonstrating a robust cognitive linkage between these domains as early as age three. The study also uncovered socioeconomic disparities which are the children from lower-SES backgrounds performed less well and were exposed to less spatial language at home, highlighting the social dimensions of early cognitive development. Interestingly, no gender differences were detected, suggesting that environmental factors, rather than inherent ability, might play a greater role at this developmental stage.

Expanding on these findings, Verdine et al. (2017) conducted a longitudinal monograph exploring the measurement, development and predictive validity of preschool spatial skills. Using the newly developed Test of Spatial Assembly (TOSA), they confirmed that spatial skills can be reliably measured in children as young as three and that these early abilities significantly predict spatial and mathematical skills at age five. The analysis identified executive function and language as additional predictors of mathematical performance and reaffirmed SES as a key determinant of spatial development. It was concluded that early and enriched spatial experiences, such as engaging with puzzles, block play and everyday spatial interactions are essential for fostering school readiness and building a strong foundation for future success in STEM fields. Their findings provided sturdy empirical evidence for the developmental continuity between early spatial reasoning and later academic achievement.

At the broader population level, Wai et al. (2009) demonstrated that spatial ability consistently predicts long-term educational and occupational outcomes in STEM domains. Aligning these findings with historical and contemporary evidence, the authors argued that spatial ability should be included in modern talent identification programs, as it identifies high-potential students often overlooked by conventional measures of verbal and quantitative reasoning. These clusters demonstrate progression from foundational theories to applied instructional strategies, suggesting that effective geometry teaching requires alignment between cognitive development, pedagogical design and classroom implementation.

5.7 Evolution of Clusters

Over time, research clusters have evolved to incorporate interdisciplinary perspectives, integrating insights from cognitive science, educational technology and curriculum design. This evolution reflects the dynamic nature of geometry education research and its responsiveness to emerging educational needs.

Table 6: Distribution of publications across clusters (1971-2022)

Year	Cluster 1	Cluster 2	Cluster 3
1971		1	
1978	1	1	
1985		1	
1986	1		
1988	1		
1992	1		
1994	1		
1997	1		
1999	1		1
2000	1		
2006		1	
2007	2		
2008			1
2009	1		1
2010		1	
2011	1		
2012		2	1
2013		1	
2014		1	1
2016		1	
2017			1
2019	1		
2022		1	
Total	**13**	**11**	**6**

To trace the intellectual progression of geometry education research, the evolution of clusters within the co-citation network was examined. Table 6 presents the distribution of publications across the three clusters from 1971 to 2022. In the early decades from 1970s to 1990s, research activity was concentrated in Cluster 1, which focuses on the educational and theoretical foundations of geometry teaching. The two works which were the foundational contributions on spatial visualization, Vygotsky (1978) and Van Hiele (1986, 1999) established core frameworks for understanding students' progression in geometric reasoning and how pedagogy can support this development. These early works laid the curricular and theoretical groundwork that continues to shape the field.

In the early 2000s, the field saw notable growth in Cluster 2, centering on cognitive development and spatial reasoning. Influential studies by Newcombe & Frick (2010), Uttal et al. (2012, 2013) and Mix (2016) reflect a shift towards integrating cognitive science perspectives, highlighting the predictive role of spatial abilities such as mental rotation and visualization in students' geometric understanding and achievement. This period marks a significant broadening of focus, with growing attention to individual differences and cognitive processes in mathematics learning.

Cluster 3, which comprises applied and empirical studies on early spatial learning, began to emerge more strongly after 2005, with steady growth from 2008 onwards. Research by Casey et al. (2008), Verdine et al. (2014, 2017) and Levine (1999) illustrates the increasing emphasis on instructional design, early interventions and classroom strategies to cultivate spatial skills and deepen geometric understanding. Entering the 2010s and 2020s, this cluster continued to expand, with contributions such as Hawes (2022) emphasizing the integration of technology and applied pedagogical methods in geometry education.

6. Discussion

This study identifies three major dimensions in teaching geometry research: (1) theoretical and pedagogical foundations, (2) cognitive development and spatial reasoning and (3) applied and technology-enhanced instructional practices. These findings reflect a shift from traditional procedural approaches toward more interactive, student-centered and cognitively informed teaching.

Teaching geometry plays a pivotal role in developing learners' higher-order thinking, spatial reasoning and problem-solving skills supporting their engagement with both mathematical and interdisciplinary domains (Serin, 2018). This systematic review provides a decade-long overview of research on teaching geometry from 2016 to 2025, supported by a bibliometric analysis that maps publication trends, thematic structures and intellectual influences in the field. Over the past decade, research on geometry teaching has expanded considerably, evidenced by the growing volume of publications, diversification of pedagogical themes and increased methodological sophistication.

The intellectual structure underlying recent research draws heavily on foundational theories that shaped the study of geometry teaching throughout the late twentieth century. Influential works such as Vygotsky (1978) and Van Hiele (1986, 1999) continue to inform contemporary pedagogical approaches especially in understanding how learners progress through levels of geometric reasoning and how instruction can scaffold this progression. The transition from visual to analytical reasoning is crucial because students often begin learning geometry through perceptual understanding by recognizing shapes and patterns based on appearance. However, meaningful geometric understanding requires them to reason about properties, relationships and logical structures.

According to Van Hiele's hierarchical model of geometric thinking (Van Hiele, 1986), learners progress through ordered stages: from recognizing shapes visually (Level 1) to analyzing their properties (Level 2) and later reasoning about relationships and proofs (Level 3 and above). Many studies explore how teachers can design tasks that move students from visual to analytical reasoning, reflecting Van Hiele's hierarchical model and how sociocultural interactions in classrooms can support this process. Thus, teachers must intentionally design instructional tasks that would connect these levels. Without such scaffolding, students may remain at a superficial level of shape recognition and unable to generalize or apply geometric concepts abstractly (Clements & Battista, 2020). The process is grounded in Van Hiele's cognitive hierarchy, which justifies the need for structured progression and social constructivism highlighting how classroom interactions facilitate that progression.

However, despite strong theoretical support, empirical studies indicate that many students do not progress beyond basic levels of geometric reasoning, suggesting a gap between theoretical models and classroom implementation. This may be attributed to constraints such as limited instructional time, insufficient teacher preparation and overreliance on procedural teaching approaches. There is also a growing attention to integrating curriculum reforms with broader STEM initiatives and positioning geometry as an isolated topic and a key component in fostering mathematical literacy. Recent research emphasizes integrating geometry within broader STEM initiatives to enhance mathematical literacy. This focus arises because geometry reinforces spatial reasoning, modelling and visualization skills that essential for problem-solving across science, technology and engineering fields (English & Sriraman, 2010; Sinclair et al., 2020).

Curriculum reforms increasingly promote cross-disciplinary learning, positioning geometry as a bridge between abstract mathematics and real-world applications. Instructionally, this integration is realized through inquiry-based and design-oriented pedagogies that employ tools such as dynamic geometry software, augmented reality and 3D modelling to connect geometric reasoning with authentic problem contexts (Erdoğmuş et al., 2021). These approaches help students recognize geometry's relevance beyond the classroom and foster deeper conceptual understanding. Therefore, embedding geometry within STEM learning supports the development of mathematical literacy by enabling students to interpret spatial information, reason quantitatively and apply their knowledge effectively in diverse domains (OECD, 2023).

Despite these advantages, the integration of geometry within STEM contexts is not without limitations. In practice, teachers may lack the pedagogical and technological expertise required to effectively design interdisciplinary tasks, leading to superficial integration rather than meaningful conceptual connections. The second cluster on cognitive development and spatial reasoning highlights the critical role of teachers in developing students' spatial abilities through targeted instructional practices. Rather than treating spatial reasoning as an innate skill, research during this decade positions it as a teachable and developable cognitive domain. Studies emphasize how teachers use visualizations, gestures, manipulatives and digital tools to help students construct mental representations and engage actively with geometric concepts (Hawes et al., 2022; Newcombe & Frick, 2010; Uttal et al., 2013).

Digital tools such as dynamic geometry environments also allow students to explore and manipulate shapes interactively, promoting deeper conceptual understanding and bridging the gap between concrete exploration and abstract thinking. These works demonstrate that pedagogical approaches that foreground spatial reasoning led to deeper conceptual understanding and improved problem-solving, reinforcing the need to embed spatial thinking systematically within geometry instruction. This suggests that spatial reasoning should be positioned as a central component of geometry instruction rather than as a supplementary skill.

However, the effectiveness of digital technologies is not consistent across contexts. Some studies report that without proper pedagogical guidance; digital tools may reinforce surface-level engagement rather than deep conceptual understanding. In addition, issues such as limited access to technology, insufficient training and increased cognitive load may hinder their effective implementation in classrooms. The third cluster comprises applied and empirical studies on early spatial learning focusing on how teaching practices in the early years can nurture foundational spatial and geometric thinking.

Research in this area often examines classroom interventions, teacher-led play-based activities and the use of spatial language in instruction (Gunderson et al., 2012; Mix, 2016). Such approaches are emphasized because spatially rich learning environments actively engage students in visualizing, reasoning and problem-solving skills that are foundational to both geometric understanding and broader STEM competence. When teachers intentionally design instruction that nurtures spatial awareness through hands-on exploration, visual modeling and discussion, students develop flexible thinking and transferable reasoning abilities. Research shows that these early instructional experiences improve immediate learning outcomes and build cognitive structures that support advanced mathematics and science learning.

Across these clusters, a significant shift is evident in how geometry is taught. Earlier approaches often emphasized rote memorization and procedural knowledge, whereas recent research focuses on integrating digital technologies, adaptive tools and interdisciplinary methods to create more interactive and student-centered classrooms. The use of dynamic geometry software augmented, virtual reality and AI-based adaptive learning platforms has expanded teachers' instructional repertoires, allowing them to support visualization, reasoning and exploration in more dynamic ways (Bujak et al., 2013; Sunzuma, 2023). These technological innovations have transformed geometry teaching from static, teacher-directed instruction to more flexible and inquiry-oriented pedagogies that align with 21st-century learning goals.

Geographical patterns reveal that contributions to research on geometry teaching are uneven. Countries with strong STEM education policies and well-supported research infrastructures such as the United States and parts of Europe have produced a significant portion of the literature especially in areas that related to spatial reasoning and technological integration (Zhang & Chen, 2023). In contrast, research from regions with limited resources remains underrepresented often due to disparities in funding, institutional priorities and access to technology. This imbalance points to the importance of fostering international collaborations and cross-cultural research to broaden perspectives on effective teaching strategies and adapt successful practices across contexts (Huang & Zhu, 2021).

Therefore, the past decade reflects a dynamic evolution in the teaching of geometry. The convergence of strong theoretical foundations that growing attention to spatial reasoning and practical classroom innovation has enriched both the research landscape and pedagogical practices. Teaching geometry has also gained increasing prominence within mathematics education with research focusing on improving instructional approaches, teacher knowledge and the integration of digital tools to enhance classroom practice (Jablonski & Ludwig, 2023). Earlier pedagogical models were often limited to traditional Euclidean content delivered through direct instruction. Recent developments, however, punctuate the role of technology, cognitive development theories and interdisciplinary methods in supporting teachers to address diverse learning needs (Kalyani, 2024).

Technological innovation has played a central role in transforming the way geometry is taught. Tools such as augmented and virtual reality have enabled teachers to design interactive and immersive activities that support spatial reasoning and make abstract concepts more tangible (Bujak et al., 2013). These tools encourage students to engage actively in problem-solving rather than passively receiving information, marking a clear shift towards more student-centred teaching. The integration of AI-based platforms and dynamic geometry software has further supported teachers in adapting instruction to students' needs, providing real-time feedback and personalized learning experiences (Jian, 2023; Sunzuma, 2023).

Recent research also highlights the integration of insights from cognitive science into teaching practice. By understanding how learners develop geometric reasoning and spatial thinking, teachers can employ strategies that promote flexibility, problem-solving and deeper conceptual understanding (Muzaini, 2023). Approaches that combine cognitive insights with technology-enhanced instruction are helping reshape geometry teaching, making it more adaptive, interactive and aligned with 21st-century educational goals.

7. Limitation and Future Research

While this review offers a comprehensive overview of research on geometry teaching, several limitations should be acknowledged. First, the analysis relied solely on the Web of Science (WoS) database. Although WoS provides extensive coverage of high-impact publications, relevant studies indexed in other databases such as Scopus or Google Scholar may have been excluded. Consequently, emerging or practice-based studies on geometry teaching strategies that are not yet widely cited might have been overlooked. Second, this review was limited to English-language publications, which may have resulted in the omission of significant research published in other languages exceptionally those documenting innovative teaching practices in local or regional journals. Furthermore, the co-citation analysis emphasized studies with high citation counts, which may have excluded more recent but potentially influential works on emerging pedagogical approaches.

Future research should aim to address these limitations by expanding the scope of data collection to include multiple databases and publications in diverse languages, thereby providing a more comprehensive representation of global teaching practices. More specifically, future studies should employ longitudinal research designs to examine the long-term impact of geometry teaching strategies, particularly those involving spatial reasoning and digital technologies. Researchers are also encouraged to develop context-sensitive instructional models that account for differences in classroom environments, technological access and student diversity. Strengthening international collaboration will be crucial in developing more contextually responsive and equitable models of teaching. Additionally, there is a need for more research conducted in underrepresented regions especially in developing countries, to ensure a more balanced and globally relevant understanding of geometry teaching practices.

8. Conclusion

This bibliometric and systematic review examines the development of research on teaching geometry from 2016 to 2025, providing a comprehensive synthesis of research developments in this field. By mapping intellectual trends and identifying key contributors and thematic directions, the study offers valuable insights for educators, policymakers and researchers seeking to strengthen instructional practices in mathematics. The findings reveal a notable increase in research output, reflecting the growing recognition of geometry teaching as a crucial component of mathematics education. This rise corresponds with advancements in spatial reasoning, digital integration and innovative pedagogical approaches aimed at enhancing conceptual understanding and classroom engagement.

To translate these insights into practice, professional development is essential for equipping teachers with strong pedagogical content knowledge and digital competence. Emphasis should be placed on active, inquiry-based and technology-enhanced instruction, including the use of dynamic geometry software and augmented reality to support conceptual visualization. The review identifies three main research clusters, theoretical and pedagogical foundations, cognitive development and spatial reasoning and empirical studies on early spatial learning, which collectively underscore the importance of integrating cognitive, technological and pedagogical perspectives in effective teaching design.

Moreover, ongoing research should focus on longitudinal studies to examine long-term impacts of spatial interventions, the integration of AI and VR-based instructional tools and strategies to enhance participation from underrepresented regions. Overall, the findings highlight the importance of theory-driven, technology-supported and evidence-based pedagogical models in advancing geometry instruction and fostering more engaging, inclusive and effective mathematics education globally.

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