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Evolving three decades of geometry learning strategies: A combination of bibliometric analysis and systematic review

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Abstract

Geometry is an essential part of mathematics education and understanding effective strategies for learning geometry is increasingly important. This study presents a combination of bibliometric and systematic review of research on geometry learning strategies, analysing on publication trends, main contributors, research topics and citation networks over the past three decades. Utilizing data from the Web of Science database, we reviewed 730 articles, identifying key themes through co-citation analysis and three major clusters: (1) Foundations of mathematics education and research methodology, (2) Spatial ability, cognitive development and STEM learning and (3) Early spatial and mathematical development in education. The study reveals that spatial reasoning is very important for understanding mathematics and training in spatial skills helps to improve problem-solving skills and achievements in STEM subjects. However, four gaps in the research were identified: limited research from Africa and Latin America, lack of long-term studies on spatial training effects, limited integration of AI and digital tools and limited interdisciplinary integration with cognitive psychology and neuroscience. The novelty of this study lies in mapping thirty years of intellectual development in geometry education by combining bibliometric and systematic review methods, offering new insights for improving teaching strategies and future research directions.

Keywords: bibliometric analysis, systematic literature review, geometry learning, geometry knowledge

INTRODUCTION

Geometry is very essential in mathematics education, helping students develop spatial reasoning, problem-solving abilities and abstract thinking skills (Crompton & Ferguson, 2024) especially during the early school years when foundational understanding of geometric reasoning should be emphasized to avoid later misconceptions. Geometry has been important part of mathematics for many years as it is closely connected to mathematical concepts (Jablonski & Ludwig, 2023). Over the last three decades, researchers study various approaches to improve geometry learning and recognizing its important role in developing mathematical skills. Seah (2015) said that geometry develops students' visualization, intuition, critical thinking, problem solving, deductive reasoning, logical argument and proof and plays an important role in acquiring advanced knowledge in science, technology, engineering and mathematics. These studies include many perspectives from cognitive and developmental aspects to technological innovations and new teaching methods as educators try to solve persistent challenges in teaching geometry effectively. However, despite the various of research, a comprehensive synthesis of these studies is lacking, making it difficult to identify variety concepts such as main trends, important findings and future research directions.

The variety of this concept is shown in many studies that explored at how people learn geometry, focuses on different approaches that enhance understanding. Liu et al. (2023) found that learning by restoring broken 3D geometry effectively captures rich geometry information. Puig et al. (2022) demonstrated that using a gamified itinerary through digital activities can attract primary school children into the world of geometry,

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Contribution to the literature

- This study provides a comprehensive synthesis of 30 years of research on geometry learning strategies, combining systematic literature review and bibliometric analysis methods.
- By identifying major thematic clusters and research gaps, the study highlights the evolving trends in geometry education, including the integration of cognitive theories, spatial reasoning and digital learning tools.
- The findings offer valuable insights for educators, policymakers and researchers in designing more effective and inclusive geometry teaching strategies.

improving their learning and interest in mathematics. Additionally, learning geometry through a scientific approach, involving observing, asking questions, reasoning, attempting and presenting, can lead to very good learning outcomes (Ramdhani et al., 2017). Beyond teaching strategies, cognitive factors also play important role in geometry learning. Cragg et al. (2017) study shows that working memory indirectly contributes to mathematics achievement through factual knowledge, procedural skill and conceptual understanding. Moreover, working memory helps students recognize and build problem representations, which is crucial for solving mathematical problems. Rivella et al. (2021) further emphasized that visuospatial working memory has a significant impact students' ability on solving geometric problems, especially when calculating the perimeter and area of a new figures. As visuospatial skills are crucial for understanding geometric relationships, technology plays an important role in supporting students' cognitive processing.

Technology has changed the ways of teaching and learning geometry. Many of primary school mathematics teachers have difficulties in explaining geometry lessons, but they are finding solutions using technology and concrete materials (Altintas et al., 2022). Arvanitaki and Zaranis (2020) shows that technology, specifically Augmented Reality (AR), has a positive impact on primary school students' achievement in geometry compared to traditional teaching methods. Interventions using new technologies also can help students in geometry, by improving working memory, reading and numerical skills (Galitskaya & Drigas, 2023). Along this, artificial intelligence plays an important role, helping mathematicians find patterns and conjectures including ones important in geometry (Davies et al., 2021). As AI continues to shape the way geometry is studied and taught, its integration into educational tools can also support students in processing complex geometric concepts more effectively. Besides that, applying abstract mathematical theories to geometry education has also expended the limits of the field.

Cognitive Load Theory explains that too much working memory can make it hard for students to understand complicated geometric ideas, suggesting that technology should be designed to reduce cognitive overload and enhance learning efficiency. Therefore, teaching strategies should aim to reduce this cognitive overload while improving abilities to visualize (Shi et al., 2023). This growing research also shows not only theoretical and practical advances in learning geometry, but also constant challenges faced by teachers and students. Many students made proportional reasoning mistakes in geometry (Van Dooren et al., 2005) and limited transfer effects from working memory training to other academic area (Gray et al., 2012) showing the need for focused interventions. Moreover, most students in vocational high school struggle with geometry due to lack of visualization ability, specific terms or symbols and insufficient reasoning related relationships within geometric shapes (Barut & Retnawati, 2020). These ongoing challenges show the need for a systematic review of current research to identify effective learning strategies, best teaching practices and areas requiring more study.

Given the extensive research in this field, a combined bibliometric analysis and systematic review is a useful tool for understanding trends and finding important studies on the evolution of geometry learning strategies over last three decades. Bibliometric analysis provides a quantitative approach to study the structure and development of research areas over time, identifying key authors, influential publications and emerging trends through citation and co-citation analysis (Aria & Cuccurullo, 2017), while systematic review provides a qualitative synthesis of findings, methodologies and focusing on specific research questions. By combining both methods, this study aims to give a comprehensive overview of geometry learning strategies. The systematic review gives deep insights by examining the specifics of existing studies, while the bibliometric analysis provides wider view by mapping the relationships and influence among studies in the academic field (Donthu et al., 2021). This combined approach ensures that the review is both detailed and contextually situated within the broader research area, providing better insights and a more complete understanding of the field.

Evidence of Geometry Learning

Over the last thirty years, geometry learning strategies have evolved significantly influenced by new teaching methods, cognitive science and technology.

Geometry education at all levels, including middle, secondary and university, focuses on curriculum, applications, computer use, explanation, argumentation, spatial abilities and teacher preparation (Laborde, 2015). It is very important for students to study geometry because it helps them develop spatial reasoning, problem-solving skills and logical thinking which are necessary for being good in mathematics (Shi et al., 2023). Recent studies show the importance of understanding how students learn and use geometric concepts. The Van Hiele Model of Geometric Thought discusses different levels of understanding, highlighting that students go through various stages as they develop their spatial reasoning (Jablonski & Ludwig, 2023). Research indicates that teaching aligned with Van Hiele's levels can greatly improve understanding of geometry and ability to solve problems. However, some studies argue that strictly following Van Hiele's stages may not suit all students, as individual differences and prior knowledge can affect learning paths (Agustiningsih et al., 2019). Van Hiele theory-based instructional activities effectively improve elementary preservice teachers' geometry knowledge for teaching 2-D shapes, enhancing their content knowledge, understanding of student levels and instructional activities (Yi et al., 2020).

In geometry education, teaching approaches have moved from being teacher-centered to focusing on student-centered methodologies. These strategies encourage students to explore geometric properties through hands-on activities and lead to a deeper understanding, supported by studies that show the effectiveness of activity-based teaching in improving students' problem-solving performance in geometry (Mifetu, 2023). Using virtual reality immersive technology in mathematics geometry learning improves students' motivation, performance and sense of accomplishment (Su et al., 2022). Traditional teaching methods, which focused a lot on memorization and passive learning have slowly changed. Technologies, specifically Augmented Reality (AR), positively impacts primary school students' achievement in geometry compared to traditional teaching methods (Arvanitaki & Zaranis, 2020). However, some research warns that overreliance on technology without proper integration into pedagogy can lead to surface-level understanding rather than deep conceptual learning (Md Sabri et al., 2024). Now, there are more interactive and student-centered approaches that help students understand concepts better and be more engaged in learning (Sunzuma, 2023), although some studies still find that traditional instruction dominates, especially in primary classrooms where passive learning environments persist (Kuzle et al., 2023)

Furthermore, studies point out the importance of spatial visualization skills in learning geometry. Using manipulatives, visual representations and interactive aids improve students' engagement and conceptual clarity. Technology has been very important in changing geometry education. Digital technologies can effectively improve geometry teaching and learning at the secondary school level (Sunzuma, 2023). Tools like Dynamic Geometry Software (DGS) including GeoGebra and Cabri allow students to explore geometric properties dynamically, which enhance their visualization and understanding (Ziatdinov & Valles, 2022). Recent studies also show that Augmented Reality (AR) and Virtual Reality (VR) can help improve spatial reasoning through immersive learning experiences (Bujak et al., 2013). Nevertheless, many of these studies rely on short-term interventions or small sample sizes, which limit the generalizability of the findings (Zhang et al., 2025). Most junior high school students agree that using technology in geometry learning has a positive effect on their learning with 67% of them using technological devices and 56% using learning videos (Lu'luilmaknun et al., 2021).

Early spatial skills, especially spatial visualization and spatial perception are strongly associated with children's mathematics performance in second grade. Engaging in spatial reasoning activities at an early age significantly influences later mathematical achievement, with visuospatial working memory and reasoning training proving to be the most effective (Judd & Klingberg, 2021). Engaging in spatial activities, such as block design, can help improve math skills in primary school children (Fernández-Méndez et al., 2020). Additionally, a child's early spatial ability can predict their future understanding of mathematics (Möhring et al., 2021).

Even with a lot of research on geometry learning strategies, there are still some gaps in this field. There are not enough longitudinal studies looking at how different teaching methods affect students' skills in geometry and spatial reasoning over time. There are also various debates in geometry learning research about the effectiveness of using technology in instruction, the importance of cognitive load in understanding geometry and how spatial intelligence is developed. The discussions around Cognitive Load Theory suggest that, even though geometry is complex, active learning methods such as visualization and solving problems can help reduce cognitive overload (Paas & Sweller, 2014). However, more empirical studies are needed to confirm how specific instructional techniques interact with cognitive load in real classroom settings (Paas & van Merriënboer, 2020). The balance between teacher-centered and student-centered learning is still being explored. Juman et al. (2022) said that student-based learning approaches are more effective than conventional methods for teaching geometry, as students face difficulties in drawing diagrams and applying more than one theorem to solve problems.

This review about geometry education shows how technology, cognitive science and interdisciplinary research have become more important in improving modern geometry teaching and learning. The change from traditional learning methods to AI-based personalized learning shows a move towards educational frameworks that are more adaptive and student-centered. Addressing these gaps will help geometry education improve, increase student engagement, improve learning outcomes and prepare students for success in mathematics and other areas.

Objective of the Study

The main purpose of this research is to review the current studies on geometry learning. This study aims to achieve several objectives in response to these three research questions:

RQ1 What are the current trends in research publications on geometry learning based on the year, key authors and top affiliations?

The first research questions examine how research publications on geometry learning have changed over time This includes analysing the number of articles published each year, identifying key authors who have contributed significantly and recognizing the top affiliations that produce the most research. By studying these trends, we can understand whether interest in geometry learning strategies is growing and which institutions are leading in this field. This analysis helps in identifying influential scholars and major research institutions that have shaped the direction of research on geometry education.

RQ2 What are the distributions of publications from different countries and research areas of geometry learning strategies?

The second research questions look at how research on strategies for learning geometry is distributed among different countries and academic fields. By analysing the number of publications from each country, it is possible to identify which nations are actively conducting research in this area. Additionally, by looking at different research areas, we can see how fields like mathematics education, psychology and cognitive science contribute to understanding geometry learning. This objective helps to provide a global view of the research and shows which countries and disciplines are leading in developing innovative geometry learning strategies, which lead to the following research question.

RQ3 What are the patterns of keywords co-occurrence, citation networks, co-citation networks and the new trends based on thematic cluster analysis in the research on geometry learning strategies?

The third research questions study the patterns of keywords co-occurrence, citation networks, co-citation networks and the new trends based on thematic cluster analysis in the research on geometry learning strategies. Analysing keyword co-occurrence help in understanding the most common research topics and themes in geometry learning. Meanwhile, citation and co-citations analysis help to identify the most influential studies, authors and research papers in this field. It shows how researchers build on previous studies and connect various theories in geometry learning. The analysis will use thematic cluster method too. This approach groups different studies together depending on what they say. This helps to identify the main themes and new topics that come up in strategies for learning geometry. This objective aims to identify major research clusters, trends and gaps that can guide future studies in this area.

The structure of this document is organized as follows. First, the research methodology is explained, including the selection of the database, the keywords used, the inclusion criteria and the methods of analysis applied. Following this, the findings are discussed with a focus on publication trends to observe how research output has changed over time. This section identifies the number of publications per year, the most influential authors and the top affiliations.

The second part analyses the distribution of research across different countries and subject areas. This helps to understand which academic fields are actively contributing to research on geometry learning strategies.

After that, a keyword analysis is conducted to highlight the most frequently occurring keywords in the literature. The analysis then focuses on citation and co-citation networks to examine the relationships and connections between cited works. Emerging trends in research on geometry learning strategies are then identified through thematic cluster analysis.

A critical discussion of findings is provided including the implications of the results for educational practice. Additionally, the limitations of the study are discussed and suggestions for future research directions are provided. Finally, the comprehensive analysis of research on geometry learning strategies presented in this study is summarised.

RESEARCH METHODOLOGY

Data Sources and Search Procedure

This study uses a bibliometric analysis approach to systematically review and summarize research on geometry learning strategies from the last 3 decades. By using bibliometric techniques, this study provides a structured and data-driven understanding of trends, influential contributions and emerging themes in the field. Bibliometric analysis has been widely used in educational research to map scientific production, identify key research themes and analyse academic

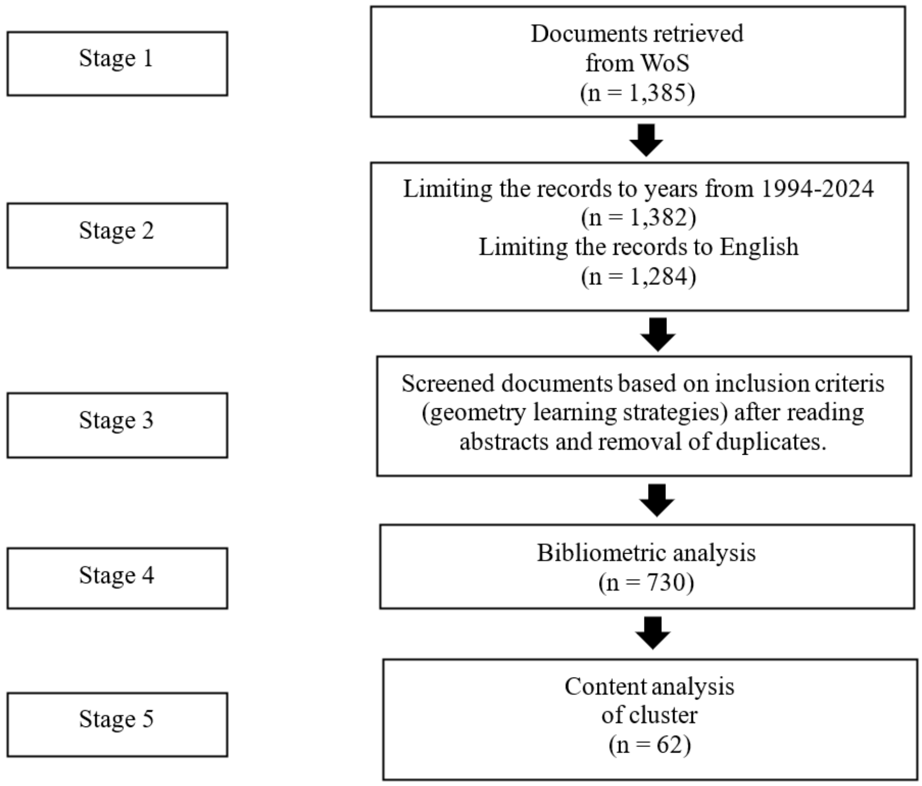

Figure 1. Data extraction process (Ismail et al., 2024)

impact (Donthu et al., 2021). The methodology consists of five main stages: data collection, data processing and cleaning, bibliometric analysis and interpretation and synthesis.

The data from the Web of Science (WoS) Core Collection extracted in December 2024. WoS was selected due to its extensive coverage of high-impact journals, robust citation tracking and powerful analytical tools, making it an ideal database for long-term trend analysis (Ellegaard & Wallin, 2015). WoS has been used in thousands of published academic studies since 1997, with its impact on science largely unreported (Li et al., 2018). Although Scopus is another widely used bibliometric database, WoS was preferred for its comprehensive historical records, facilitating an in-depth examination of research trends over the past three decades (Aydemir et al., 2023). The selection of WoS aligns with previous bibliometric studies in education and mathematics, highlighting its reliability in indexing quality publications (Julius et al., 2021).

A Boolean query then constructed to retrieve relevant publications on geometry learning strategies. Boolean search strategies are essential for systematic reviews, enabling researchers to refine results and increase retrieval precision (Zupic & Čater, 2015). The final search string used in WoS was ('learning' OR 'education' OR 'instruction' OR 'teaching') AND ('strategies' OR 'methods' OR 'approaches' OR 'techniques') AND ('mathematics' OR 'math' OR 'numeracy' OR 'arithmetic') AND ('geometry' OR 'geometric' OR 'spatial' OR 'shape').

This search returned an initial dataset of 1,385 articles. Additional filters were applied to refine the dataset and ensure its relevance, a common practice in bibliometric research to improve data accuracy and validity (Aria & Cuccurullo, 2017). Limiting the time frame from 1994-2024 reduced the dataset to 1,382 articles. Restricting results to English-language publications further refined the dataset to 1,284 articles. Only journal articles were considered, reducing the dataset to 932. Finally, the data filtered by relevant WoS subject areas, resulting in a final selection of 730 articles. Articles that did not have complete bibliometric metadata, were not part of relevant WoS categories or were not thematically related were excluded. This selection process ensures that the final dataset is comprehensive and aligned with the study's objectives. (**Figure 1**) visually represents the data search and refinement process.

Analysis Methods

This study uses a combined approach of bibliometric analysis and systematic review to examine how research on geometry learning strategies has changed over the last 30 years. Bibliometric analysis is a common method in academic research that helps to find out trends in publications, map networks of citations and discover themes in a specific research area (Donthu et al., 2021). Conducting systematic reviews is important for summarizing research content, reducing biases (Tranfield et al., 2003). and finding topics that need more study (Kumar et al., 2019; Talan & Sharma, 2019). This

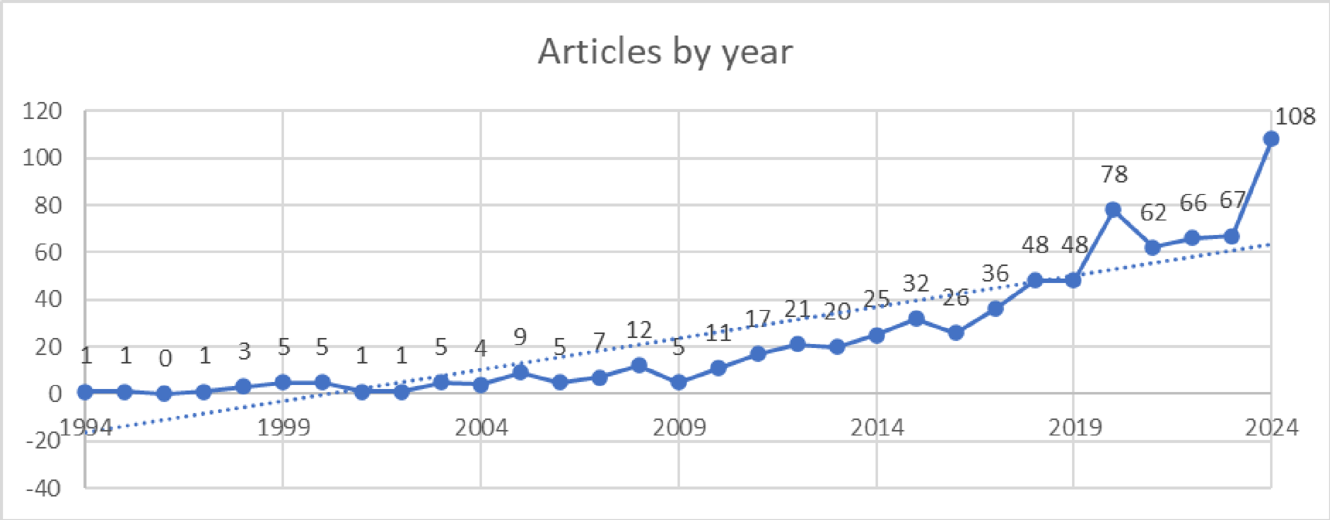

Figure 2. Yearly distribution trends for publishing 730 articles from 1994 through 2024 (Source: Authors' own elaboration)

study uses bibliometric analysis to examine the research field and followed by content analysis to highlight the main themes (Baker et al., 2020). Boyack and Klavans (2010) explain the use of standard bibliometric methods, such as citation and co-citation analysis, to explore how documents refer to each other. To do this, VOSviewer is used for citation analysis, co-citation analysis and keyword analysis. Researchers widely acknowledge VOSviewer for its efficiency in handling large datasets and providing clear visual representation of bibliometric patterns (Zupic & Čater, 2015).

FINDINGS

Yearly Productivity Trend

Figure 2 shows the yearly trend of articles published about learning strategies in geometry from 1994 to 2024. It shows a clear increase of publications over the last three decades. This growth shows the importance of geometry education for improving skills in spatial reasoning, critical thinking and problem-solving. This increase shows a strong interest from scholars, which might be because of more funding in STEM education, new teaching methods or a focus worldwide on better math skills (National Mathematics Advisory Panel, 2008).

In the early 1990s, there were very few publications in this field. Only one to three articles published a year. Then, in the late 1990s and early 2000s, the number of articles slowly increased to around five or six each year. Changes in teaching courses at higher universities, combining research on elementary and higher geometry into one course and a focus on better teaching quality were seen as necessary for improving mathematics education (Wang et al., 2016). This small increase in publications during that time also shows that geometry learning strategies started to be seen as important for mathematical education. After 2005, there was a more noticeable increase in research activity. By 2010, the number of articles hit double digits, indicating that there was a change towards more organized and systematic studies in learning geometry. Dynamic geometry software such as GeoGebra allows students to discover new knowledge by experimenting and manipulating interactive constructions in mathematics education (Polasek & Sedlacek, 2015).

The trend became stronger after 2015, with the number of published articles continuing to increase. Important milestones included 36 articles in 2017 and 78 articles in 2020. In 2023, the figure shows a big increase, reaching 108 published articles, marking a new record high. This could indicate efforts to address the disruption in education caused by the COVID-19 pandemic, which led to new approaches for online and hybrid learning. COVID-19 greatly disrupted the global education system and researchers are starting to pay attention to how this affected student learning progress, especially if there has been any learning loss (Donnelly & Patrinos, 2022).

Prominent Authors and Top Affiliations

Table 1 shows the active authors in geometry learning strategies and their contributions, identifying several authors who are important in this area. Zsolt Lavicza and Moshe Stupel are leading with five publications each, which reflects they are very engaged in geometry education research. Their contributions shows that they are important researchers in this field. Other authors, like Caglayan, Casey, Hawes, Hegarty, Jones, Lin, Maharaj and Oxman, have four publications each.

Table 1 also highlights the contribution of universities in research on geometry learning strategies. It shows which universities are leading in this area. The University of California System has the most publications, with 29, indicating their significant role in

Table 1. Prominent authors and top affiliations contributing to geometry learning research

Prominent Authors	Number of Publications	Top Affiliations	Number of Publications
Lavicza, Z.	5	University of California System	29
Stupel, M.	5	University System of Ohio	16
Caglayan, G.	4	Pennsylvania Commonwealth System of Higher Education Pcshe	13
Casey, B. M.	4	University of Wisconsin System	12
Hawes, Z.	4	Michigan State University	11
Hegarty, M.	4	State University System of Florida	11
Jones, K.	4	University of Maryland College Park	11
Lin, F. L.	4	University System of Maryland	11
Maharaj, A.	4	University of Wisconsin Madison	10
Oxman, V.	4	Boston College	9

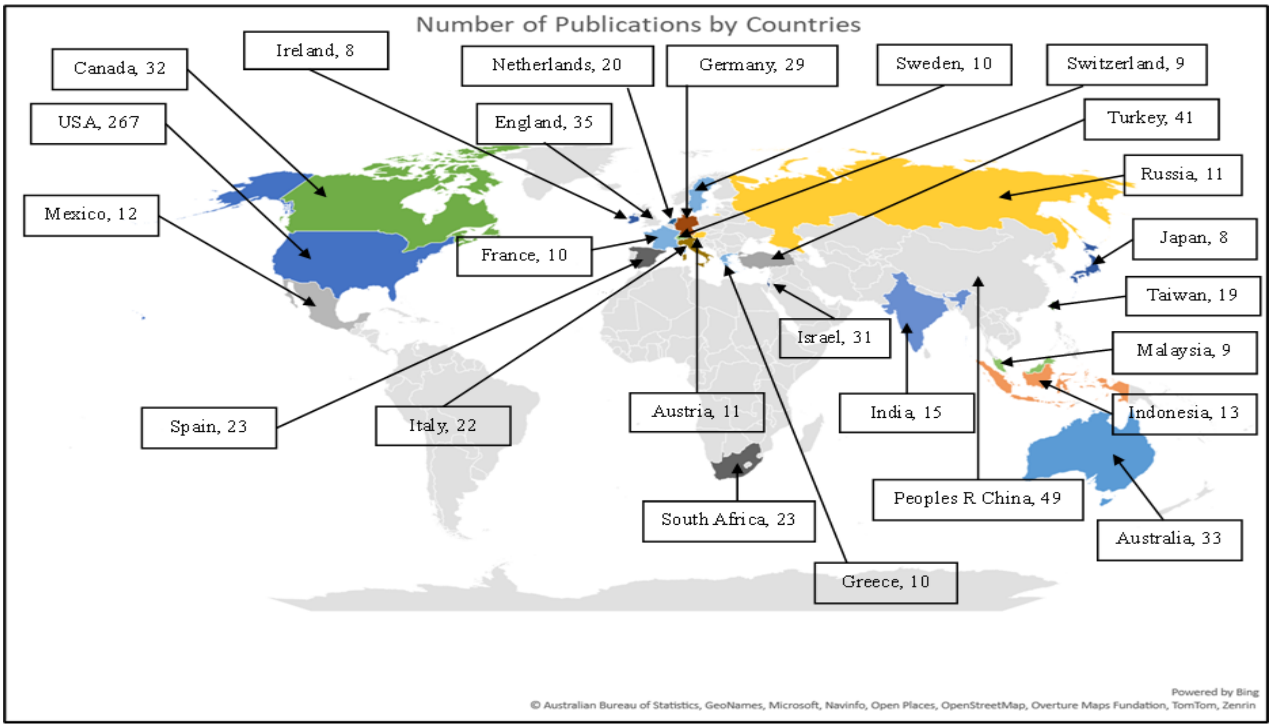

Figure 3. Countries contributing on geometry learning research (Source: Authors' own elaboration)

geometry education research. The University System of Ohio is the second largest contributor with 16 publications, showing a strong focus on education research. Other significant contributors include the Pennsylvania Commonwealth System of Higher Education (PCSHE) with 13 publications and the University of Wisconsin System with 12 publications. Some individual universities also contribute significantly, like Michigan State University, University of Maryland College Park and the State University System of Florida, with 11 publications each. The University of Wisconsin Madison has 10 publications, and Boston College has 9, both showing important contributions.

Geographical Contributions in Publications

VOSviewer is used to analyse which countries publish the most research on geometry education, as shown in **Figure 3**. The results are then reported by continent, which helps understand different regional contributions and shows where more research can be explored globally. North America emerges as the dominant contributor, with the United States (267 publications) leading in geometry learning research. Canada (32 publications) also demonstrates a significant research presence, suggesting a broader regional commitment to mathematics education.

Europe also contributes significantly to research on geometry learning strategies, though publications are more evenly distributed among multiple countries. England (35 publications) leads European research, followed closely by Germany (29), Spain (23), Italy (22) and the Netherlands (20). Several other European nations, including France, Austria, Russia, Greece, Sweden, Switzerland and Ireland, contribute between 8 to 11 publications each.

In Asia, China (49) emerges as the second-largest global contributor, indicating a growing investment in

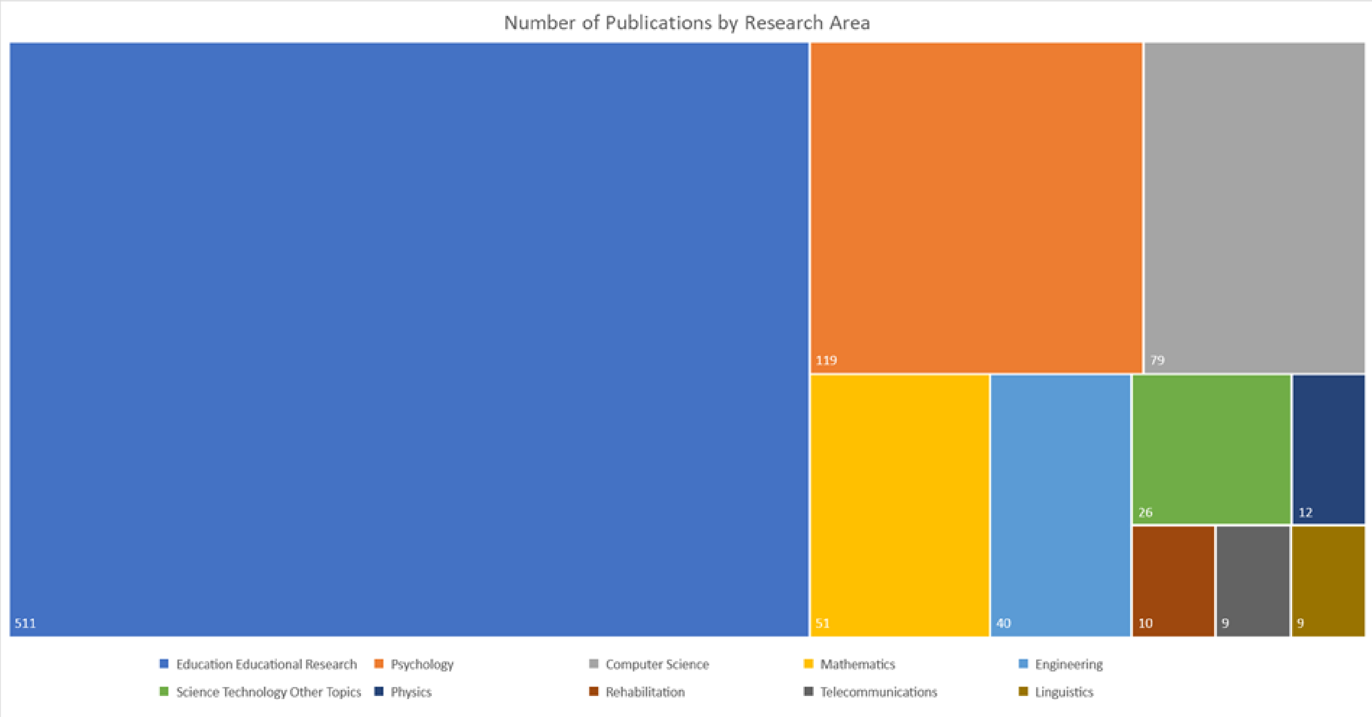

Figure 4. Research area publication in geometry learning across 730 papers (Source: Authors' own elaboration)

Table 2. Frequently occurring keywords in geometry learning research

Keywords	Occurrences
Mathematics	153
Geometry	91
Education	74
Knowledge	66
Students	61
Mathematics education	55
Achievement	47
Ability	45
Performance	44
Skills	42

mathematics education research. Turkey (41) also shows strong engagement in geometry education studies. Other Asian contributors include Israel (31), India (15), Indonesia (13), Taiwan (19), Malaysia (9) and Japan (8), showing diverse but still emerging research efforts across the continent.

Africa and Latin America have limited representation in this field, with South Africa (23 publications) and Mexico (12 publications) being the only major contributors. In Oceania, Australia (33 publications) stands out as a major research hub, reflecting its strong academic tradition in mathematics education.

Publication by Academic Landscape

Figure 4 shows the research areas that have published 730 articles which are contributing to the study of geometry learning strategies. It highlights how different fields are involved in this research and their level of contribution. The largest area is Educational Research, with 511 publications. This indicates that most of the research is focused on improving teaching and learning in education. Geometry is important in the current research in mathematics education, looking at things like geometric thinking, teaching methods, content, teacher education, argumentation, proof and digital tools for teaching and learning (Jablonski & Ludwig, 2023). The second-largest field is Psychology, with 119 publications. Computer Science has 79 publications, indicating the growing role of technology in geometry teaching.

Mathematics contributes 51 publications, which shows that studying geometry from a mathematical view is also important. Other areas like Engineering with 40 publications and Science Technology with 26 publications show how engineering and science can develop new tools and methods for teaching geometry, such as simulations or virtual environments. Smaller contributions come from fields like Physics (12), Rehabilitation (10) and Linguistics (6). Education and psychology are the most significant areas, but technology, mathematics and other fields also play important roles. This combination of disciplines helps researchers to discover new ways for improving geometry teaching and learning.

Keywords Analysis

Table 2 shows the network of keywords occurrences in geometry learning strategies. This analysis uses VOS viewer to find common keywords and how they relate to each other, which helps researchers understand main research trends and new growing areas of research. Hasumi and Chiu (2022) show that author keywords are

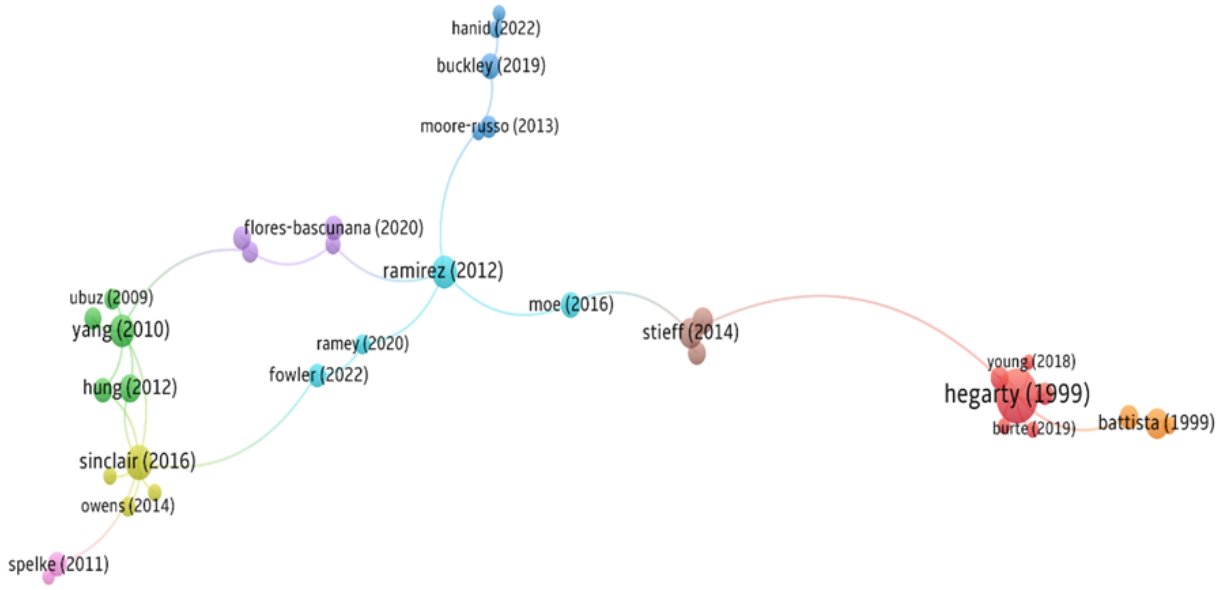

Figure 5. Citation network analysis on geometry learning research (created using VOSviewer, with a minimum citation threshold of 5) (Source: Authors' own elaboration)

important for finding the main areas of focus in research papers. The analysis shows that the most common keywords are mathematics, geometry, education, knowledge, students and mathematics education. The keyword "mathematics" appears 153 times, making it the most frequent term in the study. This shows that research on geometry learning strategies is closely related to general mathematics education. Geometry is a key part of mathematics education and current research focusing on geometric thinking, practices, teacher education, argumentation, proof and digital tools (Jablonski & Ludwig, 2023).

The keyword "geometry" occurs 91 times, which suggests a large part of research focuses on how students understand geometric concepts. The frequent use of the word "geometry" shows the importance of geometry education in improving students' overall mathematics skills. Research shows that children who struggle with geometry may also have difficulties with arithmetic, working memory and visuospatial mental imagery, especially in mental imagery and arithmetic problem solving (Bizzaro et al., 2018). The importance of education in learning geometry is clear, with the word "education" appearing 74 times and "mathematics education" appearing 55 times. The keyword "students" appears 61 times, indicating that many studies concentrate on how learners gain geometric knowledge and the factors that influence their learning process. The word "knowledge" (66 times) shows that many studies look at how students understand concepts and remember geometry ideas over time.

There are also keywords like "achievement" (47 times), "ability" (45 times), "performance" (44 times) and "skills" (42 times) that emphasize the focus on evaluating students' proficiency in learning geometry. The frequent occurrence of "skills" and "knowledge" show that research in this area is not only about basic understanding but also aims to develop students' higher-level thinking skills and problem-solving abilities.

Citation Network Analysis

Figure 5 presents citation network analysis on geometry learning research. Citation analysis is valuable bibliometric tool for measuring the impact and influence of scholarly works by analysing how frequently articles are referenced over time (Tsay, 2009). In this study, we examined a citation network of 730 articles, identifying 334 interconnected papers, which reveal key influences and trends in geometry learning strategies research. The citation network analysis highlights the most frequently cited works, demonstrating their significance in shaping contemporary research directions.

Hegarty and Kozhevnikov (1999) has the highest number of citations with 375, showing its foundational role in the study of spatial reasoning and geometry learning. Its continued influence is evident through connections with more recent works such as Young et al. (2018) and Casey and Fell (2018), suggesting that its findings still relevant for present research. Another highly cited research is Battista (1999) with 53 citations, which is closely related to Hegarty's study, further supporting the importance of spatial ability in understanding mathematics. The high citation counts of these studies show their lasting impact on how students develop spatial skills and the role of visualization in mathematical problem-solving.

Table 3. Leading articles in each cluster based on total link strength

Cluster 1 (Foundations of Mathematics Education and Research Methodology)	Cluster 2 (Spatial Ability, Cognitive Development and STEM Learning)	Cluster 3 (Early Spatial and Mathematical Development in Education)
National Council of Teachers of Mathematics (2000)	Wai et al. (2009)	Mix et al. (2016)
Grouws (1992)	Uttal et al. (2013)	Mix & Cheng (2012)
Battista (1990)	Linn & Petersen (1985)	Casey et al. (2008)
Sarama & Clements (2009)	Cheng & Mix (2014)	Gunderson et al. (2012)
Van Hiele (1986)	Voyer et al. (1995)	Newcombe & Shipley (2015)
Creswell (2013)	Uttal & Cohen (2012)	Lowrie et al. (2017)
Ball et al. (2008)	Shepard & Metzler (1971)	Levine et al. (2012)
Battista (2007)	Shea et al. (2001)	Hawes et al. (2017)
Tabachnick & Fidell (2007)	Sorby et al. (2013)	Verdine et al. (2014)
Cohen (1988)	Vandenberg & Kuse (1978)	Levine et al. (1999)

The citation network also reveals clusters of research that focus on different aspects of geometry learning strategies. One major cluster includes studies such as Ramirez et al. (2012) with 63 citations, Stieff et al. (2014) with 55 citations and Moè (2016) with 29 citations, all exploring the development of spatial ability and its impact on understanding geometric ideas. These studies contribute to research on cognitive development and provide evidence that spatial reasoning is important for success in mathematics. Another cluster in the citation network focuses on teaching methodologies and curriculum design. Studies like Sinclair et al. (2016) with 82 citations, Yang and Chen (2010) with 65 citations and Hung et al. (2012) with 42 citations focus on teaching strategies and how they influence student engagement and understanding in geometry. Additionally, Mistretta (2000) and Flores-Bascuñana et al. (2019) with 25 citations each contribute to curriculum innovations, showing the need for well-structured learning approaches to improve geometry teaching.

Findings from this citation analysis show two main themes in geometry learning research. The first theme is spatial reasoning and cognitive development, with important studies like Hegarty and Kozhevnikov (1999) and Battista (1999) showing that spatial ability is important for achievement in mathematics. The second theme is about pedagogical approaches and curriculum design, as seen in works like Sinclair et al. (2016) and Yang and Chen (2010), which look at how different teaching strategies affect learning outcomes. These themes reflect a shift from purely theoretical discussions to research that incorporates empirical investigations into instructional effectiveness.

Co-Citation Analysis

This analysis is useful to understand how different research studies are connected through their citation relationships. When two papers are referenced together in another paper, this called co-citation (Boyack & Klavans, 2010). Co-citation analysis is a method used in bibliometric studies to find important research papers, common themes and how knowledge develops in a specific area. To identify key publications, our study set a minimum co-citation threshold of 10 citations. According to Surwase et al. (2011), a citation threshold between 5 and 100 is recommended for articles that were published more than five years ago. In our analysis, out of 730 articles, 62 were identified as having been co-cited at least 10 times within the network.

Using VOSviewer for a co-citation analysis on a dataset of 62 documents identified three main clusters: Cluster 1 with 28 documents, Cluster 2 with 20 documents and Cluster 3 with 14 documents. These clusters were defined based on the total link strength, which represents the frequency of co-citations between documents, demonstrating VOSviewer's effectiveness in clustering and mapping bibliometric data. Articles were then evaluated based on their link strength within the co-citation network to identify the most influential ones in each cluster. Link strength measures an article's connections to other articles through co-citations, reflecting its prominence and impact within the network. The top articles in each cluster, ranked by total link strength, are listed in **Table 3**.

Content Analysis

After conducting a co-citation analysis, an in-depth review of 62 articles divided into three groups was performed. A detailed examination of each group revealed a dominant theme within them.

Cluster 1: Foundations of mathematics education and research methodology

The articles in Cluster 1 are about important ideas, teaching methods, cognitive development and research methodologies that influence mathematics education, especially in the teaching and learning of geometry. These works are important to understand how to teach mathematics, spatial reasoning and the basic theories of education research. A key theme in this cluster is about the standards and frameworks for mathematics education. National Council of Teachers of Mathematics (2000) talks about the importance of curriculum development, teacher preparation and assessment systems to have high-quality mathematics education. Grouws (1992) also provides an extensive review of research, important issues and advancements in methodology for mathematics education.

Another important aspect in this cluster is spatial reasoning and how it helps in mathematical thinking. Battista (1990) studies how spatial thinking affects problem solving in geometry and examines gender-related differences in visualization skills. In another study, Battista (2007) discusses how students improve their spatial reasoning skills over time. The theories of cognitive development are also very important in this cluster. Van Hiele (1986) presents a model of geometric thought developments in stages, and this model is widely used in educational research. Sarama and Clements (2009) examine how early mathematical experiences influence future learning trajectories, emphasizing the long-term impact of foundational geometry instruction on their future academic success. These studies highlight the importance of spatial reasoning and cognitive development in mathematics education. By understanding how students develop visualization and geometric reasoning skills, educators can create more effective instructional. These approaches will align with cognitive learning theories and enhance student achievement in mathematics.

Besides the conceptual ideas, this cluster includes important methodological contributions that help improve research in mathematics education. Creswell (2013) gives important advice on how to design strong research studies, while Cohen (1988) shares key statistical techniques for educational research.

Cluster 2: Spatial ability, cognitive development and STEM learning

Cluster 2 focuses on the role of spatial ability in cognitive development, its impact on STEM education and can be improved through training programs. The studies in this cluster show clearly that spatial ability is very important to success in science, technology, engineering and mathematics (STEM) fields and that training can make these abilities better, which helps in academic performance. A common point in this cluster is the importance of spatial ability in STEM learning. Wai et al. (2009) show through longitudinal study that spatial ability is important to success in STEM careers, meaning individuals with strong spatial abilities have a higher chance of success in STEM fields. Similarly, Shea et al. (2001) point out how spatial skills contribute to long-term educational and career results. These studies support the idea that spatial reasoning is an important skill for becoming an expert in STEM field.

Another important topic in this cluster is how spatial skills can be improved through specific training. Uttal et al. (2013) reviews 217 studies and finds that spatial ability can be much better with focused training programs. However, even though this analysis shows a general agreement on how effective spatial training is, it does not really explain how long these skills last over time. It is also not clear how different training methods work for students of different age and learning environment.

In the other hand, Cheng and Mix (2014), which indicates that training in mental rotation helps children solve mathematical problems better. This suggests a clear link between spatial ability and mathematical reasoning, but it also raises more questions about how different types of spatial tasks help with learning math. Furthermore, Sorby et al. (2013) shows that engineering students who had spatial training performed better in both spatial tasks and calculus, proving benefits that training can help in different learning areas. The findings bring up the idea that spatial training could be included more systematically in STEM education earlier in students' learning journey. These studies show that spatial ability can be developed through training. However, more research is needed to find out which training methods are most effective, how long the improvements last and whether some students benefit more than others. Future studies should also consider how digital and AI-based spatial training tools compare with traditional approaches. This will help ensure that interventions are accessible, widely available and suitable for different learning needs.

Cluster 3: Early spatial and mathematical development in education

This research cluster focuses on the early development of spatial and mathematical skills in young children. A common idea in these studies is the connection between spatial thinking and early mathematical learning. It shows that improving spatial skills can help young children in preschool and early elementary school develop better mathematics skills. One key area is the relationship between spatial abilities and mathematical development. Mix et al. (2016) study on how different spatial and mathematics skills are related in children aged 5 to 13 years. The findings show that mental rotation can predict mathematics ability in kindergarten, while visual-spatial working memory is important as children grow older. Additionally, Mix and Cheng (2012) mentioned that spatial ability and mathematical competence are closely connected and training in spatial skills may help improve mathematical performance.

Another key areas of this research cluster is the role of spatial interventions in supporting mathematical learning. Casey et al. (2008) explore how block-building activities can improve children's spatial reasoning. They found that using storytelling with block-building activities can greatly enhance spatial visualization and mental rotation abilities in kindergarten kids. Gunderson et al. (2012) also suggest that spatial skills help children understand numbers better by allowing them to create a more accurate mental number line, which enhances their ability to estimate in math. Several studies emphasize the need for spatial thinking in early education. Newcombe and Shipley (2015) created a new framework to categorize spatial skills and said that current assessments do not fully represent the complexity of spatial thinking. Likewise, Lowrie et al. (2017) showed that a structured 10-week program focusing on spatial training can lead to significant improvements in both spatial reasoning and mathematical achievement among elementary school students.

The cluster also includes research about specific activities that contribute to spatial skills development in young children. Levine et al. (2012) found that children who play with puzzles frequently develop better spatial transformation skills, which are closely connected to future success in STEM fields. Hawes et al. (2017) further support this idea by showing that integrating spatial reasoning into early geometry lessons can lead to great improvements in both spatial and numerical abilities. Furthermore, Verdine et al. (2014) examine how children's ability to construct complex block structures relates to their early mathematical skills. Their study shows that structured block play is linked to improvements in spatial visualization, understanding part-whole relationships and measurement concepts. Levine et al. (1999) study differences in spatial thinking between boys and girls. They find that boys as young as four to five years old perform better than girls in mental rotation tasks. This finding suggests that early intervention strategies may help reduce gender gaps in STEM areas.

DISCUSSION

Geometry education is very important for developing critical thinking, skills to solve problems and it plays a role in both science and art (Serin, 2018). This systematic review provides an overview of research about learning geometry over the last 30 years, combined with a bibliometric analysis. Over the past three decades, the strategies for learning geometry have become more important. This is shown by the increasing in publications, new themes of research and changes in methodologies used. The findings from this bibliometric and systematic review show important aspects, including trends in yearly publications, prominent authors, leading institutions, geographical contributions, academic landscapes, keyword analysis, citation network analysis, co-citation analysis and research content analysis. By looking into the main themes, research methodologies and influential studies in this area, the study shows significant trends and gaps in the research. These findings help provide a clear understanding of the development and structure of research in this field and provide ideas for teachers, policymakers and researchers.

The co-citation analysis of geometry learning strategies shows three related clusters. These clusters explain about the field of mathematics education, spatial cognition and early childhood learning. They also give better understanding of geometry education and how thinking skills develop. This analysis helps identify essential literature that connects ideas from different fields (Trujillo & Long, 2018). These clusters represent key thematic areas that scholars have focused on over the years and give insights into the development of mathematics education, the role of spatial ability in learning and the impact of early childhood interventions on mathematical reasoning. Cluster 1 covers the foundations of mathematics education and research methodology. This cluster emphasizes the importance of structured curriculum and teaching techniques. It provides theoretical and pedagogical frameworks that support both Spatial Ability, Cognitive Development and STEM Learning in Cluster 2, as well as Early Spatial and Mathematical Development in Cluster 3.

Research in spatial ability in Cluster 2, shows how spatial ability affects cognitive development and achievements in STEM subjects, emphasizing the role of training interventions in improving problem-solving skills. This cluster builds on the foundational theories from Cluster 1 to understand how spatial reasoning influences STEM learning. Yang et al. (2020) shows early spatial skills training, using diverse strategies like hands-on exploration, visual prompts and gestural training, plays a crucial role in enhancing young children's spatial skills in STEM fields. Similarly, the research in early childhood development from Cluster 3 explores how spatial abilities develop in young learners, giving useful ideas that impact educational practices and cognitive studies. This third cluster also highlights the value of play-based learning and hands-on experiences in developing numerical skills in early learners. The results in Clusters 2 and Cluster 3 reinforce that spatial reasoning is not just a predictor of success in STEM, but also a skill that can be developed from an early stage. Spatial abilities in young children are crucial for understanding and recalling spatial relationships and age-appropriate strategies can foster these abilities in early childhood education (Alkouri, 2022). The connection between these clusters indicates that focusing on spatial learning at all educational levels can enhance students' mathematical performance and cognitive skills.

Geometry now is one of the main focuses in current research in mathematics education including topics like geometric thinking, teacher training, argumentation and the use of digital tools (Jablonski & Ludwig, 2023). The increase in yearly publications shows a growing awareness of the importance of geometry education in improving spatial reasoning, critical thinking and problem-solving skills. Since 2008, seven major research areas have emerged in geometry education, including theories, visual spatial reasoning, diagrams, digital technologies, concept definitions, the proving process and new methods beyond traditional Euclidean approaches (Sinclair et al., 2016). Earlier studies focused on traditional teaching which emphasized on memorization and procedural knowledge. Now, the integration of technology-based learning, cognitive development strategies and interdisciplinary methods, researchers are developing new approaches to meet different learning needs. The history of geometry teaching movements in primary schools from the 19th to mid-20th centuries offers insights for 21st-century geometry teaching and pedagogical practices (Silva, 2022).

This growth in geometry learning strategies suggests increased interest among researchers, likely due to advancements in digital learning technologies, artificial intelligence and cognitive psychology. Using virtual reality techniques helps students understand mathematical subjects better (Simonetti et al., 2020). The integration of interactive learning platforms, AI assessment tools and spatial training interventions has further contributed to this growth, as educators and researchers search for more effective ways to improve students' mathematical understanding. Bujak et al. (2013) shows that AR and VR can help to improve spatial reasoning by providing learning experiences that are engaging and immersive. This technology change shows a big development in mathematics education because it changes from passive learning to ways of learning that are more student-centered and hands-on. The upward trajectory in publication trends shows that geometry learning strategies continue to be an important area of research in mathematics education. As researchers advance in this field, they will focus on innovative teaching methods, technology-enhanced learning and interdisciplinary collaborations to improve geometry instruction and student achievement. Sinclair et al. (2017) shows recent geometry education research highlights the importance of theories, visuospatial reasoning, diagrams, gestures, digital technologies, definitions and proving processes, offering promising future directions for research.

The research about geometry learning strategies shows that there are big differences in regions. These differences come from the level of research funding, support from institutions and priorities in education. Countries that have strong policies for STEM education and well-funded institutions have made significant contributions, especially in mathematics education, cognitive development and spatial reasoning. The United States has established a well-developed STEM education framework, providing clear guidance for its implementation while offering financial grants and research funding to support STEM initiatives (Zhang & Chen, 2023). On the other hand, some regions are not represented much due to not enough funding, lack of focus from institutions and limited access to technology resources. These gaps show the need for global collaboration, more funding and sharing of knowledge to boost inclusive research efforts. Different educational policies and teaching methods in various countries give opportunities for studies that cross regions, allowing for the sharing of best practices and new strategies in learning. Government funding and international collaboration in scientific research improve citation impact, with developing countries benefiting more from international collaboration led by developed country authors (Zhou et al., 2020).

The use of AI-based adaptive learning and dynamic geometry software, along with neuroscience methods, has changed the way students learn and engage with geometry concepts (Sunzuma, 2023). These early studies built the foundation for current research, which looks to psychology and neuroscience to create better teaching methods. The link between cognitive abilities, memory and geometry learning shows the combination of modern research in different fields. It uses ideas from cognitive science to improve teaching methods and assessment in geometry education. Cognitive flexibility and strong skills in geometry help students solve problems that need auxiliary lines (Muzaini et al., 2023).

The discussion of these findings shows how geometry education research connects different fields like mathematics, cognitive science, psychology and educational technology. The change in research from traditional learning to AI-based adaptive learning shows a turn towards personalized mathematics education that utilizes technology. Wei (2024) shows significant advancements in various branches of geometry in recent years, with computational methods becoming increasingly essential in geometry, bridging traditional approaches with modern technological advancements. This change is very important in the 21st-century learning environment where collaboration, problem-solving and computational thinking skills are necessary for students' achievement. Another important trend is the need for cross-cultural studies, which can provide ideas on how education systems approach teaching geometry. Researchers from different countries suggests that international collaboration can help to create the best teaching methods that can be used globally. Collaboration across cultures can improve teachers' understanding of mathematics education, which can help to overcome problems from cultural differences (Huang et al., 2021). In addition, using gamification, interactive simulations and virtual learning environments is becoming more important, showing a trend towards digital learning in education.

Limitations and Future Research

This study has some limitations that must be acknowledged. First, it relies only on Web of Science (WoS), which is detailed but does not include some important studies from other database like Scopus or Google Scholar. This may cause some important studies from non-indexed sources to be missed. Second, due to language restrictions, only English publications were included, which might cause us to miss valuable research that is published in different languages. Also, the co-citation analysis reflects only shows studies with high citation, which means that recent but significant research may not be included. For future research, it is important to use various databases, studies in multiple languages and add qualitative information to better understand geometry learning strategies.

The findings from this bibliometric study and systematic analysis give a clear overview of research trends and highlight important studies and groups in geometry learning strategies. Finding highly cited works and co-citation networks, researchers can gain useful information to build on current knowledge. The results also show gaps in research, including the need for more interdisciplinary studies that combine psychology, neuroscience and artificial intelligence (AI) in geometry education. Future studies should explore new themes such as personalized learning, adaptive learning environments and training in spatial intelligence to improve the effectiveness of teaching and learning geometry.

The results show the importance of interactive learning environments, spatial reasoning development and new teaching methods. Teachers can apply evidence-based strategies from the highly cited studies to improve student engagement and understand concepts better. Furthermore, the strong interdisciplinary connections suggest that using cognitive science and technology-based methods in geometry teaching can improve student learning outcomes, making geometry education easier to understand, more interesting and effective in real life situations. Future research could look at innovative learning methods, including the use of artificial intelligence, adaptive learning platforms and gamified learning environments to enhance student engagement and understanding in geometry.

CONCLUSION

The bibliometric and systematic review of geometry learning strategies has provided a comprehensive overview of research trends, key contributors and thematic developments in this field. The findings indicate a significant increase in research productivity over the past three decades, due to advancements in mathematics education, spatial reasoning and digital learning technologies. This growing research interest reflects a wider understanding of how important geometry learning is in mathematics education. This emphasizes the need for innovative teaching approaches and cognitive interventions to improve student learning outcomes.

The analysis of prominent authors and leading institutions reveals that key scholars and organizations have significantly shaped research in geometry education, spatial reasoning and cognitive skills development. Thematic research meetings and academic gatherings have also played a critical role in shaping this scholarly dialogue, particularly in Latin America, where events like the Geometry and Its Applications Meeting have highlighted national trends and gaps in curriculum and pedagogy (Castro et al., 2022). However, geographical distribution shows that most research comes from North America, Europe and Asia, with limited contributions from other regions. This highlights the urgent need for more international cooperation and expanded research efforts to build a broader and more inclusive understanding of geometry learning methods. The connections between geometry education, psychology, cognitive science and computer science suggest that integrating different approaches is important for solving challenges in mathematics learning. Developing reliable tools to assess how teachers organize their geometry instruction is equally important (Henríquez-Rivas & Vergara-Gómez, 2025), since pedagogical approaches directly affect how theoretical knowledge is implemented in classrooms.

Through citation analysis, three major research clusters have been identified: Foundations of Mathematics Education and Research Methodology, Spatial Ability and STEM Learning and Early Spatial and Mathematical Development. These clusters emphasize the importance of curriculum development, spatial reasoning enhancement and early childhood interventions in improving geometry learning strategies.

To turn these findings into practical steps, educators should use strategies based on evidence in their lessons, including spatial reasoning exercises and adaptive learning technologies. Furthermore, professional development programs should provide teachers with innovative strategies that align with advancement in cognitive research and digital learning technologies. Policymakers should prioritize initiatives that embed spatial reasoning skills into national mathematics curricula starting from early education, support investment in digital learning infrastructures and encourage cross-national research collaborations.

Further studies should explore the effectiveness of AI and VR-based learning tools, study the long-term effects of spatial interventions and find ways to reduce differences in research participation across region. By systematically mapping three decades of research and identifying critical gaps, emerging trends and future directions, this study provides a foundational reference for advancing the field of geometry learning strategies. It is hoped that the insights presented will guide researchers, educators and policymakers in developing more effective, inclusive and innovative approaches to mathematics education worldwide.

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