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Review paper

Visualization in Mathematics Education: Research Trends and Thematic Evolution

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ABSTRACT

Visualization is central to mathematical cognition, though the study of visualization in mathematical education (VME) has taken diverse, interdisciplinary directions. This paper seeks to critically chart the intellectual landscape, conceptual development, and research nature of VME literature. A revised bibliometric search strategy was implemented in the Scopus database using an expanded TITLE-ABS-KEY query that combined visualization-related terms with mathematics-education-specific terms. After applying document type, language, publication-year, duplicate-removal, and relevance-screening criteria, a final corpus of 279 journal articles published between 2014 and 2024 was retained for analysis. VOSviewer and Biblioshiny were used to conduct bibliometric mapping, thematic analysis, and temporal evolution to analyze patterns of publications, journals, and authors that emerged and disappeared, as well as influential collaboration patterns, thematic clusters, and research directions. Results indicate that studies on VME have been gradually increasing, with major contributions from the social sciences, mathematics, and computer science. The findings also indicate uneven geographical distribution and varying thematic concentration across VME research. This research offers a synthesis of VME research, organized by structural, thematic, and temporal perspectives. Also, the findings contribute to future visualization-focused mathematics education research by supporting stronger theoretical integration, methodological soundness, and broader contextual and technological representation across diverse educational settings.

Keywords: visualization in mathematics education, VME, bibliometrics, Scopus

The role of mathematics education in equipping learners with analytical, critical, and problem-solving skills cannot be underestimated, so the need to focus on instructional strategies that enable these students to learn concepts has endured. With the growing number and variety of themes in mathematics education research, the need for systematic methods to synthesize and interpret this research has become increasingly apparent. Among the existing strategies, bibliometric analysis has been identified as a powerful tool for analyzing trends in research, intellectual organizations, and patterns of knowledge production in educational research fields (van Eck & Waltman, 2010). Instead of assessing instruction effectiveness directly, bibliometric methods provide a macroscopic view of how research areas develop, which subjects become relevant, and how academic influence is distributed among journals, authors, and geographic areas.

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In mathematical education, the concept of visualization has long attracted interest as both a pedagogical tool and a cognitive mediator of learning. Visualization assists students in interpreting abstract mathematical concepts by enabling them to make sense of graphs, diagrams, symbolic-visual coordination, and even space (Arcavi, 2003; Presmeg, 2006; Umeh, 2025). Studies have consistently shown that visualization enhances conceptual knowledge, spatial ability, and problem-solving performance across all branches of mathematics, including geometry, algebra, and calculus (Battista, 1990; Godfred et al., 2021; Hadi & Csíkos, 2025). Recent meta-analytic findings also support the idea that instructional interventions based on visualization produce positive learning effects at all levels of learning, especially when visual representations are deliberately incorporated into learning activities (Schoenherr et al., 2024).

VME has been growing significantly in scope due to rapid technological advancement. Digital tools, such as dynamic geometry environments, augmented reality (AR), virtual reality (VR), and data visualization platforms, have transformed the interaction between learners and mathematical representations. Technology enables dynamic manipulation, multimodal interaction, and immersion in learning opportunities beyond the limitations of a two-dimensional visual display. Research has demonstrated that in mathematics classrooms, technology-enhanced visualization can facilitate creative thought and conceptual exploration, as well as learner engagement (Hadi & Kamarullah, 2024; Lee & Budwig, 2024), with high-tech communication practices enhancing the effectiveness of instructional delivery (Putra et al., 2020). Consequently, current VME studies increasingly overlap with the broader STEM education agenda and educational technology research, forming a complex, interdisciplinary body of knowledge.

Although there has been increasing emphasis on visualization in mathematics education, syntheses of the extant literature on this topic have predominantly been conducted in systematic reviews or meta-analyses. Numerous investigations have provided valuable insights into instructional design, learner performance, and the cognitive processes underlying the learning of visualization (Schoenherr et al., 2024; Schoenherr & Schukajlow, 2024). Nevertheless, these strategies are inherently limited in their ability to grasp the structural features of the research field itself. In particular, they fail to disclose the organization of VME research as a theme in literature, how current and emerging topics change over time, and how scholars' influence is distributed across journals, authors, and countries. As a result, questions regarding the intellectual organization and developmental trajectory of VME research remain inadequately addressed.

The limitation can be overcome through bibliometric analysis, which offers a distinct methodological perspective. Bibliometric studies can determine the most prevalent research topics and thematic processes, and reveal intellectual connections within a discipline, using performance indicators and science-mapping methods, including co-word analysis, thematic mapping, and network visualization (Assefa & Rorissa, 2013; Cevikbas et al., 2024). Bibliometric methods have also been used in research on mathematics education to investigate research priorities and methodological orientations over time, including STEM education, mathematics anxiety, metacognition, and problem-solving (Julius et al., 2021; Thi-Nga et al., 2024; Wahyuni et al., 2025). Nevertheless, in these bibliometric studies, visualization has received little attention as a critical analytical lens.

Though related domains, including STEM education (Gil-Doménech et al., 2020; Dogutas, 2025), technology-enhanced learning (Suherman et al., 2023), ethnomathematics (Deda et al., 2024), problem-based learning (Mailili et al., 2025), and inclusive education (Kamarullah et al., 2024), have been covered in bibliometric research, a systematic bibliometric mapping of visualization in mathematics education as a specific research field still cannot be found. The available literature tends to treat visualization as a secondary element within a broader theme rather than as an object of study. Consequently, little is known about how VME research has developed over the last decade, the thematic clusters underpinning the field, and which scholarly efforts have had the greatest impact.

To address this gap, the present study provides a bibliometric review of visualization in mathematics education research published between 2014 and 2024 and indexed in Scopus. The study uses an expanded and conceptually delimited search strategy that combines visualization-related terminology with mathematics-education-specific terminology. By integrating performance analysis, science mapping, co-word analysis, and thematic mapping, the study examines the intellectual structure, thematic patterns, and influential contributions represented in the analyzed corpus. To be more specific, the study will address the following research questions:

1. What key themes and emerging trends can be identified through the analysis of titles, abstracts, and keywords in VME research?
2. Which journals and authors have contributed most significantly to the development of visualization research in mathematics education?
3. Which research topics and publications have exerted the greatest scholarly influence within the VME literature?

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METHODS

Research design

The research design adopted in this study is a bibliometric research design with a scientific mapping structure, aimed at analyzing research trends and knowledge structures in VME. Bibliometric analysis, on the other hand, is a quantitative methodology applied to evaluate a research area by analyzing bibliographic metadata, including publication formats, thematic frameworks, and impactful scholarly contributions. This research design is suitable for addressing research questions focused on thematic trends, high-publication-frequency contributors, and intellectual influence, rather than on the effectiveness of instruction.

The analytical process involved five consecutive steps: planning the research, retrieving the data, filtering the data, transforming and cleaning the data, and finally analyzing and interpreting the bibliometrics. Two complementary bibliometric software (VOSviewer and Biblioshiny) were used. The former was used for network visualization and clustering, whereas the latter was used to support long-term science mapping and thematic analysis.

Full counting was applied during co-occurrence and co-authorship analyses. Network normalization in VOSviewer used the association strength method to identify relationships among keywords, authors, and thematic clusters. Minimum occurrence thresholds were adjusted for each visualization's analytical objective to balance network readability and conceptual coverage. Cluster formation and visualization parameters were set to the default values provided by the software, including attraction and repulsion values in VOSviewer. Biblioshiny was additionally used for thematic mapping and thematic evolution analyses across predefined time slices (2014–2018, 2019–2021, and 2022–2024).

Data collection

The data collection process consisted of four stages: retrieval, filtering, transformation, and cleaning. Publication data were obtained from the Scopus database due to its broad coverage and compatibility with bibliometric analysis tools. The data search targeted journal articles published between 2014 and 2024 to examine the trend in VME research over the last 10 years. The search strategy was designed to capture interdisciplinary studies related to visualization in mathematics education while minimizing premature exclusion during the initial retrieval stage.

TITLE-ABS-KEY ("visualization" AND "mathematics" AND "education") AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar"))

Accordingly, the TITLE-ABS-KEY field was used with the terms "visualization," "mathematics," and "education" connected through Boolean operators. Because visualization-related studies may appear across mathematics education, STEM education, educational technology, and cognitive learning contexts, an initially broad retrieval strategy was adopted to maximize coverage. The retrieved records were subsequently filtered at multiple stages based on subject area, document type, language, open-access status, and manual relevance screening to reduce conceptual noise and improve topical specificity.

This search, then, provided 928 journal articles. Other types of publications, such as books, conference papers, and proceedings, were ruled out to maintain uniformity in publication type.

Data filtering

After retrieval, a multi-stage filtering procedure was used to ensure relevance to visualization in mathematics education. Relevance was determined by using titles, abstracts, and keywords to screen publications. Further inclusion criteria were implemented in the following way:

1. Subject areas limited to social sciences, psychology, mathematics, and computer science
2. Keywords related to visualization, mathematics, and mathematics education
3. English-language publications
4. Open-access journal articles

The filtering process applied the following Scopus limitations:

LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "PSYC") OR LIMIT-TO (SUBJAREA, "MATH") OR LIMIT-TO (SUBJAREA, "COMP")
LIMIT-TO (EXACTKEYWORD, "Visualization") AND (LIMIT-TO (EXACTKEYWORD, "Mathematics") OR LIMIT-TO (EXACTKEYWORD, "Mathematics education"))
LIMIT-TO (LANGUAGE, "English") AND LIMIT-TO (OA, "all")

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Only open-access journal articles were included, while publications that did not directly correspond to the study's focus were excluded. A final manual relevance screening was conducted to exclude records that were conceptually unrelated to visualization in mathematics education, even if they matched the initial query terms. Author names, source titles, and keyword metadata were manually standardized where inconsistencies, abbreviations, or duplicate forms were identified prior to bibliometric mapping. At the end of this filtering step, 381 articles were left. To proceed to the next step, the data were converted into a form suitable for analysis. Subsequent manual relevance screening, duplicate removal, and metadata standardization resulted in a final corpus of 279 articles for bibliometric analysis.

Data transformation

The filtered data were saved to CSV and RIS files, including bibliographic data, abstracts, keywords, and citation data. The data were also exported in various formats, ensuring compatibility with both VOSviewer and Biblioshiny and enabling cross-validation of the analysis results.

Data cleaning was then conducted in order to enhance the accuracy and reliability of the datasets. This was done by matching and eliminating duplicate records, filling in missing or erroneous records, and standardizing differences in journal and author names. After data cleaning, as mentioned, a final dataset of 279 journal articles was retained for bibliometric analysis.

Bibliometric analysis procedures

The bibliometric analysis involved two supplementary elements. First, a performance analysis was conducted to examine the growth in publications, leading journals, most productive authors, and country-level contributions to VME research publications. Second, science mapping methods were used to reveal thematic patterns and connections among the main concepts. VOSviewer was used for co-word analysis and network visualization, and Biblioshiny was used to facilitate analysis of thematic evolution and conceptual structures. The combination of these tools enabled comprehensive mapping of the VME research field.

RESULTS

Main dataset overview

The data used in this bibliometric analysis is a sample of 279 journal articles on visualization in mathematics education published between 2014 and 2024 (see Figure 1). The references were obtained from 194 scholarly journals, indicating widespread dissemination of VME research across various publication sources. The dataset includes 1,054 authors, and single-authored publications were extremely limited, indicating that the field is highly collaborative.

Figure 1

Main information of the bibliometric dataset on VME

Publication rates are rising by 16.59%, suggesting that academic interest in research on visualization in mathematics education has remained stable over the last 10 years. The patterns of collaboration also reinforce this tendency, as the average number of co-authors per document is 6.67, accompanied by an international co-authorship rate of 15.41%, indicating moderate rates of cross-national research collaboration.

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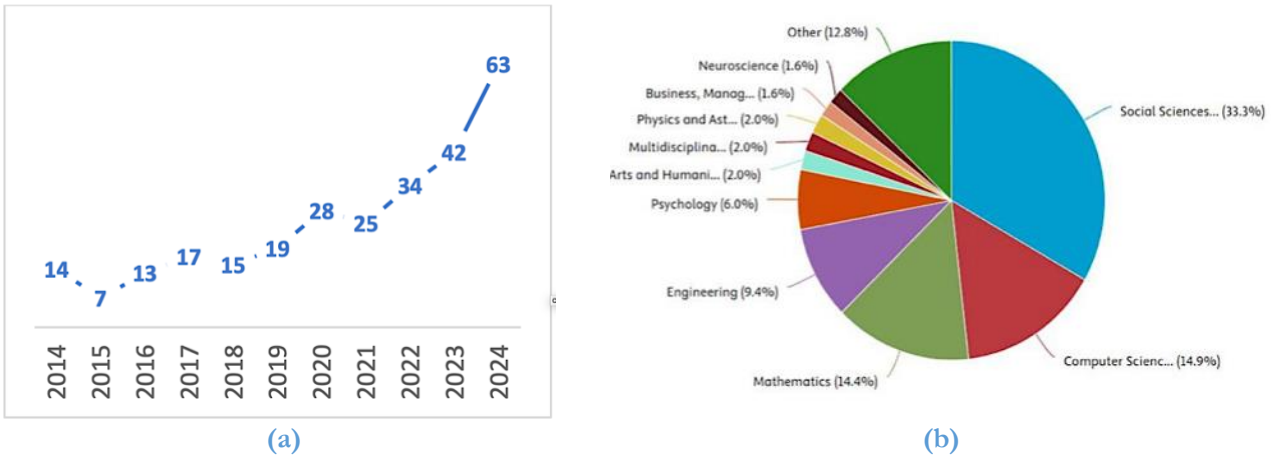
The dataset has 949 unique author keywords in thematic diversity and, therefore, a broad scope of research topics and conceptual approaches. The mean age of documents is 5.28 years, indicating that the literature base is quite new, and the average number of citations per document (13.07) suggests ongoing scholarly engagement with the published materials. All these signs give a descriptive picture of the magnitude, development, and collaborative attributes of visualization studies in math instruction.

Descriptive overview of VME research output

This subsection provides a descriptive summary of the publication properties of studies on VME, based on the ultimate dataset of 279 journal articles published in 2014-2024. The review addresses the temporal increases and decreases in publications and coverage of the subjects to determine the scope and contextual background of the discipline.

Figure 2

VME documents categorized by **(a)** *publication year and* **(b)** *subject area*



(a) **(b)**

Figure 2(a) shows the number of publications concerning VME published annually over the research period. In general, the number of publications shows an upward trend, indicating that more scholarly attention is being paid to visualization in mathematics education. Although some downward trends are evident in some years, the number of publications is higher in the second half of the period. Specifically, the number of publications increases significantly in the years following 2021, with the highest number in 2024. This trend attests to the long-term existence of research activity and to the increasing interest in visualization issues in mathematics education over the last decade.

Figure 2(b) shows the disciplinary distribution of VME research. The findings suggest that VME research spans several subject areas, reflecting its interdisciplinary nature. The largest share of publications is attributed to the social sciences, computer science, and mathematics. Other sources of contributions are found in other domains of study, underscoring the fact that visualization in mathematics education is studied at the pedagogical, technological, and disciplinary levels rather than as part of a single area of study.

Influential journals, authors, and countries

In this sub-section, the scholarly generation and impact within the VME are analyzed by identifying the top journals, the most productive authors, and country-wise contributions using the ultimate dataset of 279 journal articles.

Journals

Research on VME has been published in a variety of scholarly journals. **Table 1** shows the top ten journals in terms of publications on visualization in mathematics education, in the Scopus quartile ranges Q1-Q4. Among these sources, ZDM - Mathematics Education is the most prolific, having provided the greatest number of articles over the course of the study. Other prominent journals are the *International Journal of Mathematics Education in Science and Technology*, *Eurasia Journal of Mathematics, Science and Technology Education*, *Computers in the Schools*, and *Education Sciences*. The presence of several Q1 and Q2 journals among the top journals shows that VME research is reflected in highly impactful, established journals in education.

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Table 1

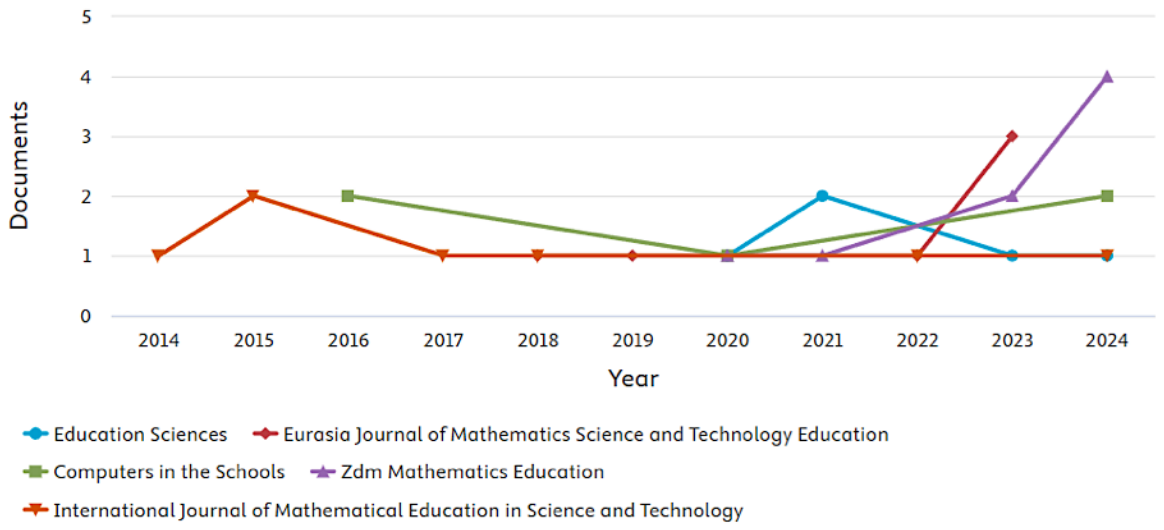
Top 10 journals publishing research on VME

No	Name of Journal	Documents (*n*)	Scopus Quartile	SJR (2024)
1	*ZDM Mathematics Education*	8	Q1	1.534
2	*International Journal of Mathematics Education in Science and Technology*	7	Q2	Discontinued 2023
3	*Eurasia Journal of Mathematics, Science and Technology Education*	6	Q2	0.554
4	*Computers in the Schools*	5	Q2	0.554
5	*Education Sciences*	5	Q1	0.730
6	*Frontiers in Education*	5	Q2	0.650
7	*Annales Mathematicae et Informaticae*	4	Q4	0.159
8	*Computer Applications in Engineering Education*	4	Q1	0.831
9	*Journal on Mathematics Education*	4	Q3	0.348
10	*Mathematics Teaching Research Journal*	4	Q3	0.301

Figure 3 shows the distribution of publications across the most popular journals over time. The findings reveal that several journals have been active over the years, but more publications have been observed in the latter years of the research period. It has been argued that this distribution indicates long-term editorial attention to topics in mathematics education concerned with visualization, rather than isolated or intermittent patterns of publication.

Figure 3

Annual publication distribution across leading VME journals



Authors

At the author level, 874 authors were identified in the VME literature for this analysis. Table 2 includes the most productive authors based on the number of publications (NP), total citations (TC), and h-index. Within the dataset, Mantri, A. has the most publications and the most citations, indicating a strong influence on scholarship. The other authors who have made considerable contributions are Gargrish, S., Singh, G., Zengin, Y., and Tatar, E., each of whom has written several articles on VME topics.

Figure 4 illustrates the publication distribution of prominent authors, highlighting differences in research productivity, whereas Figure 5 shows the collaboration patterns of authors. The collaboration network, both in the form of interrelated groups of authors and in the form of relatively independent contributors, implies the presence of collaboration clusters of researchers and separate research paths in the field.

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Table 2

Leading authors in VME based on publication and citation indicators

Author	Institute/Country	NP	TC*	H-index	Start
Mantri, A.	Anurag University/India	4	165	21	2021
Gargrish, S.	Chitkara University/India	3	159	7	2021
Singh, G.	Chitkara University/India	3	155	11	2021
Zengin, Y.	Dicle Üniversitesi/Turkey	3	112	11	2015
Tatar, E.	Atatürk University/Turkey	3	63	7	2014
Caglayan, G.	New Jersey City University/USA	3	35	7	2015
Nagy-Kondor, R.	Deprecen University/ Hungary	3	13	6	2014
Burte, H.	Carnegie Mellon University/USA	2	66	10	2017
Cole, M.	University of Nevada/USA	2	28	5	2015
Blanco, T.F.	University of Santiago de Compostela/Spain	2	4	7	2019

*Citation counts (TC) were retrieved from the Scopus database at the time of the data collection.

Figure 4

Number of publications by authors

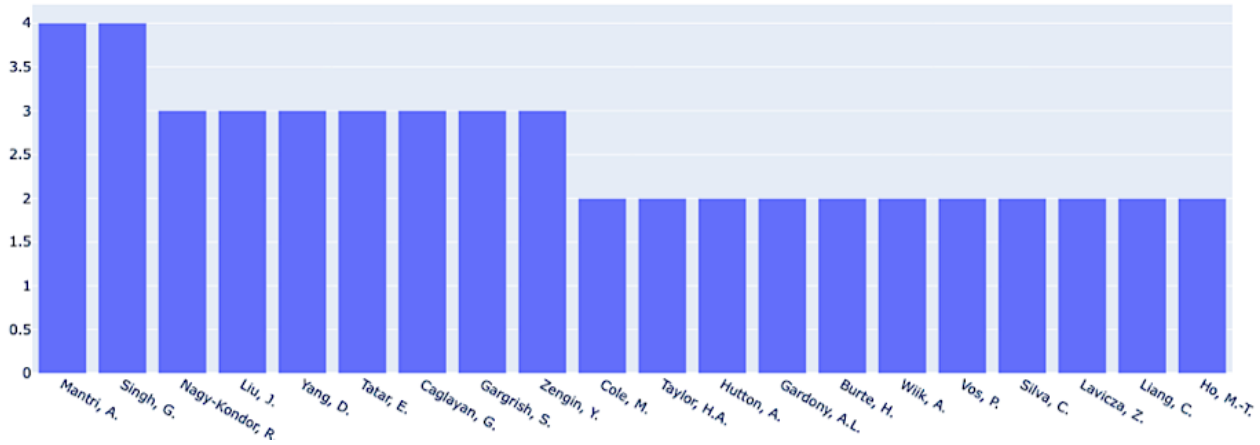
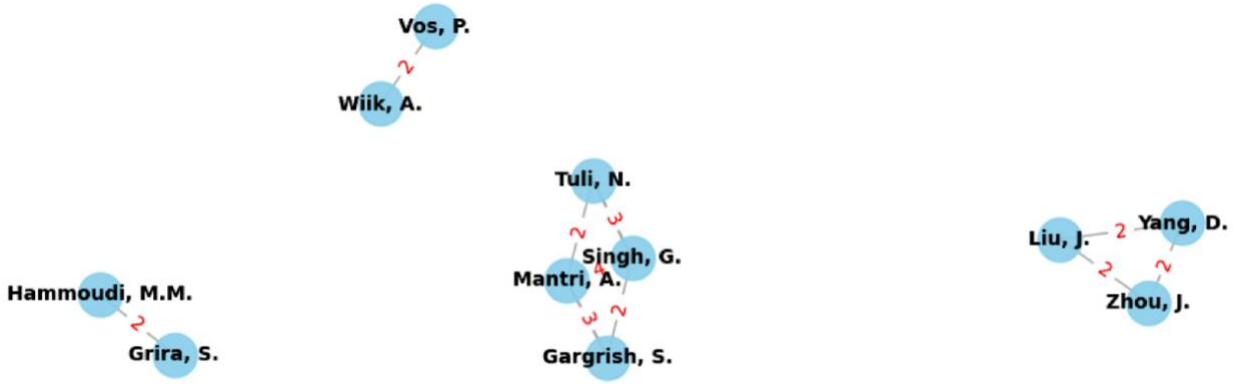


Figure 5

Author collaboration network in VME research



Countries

VME research is widely international with the geographical distribution. The dataset includes publications from approximately 69 countries, demonstrating the global nature of visualization research in mathematics education. Figure 6 presents the top countries by number of publications. The United States is the largest producer of research, followed by Indonesia, Brazil, China, and Turkey. Other contributions from European and other countries also indicate that VME research is not confined to a specific geographical setting but is spread across other educational systems.

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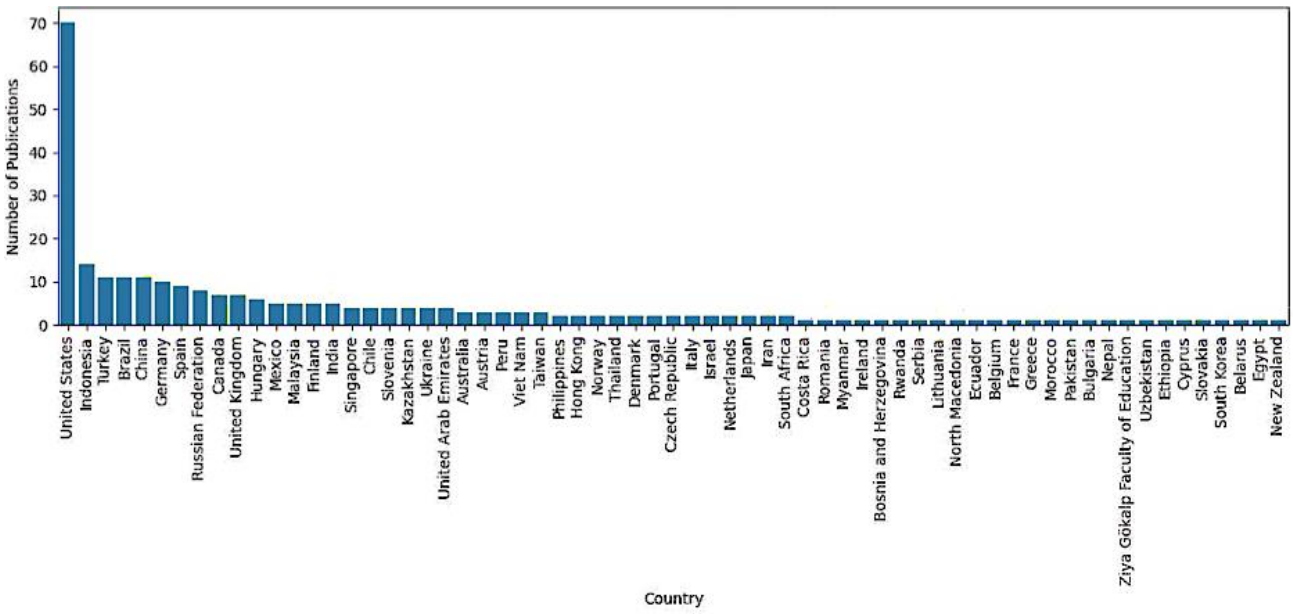
Figure 6

Number of publications by country



On the whole, the journals, authors, and country analysis give a descriptive picture of the scholarly output and impact in the VME research field. These results define the institutional and geographical background of these conceptual structures and thematic patterns in the following subsection.

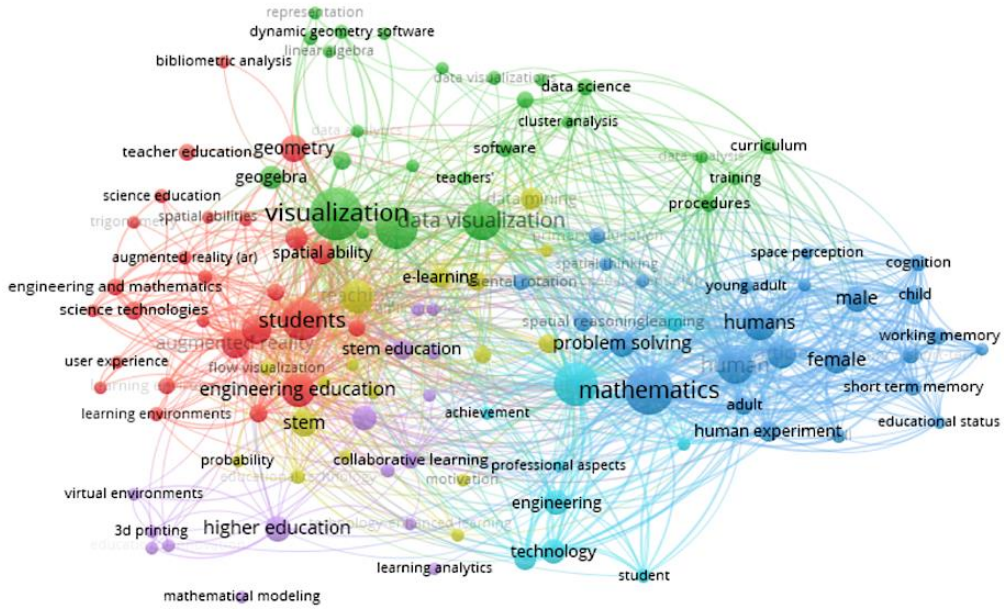
Conceptual structure of VME

Thematic clusters in VME research

To analyze the conceptual structure of VME, a co-word analysis was performed on the final dataset of 279 articles using author keywords and index terms. The resulting network representation is shown in Figure 7, where we can see a structured thematic topography with six mutually dependent clusters pointing to VME research being organized around a variety of conceptual orientations, not one giant paradigm.

Figure 7

Network visualization of thematic clusters in VME



Based on 32 keywords, the first cluster focuses on technology-based visualization and learning in the context of STEM, including themes such as augmented reality, computer-assisted learning, three-dimensional

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visualization, learning environment, and user experience. This cluster indicates a strong inclination towards integrating digital technologies to support visualization-based learning in STEM fields, highlighting the growing role of immersive and interactive technologies in mathematics education.

The second (25-item) cluster is associated with data visualization, mathematical encapsulations, and teaching aids, such as dynamic geometry software (GeoGebra), data science, statistics, linear algebra, and representation. In this cluster, the emphasis is on the pedagogical application of the visualization as a tool for representing mathematical structures and processes, as it relates to mathematical content knowledge and teacher practice.

Having almost equal numbers of items compared to the second cluster, the third cluster concerns the cognitive and psychological principles of visualization, and some of the key topics include spatial reasoning, mental rotation, working memory, problem-solving, cognition, and spatial perception. This set of studies reflects a long history of research in mathematics education, focusing on how learners process visual information and how spatial skills help them acquire mathematical knowledge.

The fourth cluster, which comprises 17 items, combines the educational technology and learning systems themes, including e-learning, human-computer interaction, learning systems, motivation, visualization tools, and virtual reality. The conceptual overlap between this cluster and the first cluster is that, whereas the first cluster focuses more on the specific application of instructional methods, this cluster focuses more on the system-level design and technology-mediated learning processes.

After that, with 16 items, the fifth cluster highlights higher education, applied visualization, and pedagogical innovation, including themes such as mathematical modeling, collaborative learning, technology-supported learning, STEM education, and higher education contexts. This group indicates that research in the field of visualization is now more likely to be situated within the context of applied and professional learning, specifically at the tertiary level.

The sixth and smallest cluster (9 items) is associated with assessment, learning outcomes, and professional dimensions, including themes such as achievement, educational measurement, professional aspects, and learning. Even less well-knit than the other clusters, this cluster points to a growing interest in assessing the consequences and broader educational implications of visualization-based approaches.

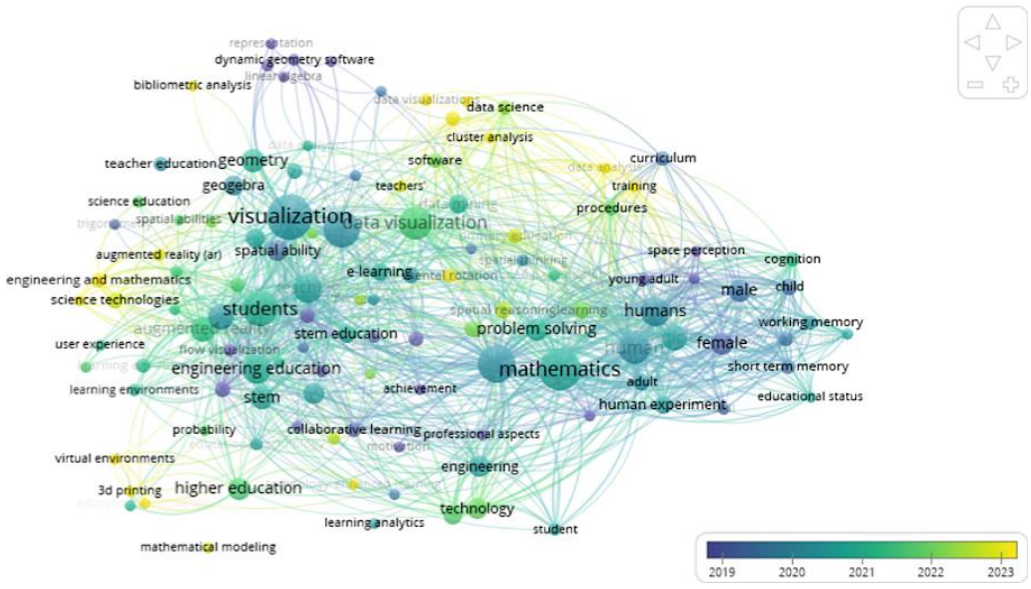
In general, the co-word network shows that VME research is theoretically grounded in three main areas, namely: (a) cognitive and spatial knowledge, (b) pedagogical representations and instructional technologies, and (c) technology-enhanced and STEM-based learning environments. These interrelationships among clusters do not imply that these domains are independent; rather, they are dynamically interacting with the rest of the VME research touchstone.

Temporal orientation of VME research themes

To discuss the temporal patterns of research topics in VME, an overlay map was created by adding the year of publication as a weighting factor (**Figure 8**). This discussion offers insight into how the thematic areas of interest have evolved over time in the discipline and provides a preliminary temporal approach to the evolution of research.

Figure 8

Overlay visualization of VME research themes by publication year



Themes from earlier research, represented by darker-colored nodes, are mostly related to cognitive and spatial constructs, including mental rotation, spatial perception, working memory, and problem-solving. These topics constitute a bottom layer of VME studies, the initial academic interest in the psychological processes of visualization and mathematical thought.

The newer themes, as shown by the lighter-colored nodes, are increasingly focused on technology-mediated visualization, such as augmented reality, virtual reality, data visualization, dynamic geometry software, and e-learning environments. These themes, being especially popular in the publications around 2021 and later, indicate a tendency toward the increased popularization of the approach to visualization in mathematics education, towards the use of technologies to enrich it.

As can also be seen in the overlay map, pedagogical and technological themes are strongly associated with the basic cognitive constructs, implying that newer research does not supersede previous theoretical views but instead extends them. This trend indicates a theme of thematic expansion, in which cognitive theories of visualization continue to guide the design and implementation of virtual and immersive learning spaces.

Notably, the temporal distribution indicates that research activity on technology-oriented visualization is growing faster in the most recent years of the data, which is also consistent with the overall trends in the digitalization of education. Although the overlay visualization only partially analyzes the temporal patterns of the thematic evolution, it provides clear indications that VME research has gradually shifted its focus from the cognitive underpinnings of its application to a more integrated pedagogical and technological implementation.

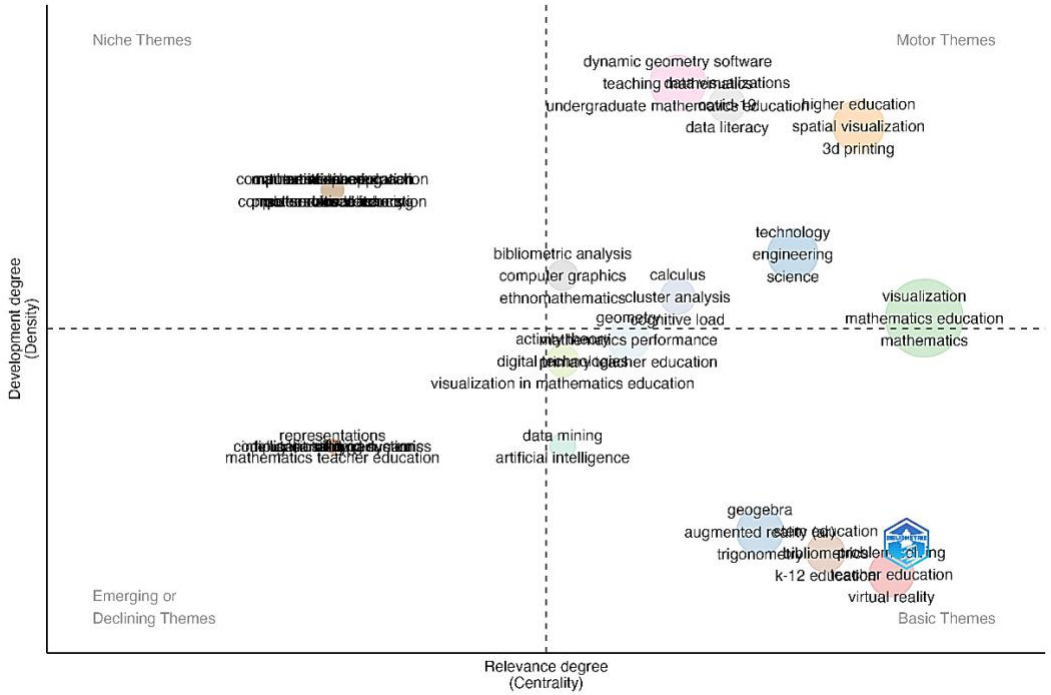
Thematic evolution of VME

To deepen discussions of the dynamics of VME, a thematic evolution analysis was conducted in Biblioshiny using author keywords and three time points (2014-2018, 2019-2021, and 2022-2024). This analysis complements the structural understanding of co-word and overlay analyses by determining how research themes change, consolidate, or emerge over time.

Figure 9 shows the thematic map, which is analyzed using the centrality and density measures, and categorizes themes into motor, basic, niche, and emerging/declining. The motor themes with high centrality and density include dynamic geometry software, data visualization, spatial visualization, and higher education. These themes are well-developed and closely related to the broader research field, as evidenced by their positioning, which characterizes them as central to modern research on VME.

Figure 9

Thematic map of VME based on centrality and density



Basic themes with high centrality and low density include visualization, mathematics education, teacher education, problem solving, virtual reality, and augmented reality. These themes are the conceptual frameworks of the field and are widespread across studies; however, their development varies. Their popularity indicates that

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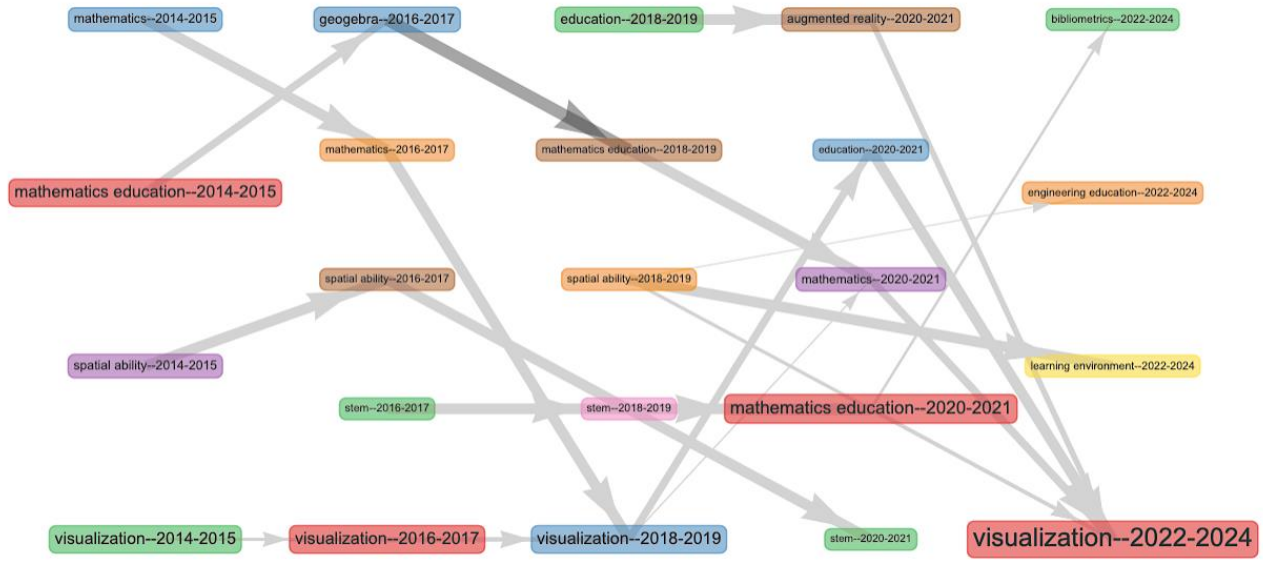
technologies and pedagogical tools that utilize visualization are now considered part of the research area of mathematics education rather than marginal inventions.

Themes placed in the niche quadrant, like computer graphics, bibliometric analysis, and ethnomathematics, have high internal cohesion but comparatively poor integration with the rest of the VME research network. These themes are customized research topics that add in-depth elements to the field, yet at a conceptual level. Conversely, new or possibly weaker-performing themes, such as artificial intelligence, data mining, and some representational techniques, have lower centrality and density, suggesting that these fields are at a low level of pattern or are receiving less research interest.

Figure 10 shows the long-term pattern of themes. In the early years (2014-2018), VME studies were largely grounded in foundational constructs such as mathematics teaching, visualization, and spatial skill. The latter themes formed the conceptual foundation on which subsequent patterns were based. During the middle period (2019-2021), the research direction broadened to STEM education, GeoGebra, and education more broadly, designating growing interest in technology-mediated visualization tools and their interdisciplinary use.

Figure 10

Thematic map of VME research across three time periods (2014–2018, 2019–2021, 2022–2024)



In the latest phase (2022–2024), the evolution map shows a focus on and diversification of themes, with visualization and mathematics education remaining at the center, alongside a subset of applications, such as learning environments, engineering education, and bibliometrics. The fact that bibliometric analysis has become a noticeable trend in the most recent era reflects growing academic concern with mapping and synthesizing VME research per se, thus pointing to a stage of conceptualization and increasing consolidation in the sector.

All in all, thematic evolution analysis shows that VME research has moved from basic cognitive and representational issues to more technologically enriched, application-driven, and reflexive research. This trend aligns with the organizational patterns identified in the VOSviewer-based analyses and provides a temporal view of how visualization in mathematics education has evolved over the last decade.

Highly influential publications and research foci

Citation analysis was performed on the final set of 279 articles to identify the most influential research areas shaping the field of visualization in mathematics education. Table 3 presents the ten most frequently cited publications, providing a perspective on the intellectual anchors that have shaped VME research over the last ten years.

The most popular source focuses on data visualization literacy, the central process that encompasses conceptual frameworks, instructional practices, and assessment methods for visual data interpretation. The eminence of this work suggests that visualization research in mathematics education is not confined to representational support but also entails the expansion of learners' interpretative and analytical skills. This concentration represents an increased correspondence between mathematics teaching and the wider movements in data literacy.

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Table 3

Top 10 most cited articles in VME

No.	Article Title	Authors	Source (Journal)	TC	Year
1	Data visualization literacy: Definitions, conceptual frameworks, exercises, and assessment	Börner et al.	Proceedings of the National Academy of Sciences of the United States of America	203	2019
2	Learning is moving in new ways: The ecological dynamics of mathematics education	Abrahamson & Sánchez-García	Journal of the Learning Sciences	161	2016
3	A framework utilizing augmented reality to improve critical thinking ability and learning gain of the students in physics	Faridi et al.	Computer Applications in Engineering Education	102	2021
4	Development of a cognition-priming model describing learning in a STEM classroom	Lamb et al.	Journal of Research in Science Teaching	90	2015
5	The effect of augmented reality on students' learning performance in STEM education	Petrov & Atanasova	Information	78	2020
6	First demonstration of effective spatial training for near transfer to spatial performance and far transfer to a range of mathematics skills at 8 years	Gilligan et al.	Developmental Science	62	2020
7	EzCADD: A rapid 2D/3D visualization-enabled web modeling environment for democratizing computer-aided drug design	Tao et al.	Journal of Chemical Information and Modeling	62	2019
8	Think3d!: Improving mathematics learning through embodied spatial training	Burte et al.	Cognitive Research: Principles and Implications	58	2017
9	Virtual engineering sciences learning lab: Giving STEM education a second life	August et al.	IEEE Transactions on Learning Technologies	55	2016
10	Investigating the use of the Khan Academy and mathematics software with a flipped classroom approach in mathematics teaching	Zengin	Educational Technology & Society	54	2017

The body of literature includes a number of works that focus on embodied, cognitive, and ecological approaches to learning, emphasizing the role of movement, perception, and interaction in learning mathematics. These writings emphasize the enduring role of cognitive and learning sciences in the study of VME and show that early theories continue to play a significant role in current visualization practice.

The other category of publications of significant influence is the one that deals with technology-enhanced visualization, especially augmented reality and virtual environments used in STEM-based learning environments. These reports highlight the potential of immersive technologies to support critical thinking, learners' gains, and a general understanding of concepts, and research on technology-oriented visualization is becoming more visible in the field.

It is important to note that the most-referenced articles represent a variety of journals spanning the boundaries among mathematics and science education, educational technology, educational science, and cognitive science. This dispersion implies that the powerful research in VME is not concentrated in a single academic source but is disseminated across different academic circles. The variety of available sources of publication can also be considered as a result of the interdisciplinary nature of the study of visualization in mathematics education.

Altogether, patterns of citations suggest that the emerging trends in influential VME studies comprise three prevailing orientations, namely: (a) data visualization and literacy, (b) cognitive/embodied learning perspectives, and (c) technology-enhanced and immersive visualization settings. These orientations are quite consistent with

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the thematic systems identified by the co-word and overlay analyses and support the alignment between the conceptual organization and the scholarly power within the discipline.

DISCUSSION

Structural characteristics of VME research: Productivity, collaboration, and geography

The structural features of VME illuminate an area that is increasing in output but remains unbalanced in its relationship patterns and geographical distribution. Bibliometric measures of VME research productivity, authorship, and contributions at the country level are examples of how VME research is structured and published within the mathematics education community worldwide.

In terms of productivity, the gradual increase in publication volume, especially since 2020, reflects growing academic interest in visualization as a cognitive and pedagogical construct. This publication pattern is in line with general trends in the research literature of mathematics education, in which technology-enhanced learning environments and representational structures have become dominant (Cevikbas et al., 2024). The fact that the publications are concentrated in a limited set of high-impact journals (**Table 1**), such as *ZDM Mathematics Education and Computer Applications in Engineering Education*, is a bibliometric indication that VME research is becoming integrated into the mainstream body of research in mathematics education and in interdisciplinary STEM journals.

Patterns in authorship also indicate that VME research is conducted by a comparatively small set of productive researchers, with more occasional contributors (**Table 2**). Although some of the authors show continued involvement in the field, the network of author collaboration (**Figure 5**) indicates moderate collaboration, mostly within stable, limited research circles. This trend aligns with previous bibliometric studies in mathematics education, which report disorganized collaboration formats and a lack of cross-group integration (Julius et al., 2021; Mailili et al., 2025). This discipline can limit the creation of cumulative research agendas and massive comparative research.

In terms of geography, VME research is highly concentrated in a few countries, such as the United States, Indonesia, and several countries in Europe and Asia, which account for most publications (**Figure 6**). Such a distribution shows both the capacity of research in the region and unequal access to technology resources that facilitate visualization-based research. The presence of similar geographic imbalances has been documented with other related bibliometric reviews of mathematics and STEM education (Assefa & Rorissa, 2013; Gil-Doménech et al., 2020). Meanwhile, the fact that developing contexts are making their contributions indicates increasing globalization, though with unequal presence and influence.

Combined, these organizational features portray VME as an area that is characterized by rising productivity and greater thematic concentration but is limited by a narrow scope of collaboration and knowledge production that is geographically centered. These trends form the necessary background of how the conceptual base and technological pathways are considered in the further sections.

Conceptual foundations in VME

VME is conceptually based on representation, cognition, and learning theories that have long been in existence. Throughout the literature, visualization has always been conceptualized as a primary process of making mathematical meaning, as an instructional means of enabling learners to learn how to interpret, transform, and coordinate many representations.

One of the major theoretical strands is based on the use of visual representations in conceptual learning. The work of pioneers stresses that visualization helps the learner to shift among the symbolic, graphical, and diagrammatic representations, thus helping in abstraction and mathematical reasoning (Arcavi, 2003; Presmeg, 2006). These systems are based on a significant amount of VME research, especially in areas of geometry and calculus, where representational coordination is mandatory.

The other prevailing conceptual background is based on the understanding of space and embodied learning. Research on this strand views visualization as being inevitably related to spatial capacity, mental rotation, and sensorimotor involvement. The treatment of visualization as embodied cognitive as opposed to a visual process is, therefore, consistent with the research that shows how spatial training can enhance mathematical performance (Battista, 1990; Burte et al., 2017; Gilligan et al., 2020). This point of view is especially strong in the works that deal with geometry, learning in STEM, and technology-based settings.

Simultaneously, interaction theories place emphasis on dynamic disposition in the relation between learners and visual representations. In this perspective, visualization-based learning is not only based on the visual representation but also on the interaction between the learners with the visual objects and the manipulation (Sedig & Sumner, 2006). This theoretical stance has been used to guide research into dynamic geometry software,

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interactive simulation, and digital visualization software, in which learner control and feedback are key design concerns.

Too, the educational value of visualization extends beyond mathematics. Bakir and Banikhalaf (2025) showed that integrating artistic representations into science learning enhanced conceptual understanding, visual memory, and student engagement, reinforcing the broader pedagogical role of visual representations across STEM disciplines.

Combined, these theoretical underpinnings put visualization in mathematics education as a complex concept that takes into consideration representational, cognitive, embodied, and interactional aspects. These views do not necessarily oppose each other, but are merged to form the modern VME studies, which offer a theoretical framework to the technological advances and changes of theme discussed in the following sections.

Technological shift and thematic evolution in VME research

The bibliometric outcomes reflect that there is an emerging trend in VME technology with the gradual change of the static environment representations to dynamic, immersive, and data-driven visualization spaces. Thematic mapping and analyses of the temporal evolution (**Figure 10**) indicate that older studies mainly focused on traditional visual representations, whereas more recent ones incorporate digital technologies as one of the key elements in the process of instructional design substantially.

One of the oldest and least volatile technology strands in VME research is represented by dynamic geometry software. Research on this topic dwells upon interactions between learners and manipulable visual objects with emphasis on the importance of full interaction, through feedback and exploration, in facilitating conceptual learning (Sedig & Sumner, 2006; Zengin, 2017). This strand is also evident throughout the study period, especially in geometry and the school's second-level setting, which has not been rendered obsolete but is relevant.

Thematic developments are more recent, and they are characterized by the increasing popularity of immersive technologies such as augmented and virtual reality (Hadi & Kamarullah, 2024). Seeing-AI, to illustrate, significantly improved mathematics retention among students with visual disabilities (Asanre et al., 2026). These technologies tend to be identified with spatial reasoning, learning with STEM, and the university environment. Although bibliometric patterns indicate the growing academic popularity, immersive visualization is not as popular as dynamic or static methods, which confirms it as an evolving and not a mainstream direction of research (Drijvers & Sinclair, 2023; Petrov & Atanasova, 2020). The extension beyond conventional graphical representations is even moving toward intelligent and accessibility-oriented learning environments.

Simultaneously, the rise of data visualization as a topic of study is indicative of more general trends in mathematics education, to data literacy and data visual analytics. The research in this cluster focuses on the skills of learners to interpret, create, and make arguments about visualized information, expanding the field of visualization to non-mathematical forms of presentation (Börner et al., 2019). This evolution comes in line with more focus on statistics and interdisciplinary applications that are found in the Results.

On the whole, the thematic temporal pattern of VME research implies that technological innovation does not substitute but is an addition to conventional visualization practices. It is a continuity and change field with new technologies being added to the already existing conceptual basis. The given pattern highlights the necessity of considering the aspects of not only technological freshness but pedagogical assimilation and learning influence as well, which is discussed further in the following sections.

Intellectual anchors and influential research directions

VME's intellectual structure has its foundations in a range of highly cited works that have provided intellectual orientations as well as empirical agendas. The citation analysis (**Table 3**) reveals that there are three directions (three directions that are interrelated) that influence studies: visualization as a cognitive process, visualization as an interactional practice, and visualization as a technology-mediated learning environment.

To begin with, some of the earliest contributions to the area of visualization theorize visualization as part of mathematical thinking and meaning-making. Classical studies on visual representations highlight how learners interpret, relate, and change representational forms as a key element to comprehend mathematics (Arcavi, 2003; Duval, 2017; Presmeg, 2006). These works are a theoretical foundation of much of the later literature on the subject of VME and have remained in popular reference in a broad range of studies.

Second, there is an active stream of influential studies regarding the importance of interaction and embodiment in learning using visual representations. The most frequently cited research shows that visualization has the greatest effect on learning when learners are actively involved in dealing with representations: manipulation, movement, or spatial reasoning (Battista, 1990; Burte et al., 2017; Gilligan et al., 2020). This is the

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direction that has guided the study of dynamic geometry environments and spatial training intervention, which supports the association between visualization and cognitive development.

Third, technology-focused studies are a more powerful anchor in the field. The studies of dynamic software, augmented reality, and virtual environments have influenced modern research agendas through the extension of the affordances of visualization beyond fixed representations (Drijvers & Sinclair, 2023; Petrov & Atanasova, 2020; Zengin, 2017). Although these works are not as uniformly mentioned as the foundational theories, their increasing impact can be observed as a result of changing priorities toward digitally mediated learning situations.

Combined, these intellectual pillars also show that powerful VME research does not cluster around a single paradigm. Rather, it represents a dialogue of the cumulative one between theory-based foundations and innovation driven by technology. In combination with the presence of timeless theoretical literature and the new scientific literature on technologies, it is possible to assume that the future powerful literature will be able to merge strong theoretical concepts with empirical and practically significant methods.

Methodological and substantive implications for future VME research

Although the theme-based diversification and gradual increase in VME research are understandable, the combined bibliometric and thematic analysis shows that there are multiple gaps in research that could be addressed methodically and substantially. These gaps indicate the unequal development of concepts, methods, and contexts, as opposed to weaknesses of the field.

Among the substantive gaps is the fact that there is scant integration of existing theories of cognition and emerging visualization technologies. Primarily, existing studies have shown that there are strong correlations between visualization, spatial reasoning, and mathematical understanding (Battista, 1990; Duval, 2017; Gilligan et al., 2020; Presmeg, 2006), and recent research studies are starting to investigate technology-based learning environments, such as augmented and virtual reality (Faridi et al., 2021; Petrov & Atanasova, 2020), and the current AI-visualized technology foregrounding human-centered ethics in the implementation (Acar et al., 2025). Nevertheless, thematic mapping and evolution studies reveal that sophisticated technologies are conceptually marginal, which implies their affordances are frequently investigated without having strong cognitive and representational paradigms. Theoretically based research on how technological visualization tools relate directly to spatial cognition, embodied learning, and representational fluency should therefore be a priority in future research (Drijvers & Sinclair, 2023).

A second gap is associated with the lack of assessment-oriented research. Although visualization is largely researched as an aid in learning procedures, there are comparatively limited studies on how visualization skills, e.g., visual reasoning, visualization coordination, or visualization literacy, can be scientifically evaluated. Even though data visualization literacy frameworks have been suggested (Börner et al., 2019), there are bibliometric trends indicating that they are not widely used in mathematics education. This gap is necessary in assessing the effectiveness, transferability, and scalability of visualization-based instructional methods.

Another substantive issue is the geographical and contextual imbalances. The country-level analysis demonstrates that the VME research is also concentrated within a few regions, raising the question of the generalizability of the current findings. Despite the proven possibilities of virtual and technology-supported learning environments to expand access to STEM learning (August et al., 2016), the research on the topic has no analogs in low- and middle-income settings. Further investigation should employ context-sensitive designs that incorporate local curricular interests, technological limitations, and teacher training systems.

In methodological terms, there is a need to conduct longitudinal and design-based research because short-term, intervention-oriented studies are the majority. The skills of visualization and representational competence are cultivated over time, but very few studies have examined long-term learning patterns or teaching effectiveness across different stages of education. Longitudinal research may offer a more thorough understanding of how the practices of visualization change in learners and how visualization may be introduced logically in curricula (Duval, 2017; Presmeg, 2006).

The contribution to the methodology of this study is also the combination of co-word network analysis, thematic mapping, and thematic evolution analysis with the tools of VOSviewer and Biblioshiny. It allows for multifaceted interpretation of VME research, going beyond the number of publications to show intellectual structure and patterns, as was promoted in earlier bibliometric research (Assefa & Rorissa, 2013; Cevikbas et al., 2024; Julius et al., 2021). The conceptualization of visualization as a cross-cutting epistemic practice instead of a tool-specific phenomenon makes the study supplementary to recent scoping reviews and meta-analyses in the field (Schoenherr et al., 2024; Schoenherr & Schukajlow, 2024).

Simultaneously, a number of restrictions are to be considered. Such analysis is limited to journal articles published in Scopus and based on keywords provided by the authors, which can limit representativeness and introduce terminological variability (Gil-Doménech et al., 2020; van Eck & Waltman, 2010). Furthermore,

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bibliometric indicators are visible and influential, but not effective pedagogically. Based on this, the results are to be viewed as trace maps of VME research and not as judgments of instructional effectiveness.

CONCLUSION

The study provides a bibliometric and thematic synthesis of VME literature published in 2014-2024. The combination of network analysis, thematic mapping, and thematic evolution contributes to the current reviews. The results point to the role of geometry and STEM-based mathematics in middle secondary and higher education, the actuality of spatial and cognitive perspectives, and the emergence of technology-enhanced visualization methods.

The study contributes methodologically to the body of work by combining VOSviewer with Biblioshiny to capture both temporal patterns and relational structures in VME research. This approach combines visualization as an epistemic practice that crosscuts cognitive theory, pedagogy, and digital innovation, rather than as a tool-focused intervention. Nevertheless, a number of limitations are to be considered. The search is limited to journal articles indexed in Scopus and uses keywords provided by the authors, which may not capture all relevant information and introduce variability in terminology. Then, as visualization is conceptually broad and interdisciplinary, some degree of conceptual overlap may remain despite the staged filtering procedures employed in this study. Also, this bibliometric study relies on indexed metadata, and variations in author naming conventions and institutional affiliations may still influence author-level mapping despite manual standardization procedures.

Moreover, bibliometric measures capture the visibility and input of research, not its teaching impact, and should therefore not be seen as directly reflecting the effectiveness of teaching. Consequently, a higher-order recommendation for future research is to conduct theoretically based, longitudinal, and design-based research that incorporates visualization technologies and well-established cognitive and representational frameworks. Increased focus on assessment, teacher education, and underserved educational and geographical environments will be necessary to make a more sensible, inclusive, and relevant VME research agenda.

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Ethical statement

This study is a bibliometric review based exclusively on publicly available bibliographic records retrieved from the Scopus database. It did not involve human participants, animals, clinical data, personal information, or any form of intervention. Therefore, ethical approval and Institutional Review Board (IRB) approval were not required in accordance with institutional and international research ethics guidelines.

Competing interests

The authors declare that there are no competing interests regarding the publication of this article.

Author contributions

The first author contributed to the research concept and design, data collection, and data analysis and interpretation. The second author contributed to data collection, data analysis and interpretation, manuscript writing, and critical revision of the article. The third author contributed to the critical revision of the manuscript and provided final approval of the version to be published. All authors have read and approved the final version of the manuscript.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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AI disclosure

The authors used artificial intelligence (AI)-assisted tools, including OpenAI's ChatGPT, solely for language refinement, grammar checking, and improving the readability of the manuscript. All conceptual development, data analysis, interpretation of findings, and final manuscript decisions were conducted entirely by the authors. The authors take full responsibility for the content of this manuscript.

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