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Learning in mathematics education. Bibliometric and network analysis (1980-2024)

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ABSTRACT

Given the diversity of theoretical approaches to mathematics learning, this study aims to characterize the predominant theoretical perspectives on the understanding of mathematical concepts within the scientific literature, as well as to identify the collaboration networks and intellectual structure of research in this field. A bibliometric and social network analysis was conducted on 4,266 records from the Scopus database (1980–2024). The findings reveal a dual structure: while the discipline's intellectual base remains anchored in educational psychology theories (Pekrun, Eccles), the current research front has evolved toward specialized didactic frameworks such as the Onto-Semiotic Approach and Embodied Cognition. The results indicate that the discipline is undergoing a phase of professionalization and theoretical specialization, although high fragmentation and a critical geographic gap persist, excluding emerging regions like Latin America from central collaboration nodes. It is concluded that an epistemological transition is occurring, moving from classical socio-constructivism toward neuro-cognitive and multimodal approaches. These findings underscore the need to integrate fragmented theoretical frameworks and promote transregional collaboration policies to diversify global theoretical production.

Keywords: data mining, education, learning, mathematics, theories

INTRODUCTION

Research in mathematics education encompasses a system of activities focused on basic and applied problems within the teaching-learning process of mathematics. This system includes the foundations, planning, implementation, evaluation, and professional development of teachers, all of which are supported by various theories (Godino et al., 2024). Moreover, educational institutions, social structures, cultural norms and historic contexts influence the way the perception and practice of Mathematics is carried out by teachers as well as by students (Díaz, 2024).

Theories on teaching mathematics are based on socio-constructivist principles with learning theories developed by Piaget, Vygotsky, Ausubel and Bruner (Toma et al., 2024). However, there are theories aimed exclusively at teaching mathematics and others which, although used in mathematics, are also used in other fields of science. The diversity of theoretical approaches leads researchers to face challenges in understanding and selecting the appropriate approach based on the object of study. In turn, the possibility of interconnecting theories raises the need to evaluate the commonality, similarity, and measurability of the approaches (Florensa et al., 2024).

Studies in Mathematics education are divided into works that focus on specific topics and that generate results limited to that context, which is why they are considered of little interest, and projects that investigate more general and abstract topics, which in turn result in medium or high-level theories. However, Asenova (2024) states that studies that address specific issues of a topic, if analyzed away from the specifics of learning theories, can create links between the two lines of research, transferring the findings to abstraction and general areas.

In the line of research to expand a theoretical framework, Burgos et al. (2024) study the development of algebraic reasoning from early educational levels. The introduction of algebraic concepts into mathematical activity requires defining the different degrees of generality of the objects and processes involved in algebraic practices. In response to these, the algebrization model proposed by the Onto-Semiotic Approach is extended by adding sublevels in the structures, in the processes of generalization, representation, and analytical calculation. Furthermore, it is stated that this would facilitate the development of mathematical didactic knowledge of pre-service teachers regarding algebraic reasoning and its teaching.

Furthermore, in the research line of specific topics, there is a study by Chen and Leung (2024), who investigate the implicit profiles of cognitive evaluations of secondary school students in mathematics classrooms through control-value theory. The findings of the profiles indicate that positive learning experiences can be enhanced by promoting students' competence beliefs, as well as intrinsic value in mathematics.

In turn, the difficulty levels of mathematical tasks are evaluated by Díaz-Chang and Arredondo (2024) through unconscious thought patterns in students' cognitive processes. The study employs cognitive load theory when analyzing undergraduate students in STEM. The findings showed that unconscious erroneous patterns in reasoning about a mathematical concept are related to the difficulty index of a task and, in turn, could be considered an indicator of mental effort.

At the same time, active learning in initial STEM courses is beneficial to students. However, not all STEM departments implement high quality active learning. In light of this, Lau et al. (2024) carried out research with the theory based on establishing the characteristics of a department which applies active STEM learning successfully. The results obtained showed that these departments shared four main components: motivated personnel, knowledge of active learning, opportunities to promote active learning, as well as culture and structure which support active learning. Moreover, these departments have positive iterative feedback cycles on teaching with active learning.

Olivares (2024) researched the perception of primary school teachers in formation related to teaching based on problem solving with a socio-constructivist perspective. The study determined that the problem-solving focus stimulates critical thinking, collaboration and deep understanding of mathematical concepts. He also identified the need for strategies to foment autonomy and collaborative learning.

Current bibliometric analyses have focused on research within specific frameworks, such as Realistic Mathematics Education (Muryaningsih et al., 2026), the integration of virtual reality in mathematics learning (Hidajat, 2026), or problem-based learning (Meiliati et al., 2026). However, there is a lack of studies providing a comprehensive overview of the diverse theories currently employed in mathematics education.

Given the multiplicity of theoretical approaches in the field of mathematics learning, this study aims to characterize the predominant theoretical perspectives on the understanding of mathematical concepts within the scientific literature, while identifying the collaboration networks and the intellectual structure of research in this domain.

METHODOLOGY

This study was conducted using a bibliometric design with a descriptive-explanatory scope, employing a mixed-methods approach that combines quantitative social network analysis with qualitative thematic analysis. To ensure data comprehensiveness and quality, the Scopus database was utilized, selected for its extensive catalog of peer-reviewed publications in the fields of social sciences and education.

The procedure was structured according to the selection criteria detailed in **Table 1**. Following the retrieval of full records, a stage of data mining and metadata normalization was performed, which was essential for the subsequent bibliometric analysis and the construction of collaboration and co-citation networks.

Table 1. Criteria for Scopus search

Criteria	Selection
Date of consultation	Sept. 28, 2024
Years	1980-2024
Field of research	Article title, abstract, keywords
Search equation	"theory" and "mathematics" and "learning"
Document type	Articles
Source type	Journal
Types of journals	All types
Registries	4266

The registry of each article includes quotes and bibliography, abstracts, keywords and references. The registries were exported in BibTex and CSV files. In the bibliometric and network analysis BibTex and CSV files with the 4266 registries were used.

To ensure the integrity of the study, the entirety of the 4,266 retrieved records was included in the initial bibliometric analysis, thereby guaranteeing an exhaustive overview of the field. No prior quality filters were applied to avoid selection bias, allowing citation and centrality metrics to naturally reflect the impact of each work. Regarding linguistic diversity, articles published in languages other than English were analyzed using technical translation tools and natural language processing, ensuring an accurate interpretation of their metadata and content for the thematic analysis.

Given the contemporary nature of educational research, the search terms employed ("theory", "mathematics", "learning") retrieved an interdisciplinary corpus. A significant presence of studies at the intersection of computer science and mathematics education was identified, particularly in the areas of intelligent tutoring systems and computational learning models. Rather than excluding these publications, they were retained to reflect the field's current evolution toward technological and digital approaches; this explains the inclusion of specialized Machine Learning journals within the productivity indicators.

The analysis of the scientific articles was conducted using the methodology of Zupic and Čater (2015), which consists of a rigorous and objective evaluation of the research. The methodology includes citation analysis, co-citation analysis, co-author analysis and thematic analysis. The citation analysis includes journals, authors, countries, and institutions with the greatest number of publications on the research topic. Furthermore, the co-citation analysis constructs the co-citation network. Similarly, author collaboration networks are generated through co-author analysis.

The data were extracted from Scopus and pre-processed in VOSviewer prior to a detailed analysis in Gephi. Within VOSviewer, the co-authorship network was constructed including only authors with a minimum of three publications, applying no citation threshold per author. Subsequently, the total link strength of co-authorship ties was calculated, and clusters of collaborating authors forming the largest connected component of the network were identified. The analysis utilized the association strength normalization method, with a resolution of 1.00 and a minimum cluster size of 1, incorporating the merging of small clusters.

In Gephi (v.0.10.1), a specialized software for social network analysis, the network was configured as an undirected, weighted graph, where nodes represent authors and edges signify co-authorship ties in scientific articles. The network segmentation into clusters was performed using the Louvain modularity algorithm with a resolution of 1.0 (Blondel et al., 2008), integrated within the software.

The overall connectivity was characterized through graph density and the clustering coefficient. Graph density was utilized to determine the level of overall cohesion by calculating the proportion of actual ties relative to potential ones. The clustering coefficient was employed to evaluate the tendency of authors to form tightly knit groups or clusters.

Centrality metrics were also obtained in Gephi to identify researchers with the greatest influence and mediation capacity. The calculated metrics included Weighted Degree, Betweenness Centrality, and Harmonic Closeness Centrality. Weighted Degree reflects collaboration intensity by accounting for both the number of collaborators and the frequency of joint publications. Betweenness Centrality was employed to identify authors who act as bridges, connecting different clusters. Harmonic Closeness Centrality was selected for its robustness in accurately processing fragmented networks or those with isolated components, measuring an author's capacity to access others within the network.

For the author co-citation analysis, an inclusion threshold of at least 20 citations per author was established. This allowed the initial database of 162,777 authors to be filtered down to 2,379 who met this requirement. From this subgroup, the Total Link Strength was calculated, ultimately selecting the 20 authors with the highest values. This procedure ensures that the analyzed network represents the theoretical pillars with the greatest influence and connectivity within the discipline's intellectual structure.

To further explore the conceptual structure of the field, a full-text thematic analysis was conducted on a strategic sample of the literature. The selection criteria for this analysis included:

(a) The scientific output of the ten most prolific authors identified,

(b) The entirety of the documents comprising the co-authorship collaboration network, and

(c) The foundational research of the leading authors within each of the three clusters of the co-citation network.

The procedure involved a systematic review of the theoretical frameworks, objectives, and key findings of each work, enabling the categorization of research fronts and the identification of the predominant theories that underpin the co-authorship and co-citation graphs.

The database exported from Scopus was analyzed using data mining techniques using the R language (https://www.r-project.org/) and the open-source Bibliometrix tool (https://www.bibliometrix.org/). The purpose of Bibliometrix is quantitative research to construct a mapping of scientific literature. In turn, an interactive interface, part of Bibliometrix and called Biblioshiny, was used to perform bibliometric and visual analyses (Aria & Cuccurullo, 2017). The Biblioshiny tool was used to perform citation analysis in terms of journals, authors, countries, and institutions. The free software VOSviewer (https://www.vosviewer.com) which specializes in generating and visualizing bibliometric networks, was used to develop the co-author network and the co-citation network.

RESULTS

The results are structured across two complementary levels: Descriptive bibliometric mapping and a multidimensional network analysis. This approach allows for the identification of the predominant theoretical frameworks documented in the literature on mathematics teaching and learning, as well as the characterization of the intellectual and collaboration structures that sustain the field. Furthermore, the analysis reveals emerging research fronts and the theoretical shifts currently shaping the international agenda in mathematics education.

Publications per Year

Figure 1 presents the annual distribution of publications concerning mathematics, education, and technology. A total of 4,266 articles were identified, with 2023 exhibiting the highest productivity ($n = 352$). While a general upward trend in publication volume is observed over time, specific periods showed statistically significant increases ($p < .001$). Statistical analyses were performed using two-proportion binomial tests and Fisher's exact test, with a 95% confidence interval, utilizing Minitab 21.1.0 software. Significant growth periods were identified as follows: 1980–1998 (5 to 52), 1993–2004 (31 to 71), 2008–2018 (128 to 197), 2018–2019 (197 to 278), and 2019–2023 (278 to 352). Notably, the decline observed in 2024 ($n = 296$) is attributable to the inclusion of only partial data at the time of the Scopus database query.

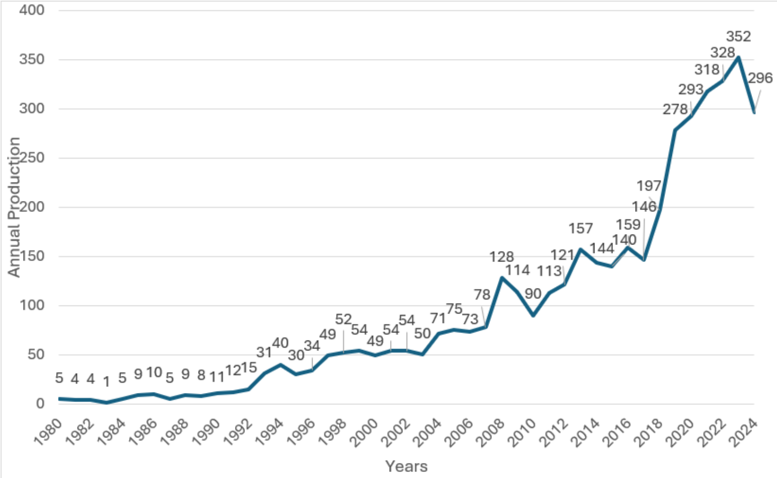

Figure 1. Articles published by year (Source: Authors' own elaboration, using Bibliometrix tool)

Analysis of Journals

The journals with the greatest impact by number of articles published on the topic are shown in **Table 2**. In addition, the number of articles published, quartile, SJR index, H index, as well as the country of origin of the journal are presented.

Table 2. Journals with greatest production for 1980 to 2024

Journal	Articles	Cuartil	SJR (2023)	H index	Country
Educational Studies in Mathematics	113	Q1	1.476	83	Netherlands
ZDM Mathematics Education	79	Q1	1.102	66	Germany
International Journal of Mathematical Education in Science and Technology	65	Q2	0.634	42	United Kingdom
Mathematics Education Research Journal	42	Q1	0.860	41	Netherlands
International Journal of Science and Mathematics Education	39	Q1	1.038	56	Netherlands
ZDM International Journal on Mathematics Education	38	Q1	1.102	66	Germany
Journal of Mathematical Behavior	37	Q1	0.787	58	United States
Journal of Mathematics Teacher Education	37	Q1	1.060	50	Netherlands
Eurasia Journal of Mathematics, Science and Technology Education	36	Q2	0.451	56	Turkey
Machine Learning	36	Q1	1.720	169	Netherlands

Table 2 shows that of the ten most important journals, half of them originate in the Netherlands, with Germany in second place with two. Eight journals are in Q1 quartile and only two in Q2 quartile, reflecting the quality and influence of current research in the field. Regarding the SJR index, the journal Machine Learning has the highest index at 1.72, followed by Educational Studies in Mathematics with 1.476, both journals in the Q1 quartile and with a country of origin being the Netherlands. Similarly, the highest H index is Machine Learning (169), significantly surpassing the second-place journal, which again belongs to Educational Studies in Mathematics (83). Furthermore, Germany is the only country, along with the Netherlands, with an H index above unity.

In addition, among the ten journals remaining on the list shown in Table 2, six journals belong to the Q1 quartile. These journals include Education Sciences (Switzerland), SIAM Journal on Computing (United States), Journal for Research in Mathematics Education (United States), International Journal for Lesson and Learning Studies (United Kingdom), Journal of Educational Psychology (United States), and Research in Mathematics Education (United States).

Country or Regional Analysis

The countries or regions with the greatest number of published articles are shown in **Table 3**. The country with the greatest production is the United States with 2,326 articles, or 28.04% of the total, followed by China with 923 articles, or 11.13%. The remaining countries contribute less than double-digit percentages of articles.

Table 3. Articles published by country or region for the years 1980 to 2024

Country or region	Article	%
United States	2326	28.04
China	923	11.13
United Kingdom	494	5.96
Australia	346	4.17
Germany	320	3.86
Canada	260	3.13
Spain	241	2.91
Brazil	192	2.31
South Africa	192	2.31
Indonesia	177	2.13
Other countries (93)	2824	34.05
Total	8295	100.00

It is important to clarify that, although the study corpus comprises 4,266 unique articles, the geographical productivity analysis yields a total of 8,295 national affiliation records. This discrepancy arises from the fact that a single article may involve multiple authors affiliated with various institutions and countries. Consequently, the count reflects the frequency of participation per country rather than the absolute number of documents, thereby highlighting the extent of international collaboration within the analyzed scientific production.

The countries form research networks where collaborative work integrates clusters (see **Figure 2**). The largest cluster is identified in green, where the United States stands out, with its close ties to Canada and China. Collaboration with the United Kingdom and Australia is next in importance. Also, part of this cluster are South Africa, Italy, Israel, Japan, India, Turkey, Hong Kong, Iran, Korea, Singapore, Poland, Thailand, and Egypt.

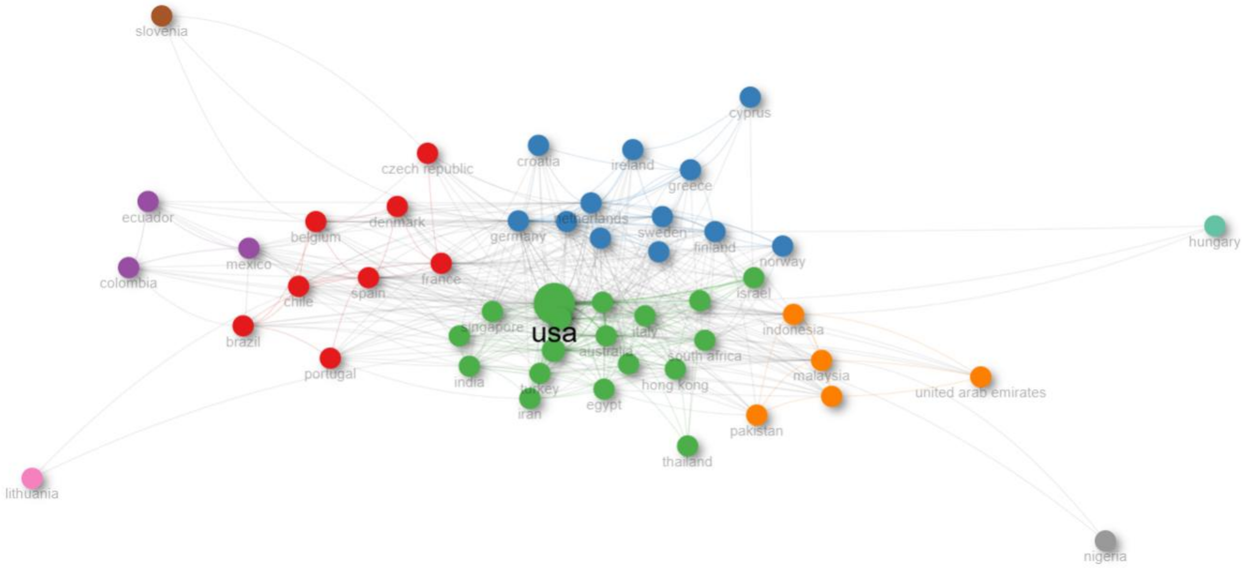

Figure 2. Collaboration among regions and countries (Source: Authors' own elaboration, using VOSviewer)

The blue cluster is in second place of significance for their collaborations. Within this cluster Germany is the most important with respect to Switzerland, Austria and the Netherlands (see **Figure 2**). Besides, Sweden, Norway, Greece, Finland, New Zealand, Ireland, Cyprus and Croatia, mainly European countries, make up this cluster.

Analysis of Institutions

The institutions with the most articles are presented in **Table 4**, in which one can see that eight of these institutions are in the United States. The most articles, 96 (1.17%) are from the University of California, followed by Purdue University with 44 articles (0.54%). The rest of the affiliations contribute less than 1% each.

Table 4. Publications by institution for the years 1980 to 2024

Affiliation	Articles	%	Country
University of California	96	1.17	United States
Purdue University	44	0.54	United States
Carnegie Mellon University	35	0.43	United States
University of Gothenburg	34	0.41	Sweden
Michigan State University	33	0.40	United States
University of Maryland	29	0.35	United States
Stanford University	28	0.34	United States
Utrecht University	28	0.34	Netherlands
University of Cambridge	25	0.30	United States
University of Pennsylvania	25	0.30	United States
Other institutions (3760)	7858	95.42	
Total	8235	100.00	

Collaboration among institutions makes up eight clusters (see **Figure 3**). The largest cluster, red, is led by the University of California which has a close relationship with Columbia University, the University of Maryland, Stanford University, Oxford University and New York University. Stanford University has important ties with Oxford University, the University of Calgary and Carnegie Mellon University. Carnegie Mellon University has close ties with Beijing Normal University. The University of California also has an important relation with the Massachusetts Institute of Technology, although this school belongs to another cluster. In this cluster, with weaker ties one may find the University of Pittsburgh, Purdue University, the University of London, the University of Michigan, Vanderbilt University, Michigan State University, North Carolina State University, the University of Pittsburgh, Northwestern University, the University of Georgia and Putra University in Malaysia.

The University of New South Wales and six other institutions make up another important cluster (blue). There is strong collaboration between the University of New South Wales and the University of Sydney (both in Australia). There is also an important relationship between Utrecht University and the University of Amsterdam (both in the Netherlands). Moreover, the University of New South Wales has close collaboration with Loughborough University (England) and weaker relationships with Nanyang Technological University and the Australian Catholic University (See **Figure 3**).

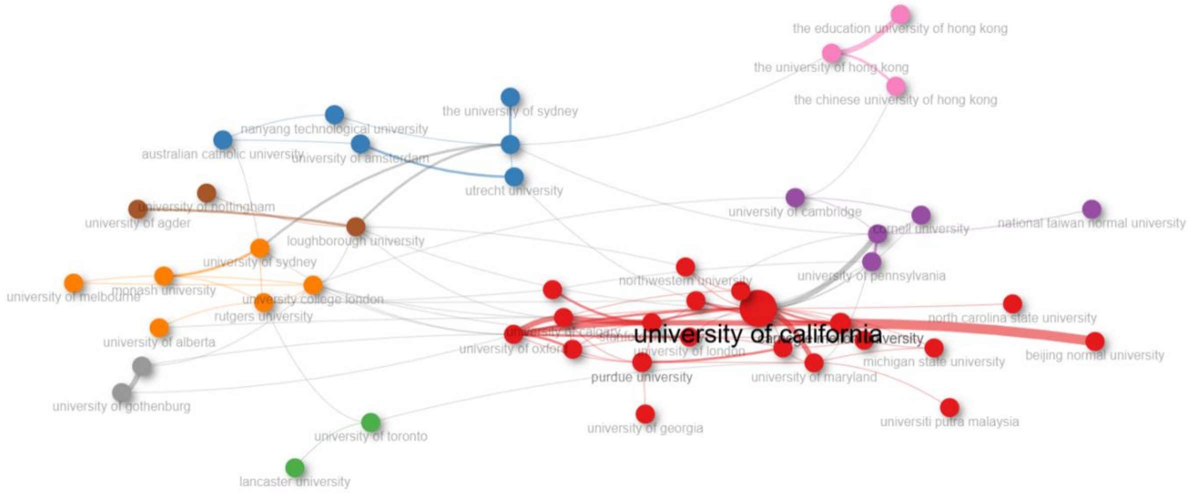

Figure 3. Collaboration among institutions (Source: Authors' own elaboration, using VOSviewer)

Analysis of Authors

In the analysis of the number of publications per author, the top ten authors were selected, as shown in **Table 5**. The top author is Zsolt Lavicza with thirteen articles, followed by Robert Weinhandl with twelve, both from Johannes Kepler University Linz (Austria). The next six authors have nine publications each, but among them is Reinhard H. Pekrun, who has the highest H-index (82) and the largest number of citations (29,137).

Table 5. Publications per author 1980 to 2024

Author	Articles	Citations	H-index	Affiliation	Country
Lavicza, Zsolt	13	770	15	Johannes Kepler University Linz	Austria
Weinhandl, Robert	12	239	9	Johannes Kepler University Linz	Austria
Björklund, Camilla	9	359	13	Göteborgs Universitet	Sweden
Kullberg, Angelika	9	236	9	Göteborgs Universitet	Sweden
Lo, Chung Kwan	9	2847	19	The Education University of Hong Kong	China
Pekrun, Reinhard H.	9	29137	82	Australian Catholic University	Australia
Roth, Wolff Michael	9	15399	61	University of Victoria	Canada
Walkington, Candace Ann	9	1300	18	Southern Methodist University	United States
Abrahamson, Dor	8	2100	23	Korea University	South Korea
Goos, Merrilyn E.	8	2148	25	University of the Sunshine Coast	Australia

FooterWillBeHere

Regarding affiliations, **Table 5** shows that both Johannes Kepler University Linz and Gothenburg University have two authors affiliated with each. Furthermore, two European countries (Austria and Sweden) and one Oceanian country (Australia) contribute with two authors each.

Zsolt Lavicza and Robert Weinhandl, the two authors with the greatest production, collaborate on research using grounded theory to investigate features of characters that represent students within digital resources developed by pre-service mathematics teachers (Weinhandl et al., 2023a, 2023b). Similarly, Weinhandl et al. (2022) consider math anxiety for character development using grounded theory. In turn, in Weinhandl et al. (2021a), they use grounded theory to analyze mathematics teachers' concerns and the benefits they expect from using digital devices in class. Likewise, they used grounded theory to determine the factors that favor mathematics learning environments combining technology and real-world objects (Weinhandl et al., 2021b). Using grounded theory, they study the aspects to consider for professional development of mathematics teachers for flipped approaches (Weinhandl et al., 2020a, 2020b). Similarly, in Weinhandl et al. (2020c), they investigate the design of learning environments involving flipped approaches and GeoGebra using grounded theory. In these studies, Zsolt Lavicza and Robert Weinhandl employ grounded theory to promote learning with digital resources through qualitative data.

Camilla Björklund and Angelika Kullberg collaborate on studies to develop arithmetic skills in children in Kullberg et al. (2024) with the structured approach and in Björklund et al. (2022) with the theory of learning variation and the phenomenographic approach. Camila Björklund investigates mathematics learning in children with the theory of learning variation (Björklund, 2010, 2012a, 2014a, 2014b, 2016; Björklund & Pramling, 2014). Also, Björklund (2012b) analyzes the special education teacher of children with the theory of learning variation. Angelika Kullberg studies critical characteristics for student learning (Kullberg, 2012a) and children's arithmetic understanding (Kullberg & Runesson, 2013) using the learning variation theory. She also investigates teachers using the learning variation theory (Kullberg et al., 2012b, 2017, 2019). In these studies, Camilla Björklund and Angelika Kullberg collaborate on research on children's arithmetic learning using the variation theory, where students' understanding occurs when concepts are presented with different characteristics.

Chung Kwan Lo investigates the creation of educational resources using Kolb's experiential learning theory (Lo et al., 2023, 2024a, 2024b). Likewise, Lo and Hew (2017a, 2017b) propose a flipped classroom design using Kolb's experiential learning theory. They also outline principles for designing flipped mathematics learning (Lo and Hew, 2020a) and analyze gamified learning (Lo and Hew, 2020b) using self-determination theory. In these works, Chung Kwan Lo uses Kolb's experiential learning theory and self-determination theory to investigate the development of digital resources. Kolb's experiential learning theory promotes learning through a four-phase cycle: Concrete experience, observation, conceptualization, and active experimentation. Furthermore, self-determination theory grounds learning in motivation, promoting autonomy, competence, and relationships among students.

Reinhard H. Pekrun studies students' emotions about mathematics using the control-value theory (Bieleke et al., 2023; Camacho-Morles et al., 2021; Frenzel et al., 2007; Goetz et al., 2023; Lichtenfeld et al., 2023; Putwain et al., 2021; Schukajlow et al., 2023). Also, Tracey et al. (2020) through the expectancy-value theory study the motivation of students with low levels of cognitive ability. In turn, with the expectancy-value theory and the control-value theory, Lauermann et al. (2017) analyze the motivations of elementary school students with low performance in mathematics and reading. In these articles Reinhard H. Pekrun studies students' emotions and motivations with the control-value theory and the expectancy-value theory. Control-value theory suggests that there are predictive relationships between emotions, engagement, and student achievement. Similarly, expectancy-value theory establishes that achievement motivation, and thus the tendency to perform a task, is comprised of the success motive, the perceived probability of success, and the value of success.

Wolff Michael Roth suggests an emerging theory for mathematics education based on nature and the function of language (Roth, 2018). Similarly, Roth (2016, 2017) presents eaching for wonder as a way of thinking about learning mathematics. Roth (2013) also affirms that students learn what they are supposed to when they know the object which emerges from their own actions. Bautista et al. (2011) confirm that learning can arise from kinetic movements of the human body. In addition, Thom and Roth (2011) theorize about the living body as a semiotic expression that grounds thought and leads to its development.

Candace Ann Walkington studies the theories of grounded cognition and embodied cognition (Nathan & Walkington, 2017; Walkington et al., 2022). Also, Abrahamson et al. (2020) present this by using embodied cognition and analytics of multi-modal learning it is possible to trace and evaluate emerging conceptual capabilities. Furthermore, they explore connecting students' individual interests to personalize learning systems (Bernacki & Walkington, 2018; Walkington & Bernacki, 2018, 2019; Walkington et al., 2024a).

Dor Abrahamson combines theories of complex dynamic systems knowledge, embodied interactions, and multimodal data analysis (Abdu et al., 2025). Abrahamson and Abdu (2021) evaluate dynamic mathematics environments with interactive modules for content learning. They also expose perceptual-motor learning dynamics for embodied interaction (Abrahamson & Bakker, 2016; Shvarts & Abrahamson, 2019; Tancredi et al., 2021). Furthermore, Abrahamson and Sánchez-García (2016) argue that students in embodied interaction transform artifacts into frames of reference, that is, mathematics reasoning.

Researchers Wolff Michael Roth, Candace Ann Walkington y Dor Abrahamson work on the embodied cognition theory together with multimodal data analysis. The embodied cognition theory maintains that bodily feelings and experiences are necessary for understanding concepts. Wolf Michael Roth also focuses his studies on wonder in which curiosity or surprise increase the interest and motivation of learning.

Merrilyn E. Goos theorizes teacher learning as identity formation using Valsiner's theory (Goos, 2005, 2013, 2014; Goos & Bennison, 2019). Furthermore, Goos and Geiger (2012) investigate online learning environments for mathematics teacher training through communities of practice. Likewise, Goos et al. (2002) study the creation of a collaborative zone of proximal development with peer interaction. In this research, Merrilyn E. Goos employs Valsiner's theory, which focuses on human development from a socio-cultural and symbolic perspective. Furthermore, this theory expands Vygotsky's zone of proximal development to include the zone of free movement and the zone of social support.

Co-Author Analysis

The co-authorship network was developed by establishing a minimum productivity threshold of three articles per author. Out of a total universe of 10,437 authors, only 285 (2.7%) met this requirement. After calculating the total link strength, it was identified that the largest connected component consists of 25 authors, organized into six primary clusters. Detailed information regarding these clusters, including the number of articles and their respective link strengths, is presented in **Table 6**.

Table 6. Total link strength and documents per author

Cluster	Author	Links	Total link strength	Documents
1	Artigue, M.	1	1	6
	Burgos, M.	1	3	3
	Font, V.	3	4	3
	Godino, J. D.	4	7	6
	Trouche, L.	4	4	3
2	González-Martín, A.	1	1	4
	Mellroth, E.	1	1	3
	Nardi, E.	2	2	3
	Nilsson, P.	3	3	4
	Ryve, A.	2	2	3
3	Abdu, R.	2	4	5
	Abrahamson, D.	5	7	8
	Bakker, A.	4	4	5
	Shvarts, A.	2	2	3

Table 6 (Continued). Total link strength and documents per author

Cluster	Author	Links	Total link strength	Documents
4	Doorman, M.	2	2	4
	Drijvers, P.	7	7	5
	Gravemeijer, K.	4	4	3
	Prediger, S.	2	2	3
5	Confrey, J.	4	6	5
	Hackenberg, A. J.	1	1	3
	Shah, M.	1	3	3
	Sztajn, P.	2	2	3
6	Bernacki, M. L.	1	4	6
	Nathan, M. J.	2	4	4
	Walkington, C.	3	8	9

The co-authorship network was composed of 25 authors and 32 connections. Topological analysis of the graph reveals a density of 0.107, indicating that only 10.7% of the potential collaborations among the members of this scientific elite have been realized. This value, combined with a network diameter of 9, describes a fragmented and selective structure where communication between different research groups is not direct but rather depends on specific nodes. The modularity index (0.621) confirms a clear organization into disconnected communities, while the average clustering coefficient (0.411) suggests that, although the global network is sparse, the internal groups are highly cohesive. Detailed centrality metrics for each researcher are presented in **Table 7**, following a normalization process within the [0, 1] range to facilitate comparability.

Table 7. Network centrality metrics

Author	Weighted degree	Betweenness	Harmonic closeness	Clustering coefficient
Paul Drijvers	7	0.659	0.560	0.190
Arthur Bakker	4	0.486	0.498	0.167
Koeno Gravemeijer	4	0.344	0.461	0.333
Per Nilsson	3	0.301	0.409	0.000
Dor Abrahamson	7	0.243	0.452	0.200
Jere Confrey	6	0.236	0.404	0.167
Andreas Ryve	2	0.159	0.332	0.000
Anna Shvarts	2	0.094	0.419	0.000
Juan D. Godino	7	0.083	0.435	0.500
Elena Nardi	2	0.083	0.282	0.000
Paola Sztajn	2	0.083	0.312	0.000
Luc Trouche	4	0.083	0.435	0.500
Candace Walkington	8	0.083	0.357	0.333
Rotem Abdu	4	0.000	0.383	1.000
Michèle Artigue	1	0.000	0.302	0.000
Matthew L. Bernacki	4	0.000	0.262	0.000
María Burgos	3	0.000	0.302	0.000
Michiel Doorman	2	0.000	0.402	1.000
Vicenç Font	4	0.000	0.414	1.000
Alejandro S. González-Martín	1	0.000	0.223	0.000
Amy J. Hackenberg	1	0.000	0.240	0.000
Elisabet Mellroth	1	0.000	0.294	0.000
Mitchell J. Nathan	4	0.000	0.336	1.000
Susanne Prediger	2	0.000	0.355	1.000
Meetal Shah	3	0.000	0.284	0.000

Note: Centrality values were normalized within the [0, 1] range to ensure internal comparability

Based on the values presented in **Table 7**, three critical profiles are identified within the research structure. Paul Drijvers is characterized as a strategic intermediary, standing out as the most critical node in the network with the highest Betweenness Centrality (0.659) and Harmonic Closeness (0.560). These values position him as the primary articulator, capable of bridging theoretical clusters that would otherwise remain isolated. Arthur Bakker (0.486) and Per Nilsson (0.301) occupy similar positions of moderate intermediation.

Another profile identified is that of group leaders and authorities, exemplified by Candace Walkington, who exhibits the highest Weighted Degree (8), followed closely by Dor Abrahamson and Juan D. Godino (both with a value of 7). These metrics reflect a high intensity of collaboration and leadership within their respective research cores. The core specialist profile comprises researchers with a Clustering Coefficient of 1.0 (such as Vicenç Font, Susanne Prediger, and Mitchell J. Nathan), representing the heart of fully cohesive communities. Their Betweenness Centrality of 0.0 indicates that their impact is concentrated on the in-depth development of their own working groups, acting as specialists within particular thematic areas.

Conversely, authors with a clustering coefficient of 0.0 (such as María Burgos or Elena Nardi) exhibit linear collaboration profiles, wherein the researcher serves as the sole nexus for their collaborators. This suggests emerging or highly focused lines of research that have yet to establish reciprocal internal support networks.

The thematic analysis revealed that one of the most significant clusters, due to the number of members, is identified in red (see **Figure 4**) and consists of five authors (three from Spain and two from France). This cluster is led by two researchers, Juan D.

Godino (University of Granada) and Michèle Artigue (Université Paris Cité). Also belonging to this cluster are Luc Trouche (École Normale Supérieure de Lyon), Vicenç Font (University of Barcelona), and María J. Burgos (University of Granada). The significance of the cluster is identified by the number of citations (6,353) and documents registered in Scopus (337) by all the members that make up the cluster

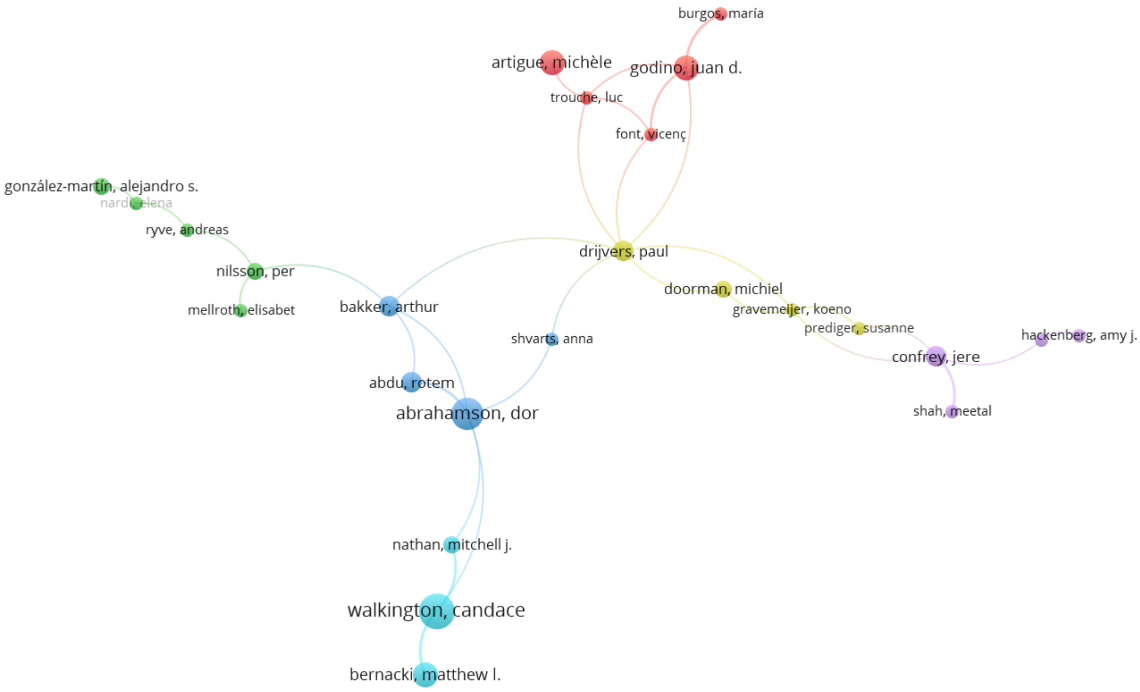

Figure 4. Co-author collaboration (Source: Authors' own elaboration, using VOSviewer)

Researcher Juan D. Godino (h-index 20), who is part of the red cluster, developed the theoretical model for mathematical cognition and instruction, called the Onto-Semiotic Approach (Godino et al., 2005, 2007, 2009, 2011). Another key author in the red cluster, Michèle Artigue (h-index 11), has conducted research on mathematics didactics, the relationship between epistemology and didactics, didactic situations, the articulation of theoretical frameworks, and teaching with digital technologies (Artigue, 2021, 2024a, 2024b; Artigue et al., 2023; Artigue & Masselin, 2024).

Luc Trouche (h-index 20), part of the red cluster, in one of his initial works, proposes the concept of instrumental orchestration to design devices that can be constructed in class and strengthen the socialized part of instrumental genesis (Trouche, 2003). Subsequently, Trouche (2004) describes the foundations of the Instrumental Approach, and Trouche and Drijvers (2010) address the Theories of Instrumentation and Orchestration for mathematics teaching. Researcher Vicenç Font (h-index 21), also part of the red cluster, collaborates in the development of the Onto-Semiotic Approach for research in mathematics education (Breda et al., 2017, 2018; Font & Contreras, 2008; Font et al., 2010, 2013; Godino et al., 2007, 2009, 2017). Vicenç Font also proposes the Model of Didactic-Mathematical Knowledge to characterize and develop the competencies of mathematics teachers (Pino-Fan et al., 2023).

Researcher María J. Burgos (h-index 16), who is part of the red cluster, studies the knowledge of proportionality in pre-service teachers through the didactic-mathematical knowledge of the Onto-Semiotic Approach (Burgos et al., 2018, 2019, 2022, 2023, 2024a, 2024b; Burgos & Godino, 2022a, 2022b, 2022c; Burgos & Chaverri, 2022, 2023; Burgos & Chaverri-Hernández, 2023, 2024).

In the red cluster research uses an onto-semiotic approach to study didactic-mathematics knowledge, theory of didactic situations and the theory of instrumentation and orchestration. The onto-semiotic approach is a framework for analyzing mathematics activity during the teaching/learning process. Mathematics didactic knowledge analyzes the teachers' knowledge, how students learn, and teachers' knowledge of teaching. As for Brousseau's theory of didactic situations, it focuses on designing situations that motivate students to construct mathematics knowledge. On the other hand, the theory of instrumentation and orchestration promotes learning by creating environments where students actively use instruments to solve problems.

The green cluster (see **Figure 4**) also includes five researchers; however, its impact is less than the red cluster based on the number of citations (1,321) and documents published in Scopus (127) by the cluster members. In this cluster, two authors are affiliated with universities in Sweden, while the other three researchers are affiliated with universities in Canada, the United Kingdom, and Norway. Two of the authors in this cluster, Alejandro S. González-Martín (University of Montreal, h-index 8) and Elena Nardi (University of East Anglia, h-index 12), research teachers through Chevallard's Anthropological Theory of Didactics (González-Martín et al., 2018) and including Duval's Theory of Registers of Semiotic Representation (González-Martín et al., 2011). On the other hand, Andreas Ryve (Mälardalen University, h-index 14) and Per Nilsson (Nord University, h-index 8) analyze the learning object represented by the teacher through the Variation Theory (Ryve et al., 2012, 2013a). Also, the Cognitive Approach is addressed by Nardi et al. (2014). In turn, Nilsson and Ryve (2010) and Ryve et al. (2013b) propose an Analytical Approach to conceptualize and analyze mathematical communication in collaborative activities. On the other hand, Elisabet Mellroth (Karlstad University, h-index 3) researches teachers who teach highly capable students through Positioning Theory (Mellroth et al., 2019;

Mellroth, 2021). Similarly, Mellroth et al. (2021) analyze the design of mathematical tasks by teachers with Cultural-Historical Activity Theory.

The green cluster uses the anthropological theory of didactics, theory of semiotic representation registers, the cognitive approach, variation theory, positioning theory, and cultural-historical activity theory. Chevallard’s anthropological theory of didactics establishes that knowledge is a social and cultural construct. Duval’s theory of semiotic representation registers states that learning mathematics is achieved when the student is able to perform transformations and conversions between the registers of representation of mathematics objects. The cognitive approach seeks to understand how a student processes the information and how this influences their behavior. Variation theory grounds learning in presenting students with an learning object highlighting the characteristics that change and those that remain constant. The positioning theory focuses on analyzing the social dynamics, identities and relations between individuals and their position in the face of others. The cultural-historical activity theory mentions that learning is a social and cultural construct through interaction and measuring with tools and symbols.

The blue cluster (see **Figure 4**) is composed of four researchers, who together total 6,930 citations and 253 published documents. In this cluster, two authors are affiliated with universities in the Netherlands, another researcher is affiliated with a university in South Korea, and the fourth author is affiliated with a university in Israel. The authors in this cluster are Dor Abrahamson (Korea University), Arthur Bakker (Utrecht University), Rotem Abdu (David Yellin School of Education), and Anna Y. Shvarts (Freudenthal Institute).

Abrahamson Dor (h-index 23), who belongs to the blue cluster (see **Figure 4**), proposes embodied design, a pedagogical framework that seeks to promote learning by creating situations in which students can be guided to negotiate tacit and cultural perspectives on the phenomena under study (Abrahamson, 2014; Abrahamson & Bakker, 2016; Abrahamson & Sánchez-García, 2016; Abrahamson & Trninic, 2015).

Arthur Bakker (h-index 31), also in the blue cluster (see **Figure 4**), presents in his studies a semiotic analysis of learning through diagrammatic reasoning in statistical distribution (Bakker & Hoffmann, 2005). On the other hand, he works with Abrahamson et al. (2016) on Piaget’s theory, enactivism, dynamic systems theory, ecological psychology, and sociokinesiology. He also establishes embodied design as a pedagogical framework (Abrahamson & Bakker, 2016).

Rotem Abdu (h-index 9), also in the blue cluster (see **Figure 4**), studies multimodal dialogue in mathematics learning with dialogic and embodied theories (Abdu et al., 2021). Additionally, they work with the combination of complex dynamic systems, embodied interactions, and multimodal data collection and analysis (Abdu et al., 2025; Abrahamson & Abdu, 2021; Tancredi et al., 2021). Similarly, Anna Y. Shvarts (h-index 7), a member of the blue cluster, investigates the origin of the scaffolding concept and its relationship with the development of motor control (Shvarts & Bakker, 2019). However, studies on the embodied approach and Dynamic Systems Theory for mathematics learning stand out (Shvarts & Abrahamson, 2019; Flood et al., 2020; Shvarts et al., 2021; Shvarts & Abrahamson, 2023).

In the blue cluster the theory of embodied cognition learning which states that learning is a sensorimotor activity involving the interaction between the body and the environment is used. Dynamic systems theory asserts that the individual and the environment interact, influencing the development of skills and knowledge.

The yellow cluster consists of four authors, with a total of 7,281 citations and 287 published documents. Furthermore, three authors are affiliated with universities in the Netherlands, and the fourth researcher is affiliated with a university in Germany. The researchers in this cluster are Paul H. M. Drijvers (Utrecht University), Michiel Doorman (Utrecht University), Koeno P. E. Gravemeijer (Eindhoven University of Technology), and Susanne Prediger (Leibniz Institute for Science and Mathematics Education).

Paul H. M. Drijvers (h-index 24), a member of the yellow cluster (see **Figure 4**), begins his research with a study on computer algebra at the upper secondary level with the theoretical framework of Realistic Mathematics Education and Developmental Research (Drijvers, 2000). On the other hand, he employs the Instrumental Orchestration Theory to investigate how teachers use technology (Drijvers et al., 2010).

Michiel Doorman (h-index 18), also in the yellow cluster (see **Figure 4**), analyzes the implementation of a problem-oriented curriculum according to the Realistic Mathematics Education Theory and with the integrated use of technology (Doorman et al., 2007). Furthermore, he conducts work on the basic principles of rate of change and velocity with the Realistic Mathematics Education Theory (Doorman & Gravemeijer, 2009).

Koeno P. E. Gravemeijer (h-index 21), a member of the yellow cluster (see **Figure 4**), develops a calculus course with contextual problems through the Realistic Mathematics Education Theory (Gravemeijer & Doorman, 1999). In turn, he presents the foundations of the Realistic Mathematics Education Theory (Gravemeijer & Terwel, 2000).

The fourth member of the yellow cluster (see **Figure 4**) is Susanne Prediger (h-index 22), who researches learning difficulties with the theoretical framework of Conceptual Change (Prediger, 2008). Furthermore, she presents the interaction between the construction of meanings and the activation of linguistic means in school records (Prediger & Wessel, 2013).

The yellow cluster deals with the realistic mathematics education theory and the conceptual change theory. The realistic mathematics education theory learning mathematics concepts occurs in situations which are significative and contextualized for the students. The conceptual change theory states that learning arises from restructuring mental schemes to build new concepts based on the modification of previous concepts.

The purple cluster is composed of four researchers affiliated with universities in the United States. Collectively, the cluster has 4,451 citations with 99 documents. Authors Jere Confrey, Paola Sztajn, and Meetal Shah belong to NC State University. Amy J. Hackenberg from Indiana University Bloomington also forms part of this cluster (see **Figure 4**).

Jere Confrey (h-index 19), a member of the purple cluster (see **Figure 4**), studies a framework for connecting standards with curriculum through learning trajectories (Confrey et al., 2014). She also works on student-centered curricular scaffolding with learning trajectories, using learning maps and diagnostic assessments (Confrey et al., 2017).

Paola Sztajn (h-index 12), also in the purple cluster (see **Figure 4**), studies the professional development of elementary mathematics teachers (Sztajn et al., 2007). Additionally, they propose a teaching theory called Learning Trajectory-Based Instruction (Sztajn et al., 2012).

Meetal Shah (h-index 4), part of the purple cluster (see **Figure 4**), collaborates on research into student-centered curricular scaffolding with learning trajectories (Confrey et al., 2017) and the development of an agile curriculum framework for digital learning systems (Confrey et al., 2018).

Amy J. Hackenberg (h-index 11), also part of the purple cluster (see **Figure 4**), researches students' fractional knowledge and algebraic reasoning (Hackenberg, 2013; Hackenberg & Lee, 2015, 2016; Hackenberg et al., 2017). Furthermore, she proposes the Differentiated Instruction approach for mathematics instruction (Hackenberg et al., 2021).

The purple cluster includes research on the theory of teaching based on learning trajectories and the differentiated instruction approach for mathematics instruction. The theory of learning trajectories proposes guiding the students based on a base of knowledge on various levels of thinking and understanding to achieve specific learning. The differentiated instruction approach consists of adapting teaching to the needs and learning styles of each student.

The turquoise cluster (see **Figure 4**) is composed of three authors with affiliations in the United States. This cluster is the strongest in terms of citations, with 8,971, and 249 published documents. The researchers in this cluster are Candace Ann Walkington of Southern Methodist University, Matthew L. Bernacki of The University of North Carolina at Chapel Hill, and Mitchell J. Nathan of the University of Wisconsin-Madison.

Researcher Candace Ann Walkington (h-index 18), part of the turquoise cluster (see Figure 4), begins her contributions with a critical study on the idea that contextualization facilitates the understanding of mathematical concepts, using the situated cognition approach for analysis (Walkington et al., 2012). Furthermore, she researches students' embodied gestural actions when performing mathematical tasks (Walkington et al., 2019a, 2019b, 2022). She also presents an educational technology research method called multimodal analysis for embodied technologies (Walkington et al., 2024b).

Matthew L. Bernacki (h-index 24), also in the turquoise cluster (see **Figure 4**), studies the effects of achievement goals on self-regulated learning in a technology-enhanced environment through a behavioral approach (Bernacki et al., 2012, 2014, 2015). Furthermore, he researches learning in personalized contexts in intelligent tutoring systems (Bernacki & Walkington, 2018).

Mitchell J. Nathan (h-index 32), the third member of the turquoise cluster (see **Figure 4**), analyzes a mathematics class to identify discourse through speech, gestures, drawing, and object use (Nathan et al., 2007). Furthermore, he participates in the development of the Theory of Grounded and Embodied Mathematical Cognition, which asserts that action-cognition supports mathematical reasoning (Nathan & Walkington, 2017; Nathan et al., 2021; Nathan, 2024).

In the turquoise cluster, the following are proposed: Personalization in context for instruction, multimodal analysis for embodied technologies, and the theory of grounded and embodied mathematics cognition. Instruction with personalization in context involves creating real-world situations that are of interest to the student, where they have to solve mathematics problems. Multimodal analysis for embodied technologies tracks students' gestures, actions on physical and virtual objects, full-body movements and positions, as well as their speech. The theory of grounded and embodied mathematics cognition posits that the understanding of mathematics concepts is related to bodily experiences and actions.

Co-Citation Analysis

Following the application of the inclusion criteria, the co-citation analysis identified 2,379 authors who exceeded the threshold of 20 citations. Filtering by Total Link Strength enabled the consolidation of a network comprising the 20 most influential researchers, whose citation and linkage data are detailed in **Table 8**. This selection highlights figures such as Pekrun, R. (681 citations) and Eccles, J. S. (575 citations) as the most prominent nodes within the analyzed knowledge base.

Table 8. Citations per author and total link strength

Author	Citations	Total link strength
Pekrun, R.	681	13099
Eccles, J. S.	575	10975
Wigfield, A.	475	9754
Goetz, T.	388	9182
Marsh, H. W.	389	8530
Trautwein, U.	235	5861
Ryan, R. M.	409	5099
Ludtke, O.	192	4978
Deci, E. L.	333	4452
Midgley, C.	253	3929
Pintrich, P. R.	265	3573
Bandura, A.	429	3303
Harackiewicz, J. M.	177	3132
Dweck, C. S.	287	2294
Sweller, J.	531	756
Cobb, P.	631	721

Table 8 (Continued). Citations per author and total link strength

Author	Citations	Total link strength
Hiebert, J.	314	696
Siegler, R. S.	331	431
Wang, Y.	464	291
Abrahamson, D.	247	168

The co-citation analysis was performed through a network with the 20 researchers with the highest total link strength (see **Figure 5**). In the network, each node corresponds to an author, and the number of co-citations is reflected by the size of the node. The network is composed of three clusters.

The thematic analysis of the lead author in each cluster revealed that in the blue cluster (see **Figure 5**), the researcher with the highest total link strength is Reinhard H. Pekrun of Australian Catholic University (Australia) with an h-index of 84. He conducts studies on the control-value theory of emotions of achievement (Pekrun, 2006; Pekrun et al., 2010).

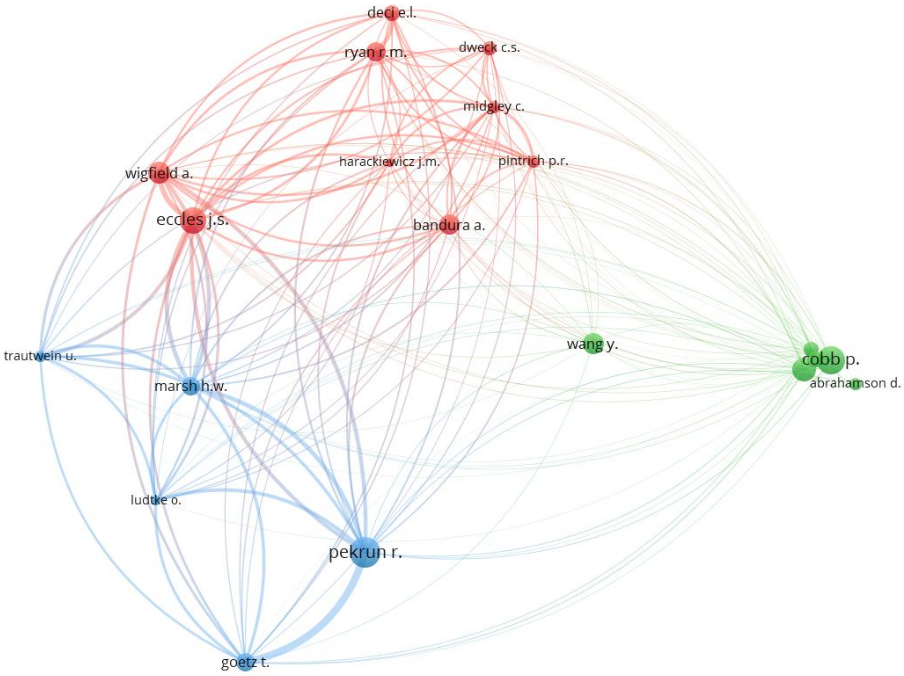

Figure 5. Network of co-citations (Source: Authors' own elaboration, using VOSviewer)

The author with the second highest total link strength is Paul Cobb (h-index 33) of Vanderbilt University (United States). He belongs to the green cluster (see **Figure 5**). The researcher discusses constructivist and sociocultural perspectives on mathematical development (Cobb, 1994). In turn, he explores the relationship between classroom discourse and mathematical development (Cobb et al., 1997). He compares the cognitive approach and situated learning theory (Cobb & Bowers, 1999). In Cobb et al. (2001), they propose a methodology for analyzing collective learning in the classroom. They also outline the characteristics of experimental design in educational research (Cobb et al., 2003a). Furthermore, they propose an analytical approach to the situated practice of teacher instruction (Cobb et al., 2003b).

The cluster leader in red (see **Figure 5**) is Jaquelynne S. Eccles (h-index 113) from the University of California (United States). The researcher conducts studies on age and gender differences in children's perceptions of themselves and tasks in elementary school (Eccles et al., 1993a). Similarly, she studies adolescence and its impact on adaptation to school and families (Eccles et al., 1993b). She also studies beliefs, values, and motivational goals (Eccles & Wigfield, 2002). In turn, they argue that expectancy-value theory should be called situated expectancy-value theory (Eccles & Wigfield, 2020).

This co-citation analysis highlights the control-value theory of achievement emotions, the analytical approach to situated instructional practice, and situated expectancy-value theory. The control-value theory of achievement emotions states that academic achievement, motivation, and engagement are determined by perceived control and the value an individual assigns to a task or situation. Situated learning theory asserts that learning occurs in sociocultural contexts through social interaction and participation. Situated expectancy-value theory suggests that student motivation and performance are related to beliefs about success expectancy and the value placed on a task.

Longitudinal Evolution of Theoretical Approaches

The analysis of the temporal trajectory reveals a significant shift in the theoretical concerns of the discipline. During the initial decades of the study (1980–2000), the literature focused predominantly on socio-constructivist frameworks and problem-solving. From 2008 onwards, coinciding with the acceleration of scientific production, a diversification toward Realistic Mathematics Education and the Onto-semiotic Approach is observed. Finally, in the 2018–2024 period, Embodied Mathematical Cognition and Multimodal Analysis emerged prominently, currently representing the research fronts with the highest growth and cumulative citation rates. This transition reflects an evolution from purely cognitive approaches toward perspectives that integrate embodiment, technology, and semiotics into mathematics learning.

Hierarchy and Influence of Theoretical Approaches

In assessing the influence of the identified theories, a distinction emerges between widespread adoption and structural influence. The Embodied Mathematical Cognition framework stands out as the most frequently cited and currently adopted, driven by its robust connection to multimodal analysis and the use of advanced technologies. Conversely, frameworks such as the Onto-semiotic Approach and Realistic Mathematics Education prove to be the most influential in terms of institutional consolidation, as they exhibit the densest and most extensive co-authorship networks. Finally, it is observed that social constructivism, despite possessing a substantial historical citation base, has lost ground in recent adoption to neuro-cognitive approaches, which demonstrate the highest growth rate over the last decade.

DISCUSSION AND CONCLUSIONS

Unlike previous reviews focusing on specific niches, such as Realistic Mathematics Education (Muryaningsih et al., 2026) or Virtual Reality (Hidajat, 2026), this bibliometric analysis reveals a dual structure within the field. The findings demonstrate that while the intellectual base (co-citation network) remains anchored in general educational psychology—specifically Pekrun's Control-Value Theory and Eccles's Expectancy-Value Theory the current research front (co-authorship network) has evolved toward specialized didactic frameworks, such as the Onto-semiotic Approach and Embodied Cognition. This transition suggests that the discipline is shifting away from "importing" general psychological laws in favor of developing ad hoc theories tailored to the inherent nature of mathematical objects. This trend aligns with the arguments presented by Godino et al. (2024) regarding the complexity of mathematical activity systems.

Network analysis provides an explicit explanation for the clustering of specific theories. The Red Cluster (Godino, Font, Burgos) exhibits high cohesion (clustering coefficient of 1.0), reflecting total theoretical compatibility under the Onto-semiotic Approach. This density suggests that these groups function as closed "schools of thought" where both methodology and ontology are mutually shared.

Conversely, a critical geographical gap is identified. While the Global North dominates the production of high-level theoretical abstractions (Asenova, 2024), Latin America and other emerging regions remain absent from the central collaboration nodes. This implies that the "diversity of approaches" noted by Florensa et al. (2024) is, in fact, a localized phenomenon. Such disparity jeopardizes the universal applicability of theories that fail to account for diverse socioeconomic contexts.

It is essential to clarify that, as this is a bibliometric study, the findings do not validate the empirical efficacy of learning processes; rather, they demonstrate theoretical preeminence and academic consensus within literature. For instance, the centrality of Pekrun and Eccles in the co-citation network does not prove that learning occurs through control-value mechanisms; instead, it indicates that the scientific community predominantly grounds its research upon that premise. Similarly, the inclusion of Self-Determination Theory should be understood as the dominant narrative framework for explaining motivation within the analyzed articles, rather than an empirical result derived from this study.

This study concludes that research in mathematics education is currently in a phase of professionalization and theoretical specialization, with a distinct inclination toward high-impact journals (Q1/Q2). However, the global network exhibits high fragmentation (density: 0.107), evidencing a lack of integration between foundational psychological theories and specific didactic practices.

Regarding the practical implications for educators, teacher training programs should prioritize the Onto-semiotic Approach and Realistic Mathematics Education, as these represent the most established frameworks for bridging the gap between theory and classroom practice. For researchers, there is a critical need to "build bridges" between the Embodied Cognition cluster and those focused on Learning Trajectories, seeking a synthesis between sensory-based learning and curricular development. At the institutional level, funding policies should be promoted to prioritize transregional collaborations, integrating Latin American researchers into the dominant clusters of the United States and Europe to diversify theoretical production.

The findings of this study identify critical gaps that define future research avenues in the field. A fundamental priority is the development of frameworks that facilitate the integration of Multimodal Analysis findings with the Onto-semiotic Approach, directing efforts toward the construction of a unified theory of the mathematical object that links embodied cognition with institutional structures. Furthermore, there is a clear need to investigate the structural and academic causes of the observed disconnection between Latin American collaboration networks and the leading nodes in the United States and Europe, aimed at diversifying global theoretical production. Finally, a necessary line of inquiry involves the analysis of the evolutionary trajectory of dominant clusters since 1980; this would formally document the epistemological transition from classical socio-constructivism toward the neuro-cognitive approaches that are currently emerging as dominant within high-impact literature.

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AI statement: The authors stated that generative AI tools were used only to assist with minor rewording and language editing of select sentences. All conceptualization, analysis, and results are solely the responsibility of the authors.

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