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35 years of fraction learning: Integrating systematic review and bibliometric analysis on a global scale

Syed Azman Syed Ismail [1*], Siti Mistima Maat [1], Fariza Khalid [1]

[1] Faculty of Education, Universiti Kebangsaan Malaysia, Bangi, MALAYSIA

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Abstract

Fraction learning is a fundamental yet challenging component of mathematical education, critical to students' broader mathematical development. This study presents a comprehensive review of fraction learning research spanning the years 1989 to 2024, integrating a systematic literature review with bibliometric analysis to explore the evolution, trends and gaps in this domain. Utilizing data from the Web of Science database, we reviewed 725 articles, identifying key themes through co-citation analysis and categorizing the literature into three primary clusters: cognitive and conceptual understanding of fractions, developmental and educational aspects of fraction learning and teacher knowledge and its impact on mathematics teaching. Our findings reveal a shift from early research focused on conceptual foundations to more recent studies emphasizing educational interventions and teacher preparation. The analysis also highlights significant geographical imbalances, with most research originating from Western countries, particularly the USA. Despite advancements, critical gaps remain, particularly concerning the long-term retention of fraction knowledge and the effectiveness of adaptive learning strategies. This study underscores the importance of a multifaceted approach to improving fraction learning outcomes and calls for future research that addresses these gaps, particularly in diverse educational contexts. The findings provide valuable insights for educators, policymakers and researchers, guiding future efforts to enhance fraction education globally.

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

INTRODUCTION

In mathematics education, understanding fractions is a key challenge that affects students' overall math skills and their ability to learn more advanced topics. Because of this, many researchers have studied how to teach fractions effectively and what makes learning fractions difficult (Alshahri, 2020; Just & Siller, 2022; Pramudiani et al., 2022). The importance of fractions in math literacy and problem-solving makes it essential to explore research trends in this area carefully (Lee & Boyadzhiev, 2020). This paper looks at thirty-five years of research on learning fractions, using the Web of Science (WoS) database for data. The study covers the period from 1989 to 2024, a time of major changes in teaching methods, technology and educational theories. By looking at such a long period, we can see how research focus has shifted, what new topics have emerged and the overall direction of studies on fraction learning. The study takes a global approach, recognizing that the challenges and practices in learning fractions are influenced by cultural, educational and policy factors around the world. This global perspective allows us to identify both universal trends and region-specific insights, offering a complete view of the research field (Leydesdorff & Rafols, 2009).

Using bibliometric analysis, this study maps out the key authors, important works and influential studies that have shaped fraction learning research. It also looks at how researchers collaborate and how knowledge spreads across different regions and educational contexts. This method allows us to measure research output, examine citation patterns and assess the impact of certain studies in this area (Ellegaard & Wallin, 2015). The value of this analysis is in its potential to guide future research, inform educational policies and

✉ syedazman86@gmail.com **(*Correspondence)** ✉ sitimistima@ukm.edu.my ✉ fariza.khalid@ukm.edu.my

Contribution to the literature

- This article provides a comprehensive synthesis of 35 years of research on fraction learning, integrating systematic literature review (SLR) and bibliometric analysis methodologies.
- By categorizing the literature into distinct thematic clusters, it reveals significant shifts in research focus over time and identifies critical gaps in the long-term retention of fraction knowledge and the application of adaptive learning strategies.
- This study also offers a detailed mapping of intellectual connections within the field, providing valuable insights for future research and educational practice.

Table 1. Overview of existing reviews in the fraction learning field (2004-2024)

Author(s)	Scope of the review	Study type
Rittle-Johnson et al. (2015)	Bidirectional relations between procedural and conceptual knowledge in mathematics.	Review
Byrne et al. (2023)	Effectiveness of educational interventions involving physical manipulatives for children's learning and development.	Review
Kim et al. (2023)	Effects of whole number computation interventions for students with learning disabilities through multilevel meta-analysis.	Meta-analysis
Roesslein and Codding (2019)	Fraction interventions for elementary students struggling with math, focusing on instructional components and effectiveness.	Review
Özkaya and Karamık (2022)	Experimental research on the learning fields of numbers and operations in Turkish middle schools, emphasizing fractions.	Review
Tian and Siegler (2018)	Evidence on whether decimals or fractions should be taught first to ease learning of rational numbers.	Review
Ubah (2021)	Impact of different teaching approaches on grade 5 fractions learning in South Africa.	Review
Ngu and Phan (2016)	Complexity of linear equations from a cognitive load theory perspective.	Conceptual
Rojo et al. (2023)	Rational number interventions for students with math difficulties.	Meta-analysis
Chang and Silalahi (2017)	Analyzes mathematics textbooks in educational research.	Review
Pouta et al. (2021)	Investigates differences in professional vision between student and experienced teachers regarding rational number concept teaching.	Review
Shin et al. (2023)	Technology use in math teaching for students with disabilities.	Review
Osana and Pelczer (2015)	Problem posing in mathematics teacher education.	Review
Reyna and Brainerd (2008)	Discusses numeracy, ratio bias and denominator neglect in risk and probability judgments.	Review
Dietrichson et al. (2021)	School-based interventions for reading and math improvements.	Review

improve teaching practices. By tracing the development of fraction learning research, this study highlights successful strategies, ongoing challenges and gaps in the current literature. It also shows how educational research evolves in response to changing educational environments, technological advances and societal needs. In the past twenty years, most reviews on fraction learning have focused on specific topics.

Table 1 lists these reviews, showing that they usually address only parts of the fraction learning process instead of the whole picture. Additionally, there have been few studies that explore the deeper ideas and frameworks within this growing field. **Table 1** highlights the diversity of topics that have been explored in previous reviews and meta-analyses, showing that most of these studies have focused on specific aspects of fraction learning rather than offering a comprehensive overview of the field (Gough et al., 2017). For example, Rittle-Johnson et al. (2015) examines the bidirectional relations between procedural and conceptual knowledge in mathematics, while Byrne et al. (2023) focuses on the effectiveness of educational interventions involving physical manipulatives for children's learning and development. Similarly, Roesslein and Codding (2019) target fraction interventions for students with learning disabilities, emphasizing instructional components and effectiveness. While significant research addresses various specific topics within fraction learning, there is a notable lack of studies that integrate these findings to provide a holistic understanding of the field. This highlights the need for a more comprehensive approach that considers the full spectrum of fraction learning research, rather than isolated topics. Such an approach can reveal broader patterns and connections that might not be evident when studies are considered in isolation (Booth et al., 2016).

To address these gaps, we employed both quantitative and qualitative approaches to conduct a comprehensive review and mapping of the existing research. The decision to combine an SLR with bibliometric analysis in this study is motivated by the need to bridge the gaps identified in previous reviews (Zupic & Čater, 2015). While an SLR allows for a thorough examination of the literature, focusing on

specific research questions, methodologies and findings, it may not fully capture the broader intellectual landscape of a research field. This is where bibliometric analysis is particularly valuable, as it enables the analysis of the structure and development of research areas over time, identifying key authors, influential publications and emerging trends through citation and co-citation analysis (Aria & Cuccurullo, 2017). By combining SLR with bibliometric analysis, this study provides a more comprehensive understanding of fraction learning research. The SLR offers depth by delving into the specifics of existing studies, while the bibliometric analysis provides breadth by mapping the relationships and influence of those studies within the larger academic discourse (Donthu et al., 2021). This dual approach ensures that the review is both detailed and contextually situated within the broader research landscape, offering richer insights and a more complete picture of the field.

International Evidence on Fraction Learning

Research on fraction learning covers many perspectives, showing the global efforts in this field. Several studies have looked at how technology, cognitive skills and teaching methods affect students' ability to learn fractions. For example, Olive et al. (2010) discusses the role of technology in math education, especially in fractions, suggesting that digital tools provide new, interactive ways for students to engage with mathematical concepts, enhancing their understanding. Similarly, Hecht and Vagi (2010) focus on the challenges of developing fraction skills, emphasizing the importance of understanding concepts and attention to detail. Both studies show that innovative methods, such as using technology or focusing on cognitive development, can significantly improve fraction learning. On the other hand, Desimone et al. (2013) examine how teacher training affects student performance in math. Unlike Olive et al. (2010) and Hecht and Vagi (2010), who focus on student-centered approaches, Desimone et al. (2013) emphasize the importance of professional development for teachers. Their research shows that when teachers receive targeted training in math content, particularly fractions, it improves their teaching and, as a result, student learning. This shifts the focus from student engagement to teacher preparedness as a key factor in fraction learning.

Good et al. (2013) and Ustinov (2015) add to the discussion on foundational skills with different perspectives. Good et al. (2013) stress the need for mastering rational numbers to succeed in algebra and STEM fields, highlighting the importance of early math education. In contrast, Ustinov (2015) looks at the theoretical side of mathematics, analyzing the relationship between mathematical structures and fraction learning. While both studies discuss the importance of foundational knowledge, Good et al. (2013) focus on practical readiness for future learning, while Ustinov (2015) takes a more abstract, theoretical approach. Further exploring teaching methods, Martin et al. (2015), Montserrat and Gorgorió (2016), and Lewis and Perry (2017) examine different educational approaches. Martin et al. (2015) use learning analytics to study the impact of game-based activities, finding that these methods can greatly improve students' understanding of fractions. Montserrat and Gorgorió (2016), along with Lewis and Perry (2017), focus on traditional methods like number line exercises and lesson study approaches. While all three studies look at effective teaching strategies, Martin et al. (2015) represent a more modern, technology-driven approach, whereas Montserrat and Gorgorió (2016), and Lewis and Perry (2017) support more conventional, but still effective methods.

Sidney et al. (2019) and Izsák et al. (2019) explore the cognitive and instructional aspects of fraction learning, focusing on how students and teachers understand fractions. Both studies emphasize the importance of reasoning and measurement in understanding fractions, but Sidney et al. (2019) focus more on student thinking, while Izsák et al. (2019) look at teacher thought processes. This difference shows how these studies complement each other, helping to deepen the understanding of how both students and teachers approach fractions. Recent studies by Kiuhara et al. (2020), Barbieri et al. (2020) and Kalra et al. (2020) continue to explore innovative teaching methods, looking at written argumentation, number line strategies and digital games. These studies integrate traditional and modern approaches to improve fraction learning while introducing new, evidence-based techniques tailored to various learning environments. Finally, the latest research, such as that by by Rodríguez-Martínez et al. (2023), Schadl and Ufer (2023), and Gesuelli and Jordan (2024), examines personalized learning paths and the role of basic math skills in fraction proficiency. These studies highlight the importance of individualized learning approaches and the critical link between foundational math skills and success in fraction learning. This research builds on previous findings and suggests a future direction where tailored interventions could meet the unique needs of each student.

Objectives of the Study

The primary goal of this research is to explore the current landscape of studies focusing on fraction learning. The outlined questions will help define the extent of this exploration:

RQ1. What are the current trends in fraction learning research publications regarding their distribution over time, the journals they appear in, the academic disciplines involved, key authors and the associated countries and institutions?

This question aims to map the distribution and evolution of fraction learning research, identifying key contributors and platforms that publish significant findings in the field.

RQ2. Which studies are most influential in the area of fraction learning based on keyword analysis, local citations and global citations?

Here, the focus is on identifying seminal works and major themes that have shaped the understanding and methodologies applied in fraction learning, highlighting the contributions that have had lasting impacts.

RQ3. How has research about fraction learning changed over time and what are the new trends based on thematic cluster analysis?

This question aims to explore how the theoretical and methodological frameworks in the field have developed over time and to identify the latest emerging trends.

The structure of this document is organized in the following way: We first explain the research methodology, including the database selection, keywords, inclusion criteria and the analysis methods used. We then discuss the findings, focusing on the trend of publication over time, publication outlets and prominent authors along with their affiliated institutions and countries. Next, we delve into keyword analysis, highlighting the most frequently occurring keywords in the literature. After that we focus on the citation network analysis, examining the relationships and connections between cited works. We then explore the co-citation analysis, detailing the theme-based clustering of the literature. This section also includes a content analysis of each cluster. After that we analyze the evolution of clusters over the years. We provide a critical discussion of the findings, while we outline the implications for practice. We also address the limitations of the study and suggests directions for future research. We finally encapsulate the study's comprehensive analysis of fraction learning research.

RESEARCH METHODOLOGY

Data Collection Methodology and Search Strategy

In designing bibliometric research, some scholars and reviewers recommend using multiple databases, such as WoS and Scopus. However, this approach is not always beneficial. Using more than one database can lead to overlapping or duplicate publications, which may produce unreliable research results. Since most journals are indexed in both Scopus and WoS, especially in certain fields, using a single, comprehensive database like WoS is often sufficient to capture the relevant literature. This avoids the complexity of merging data from different sources (Öztürk et al., 2024). Therefore, to maintain data integrity and simplicity, this study exclusively uses the WoS database for bibliometric analysis. In March 2024, this research harvested information from the core collection of the WoS platform, overseen by Clarivate Analytics. Acknowledged for its extensive inclusion of leading journals and citation data, the database serves as an optimal tool for conducting bibliometric analysis (Korom, 2019). It offers the most established and thorough records of citation indexes, coupled with valuable analytical tools that enhance the depth and accuracy of the analysis (Ellegaard & Wallin, 2015). Additionally, WoS Core Collection by Clarivate Analytics is renowned for its widespread coverage of citation and bibliographic records, particularly in the social sciences and humanities, making it the ideal choice for retrieving articles in this study (Chadegani et al., 2013; Olijnyk, 2015).

The search covered the period from 1989 to 2024 and the data were analyzed accordingly. A string of suitable search keywords *("learning" OR "knowledge" OR "studying") AND ("mathematic*") AND (("fraction*") NOT ("fractional"))* was used. The initial search across titles, abstracts or keywords generated 2,468 results. This number was narrowed down to 2,375 after filtering for articles published in English. Next, the search was further narrowed to exclude categories that were not related to mathematics education. The remaining articles were screened by reading the abstracts and in cases where there was uncertainty about relevance, full papers were reviewed. To ensure only relevant articles were included, the final selection focused on those discussing fraction learning (concepts, strategies and outcomes) and interventions aimed at improving fraction learning. Following the elimination of duplicate entries, the ultimate collection consisted of 725 papers. Subsequently, a co-citation examination was conducted on this cohort of 725 papers, leading to the formation of clusters with 99 articles for an in-depth examination of their content. The entire process of data extraction is illustrated in **Figure 1**.

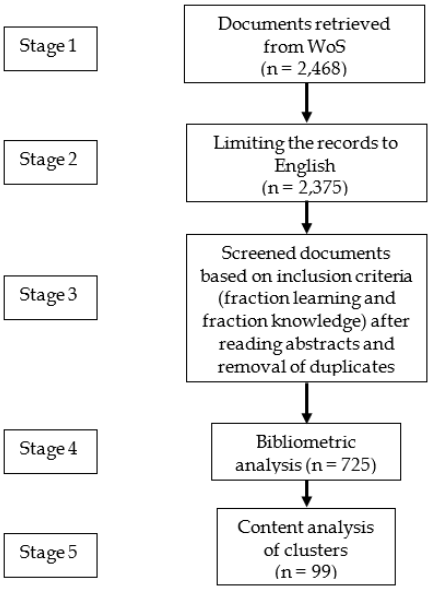

Figure 1. Data extraction process (Korom, 2019)

Analysis Method

There are multiple types of systematic review papers, including narrative reviews that incorporate framework to establish a future research agenda (Migliavaca et al., 2020), scoping reviews that map the key concepts, types of evidence and aiming for model/framework development (Munn et al., 2022), meta-analyses (Knoll & Matthes, 2017), bibliometric analyses (Donthu et al., 2021) and umbrella reviews that summarize evidence from multiple systematic reviews on a broad question (Faulkner et al., 2022).

This research uses a combined approach of bibliometrics and SLR, similar to the method used by Linnenluecke et al. (2020). Bibliometrics is frequently applied to delineate the academic framework of a particular field of study (Li et al., 2017) and to delve into various research themes (Blanco-Mesa et al., 2017). Conducting systematic reviews of the literature is crucial for synthesizing the content of research, minimizing biases (Tranfield et al., 2003) and pinpointing areas that require further investigation (Kumar et al., 2019; Talan & Sharma, 2019). In this study, a bibliometric analysis is employed to scrutinize the field of study in question, which is then augmented by a content analysis focusing on the principal themes (Baker et al., 2020).

Boyack and Klavans (2010) detail the use of standard bibliometric methods, such as analysis of citations and co-citations, to explore how documents refer to each other. In this study, we investigate trends in publications and analyze networks of citations, clusters of co-citations, patterns in keyword usage and both local and global impacts of citations, in addition to conducting a thorough analysis of content (Donthu et al., 2021). To accomplish this, we employ the VOSviewer software. VOSviewer generates a visual map indicating the relatedness of items by their spatial distance, grounded on the "visualization of similarities" (VOS) technique (van Eck & Waltman, 2010). We specifically utilize VOSviewer for our citation, co-citation and keyword analyses. An initial pool of 725 articles was analyzed using VOSviewer, with the process depicted in **Figure 2**.

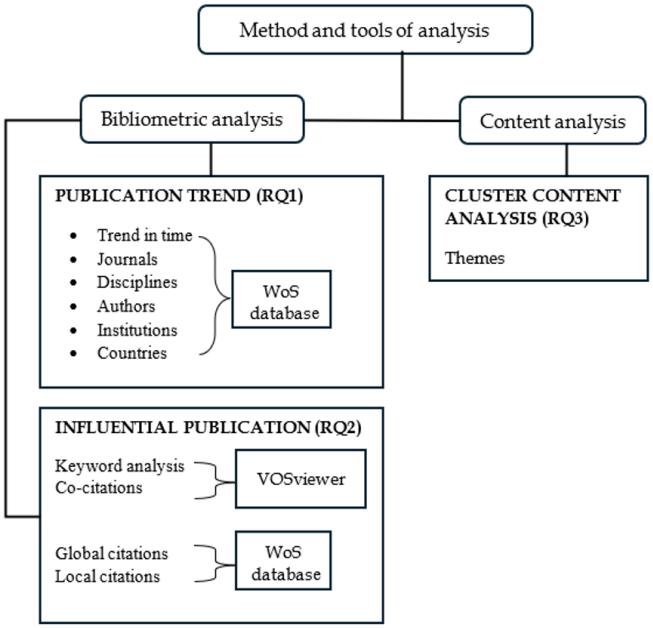

Figure 2. Analysis process in the current study (Source: Authors' own elaboration)

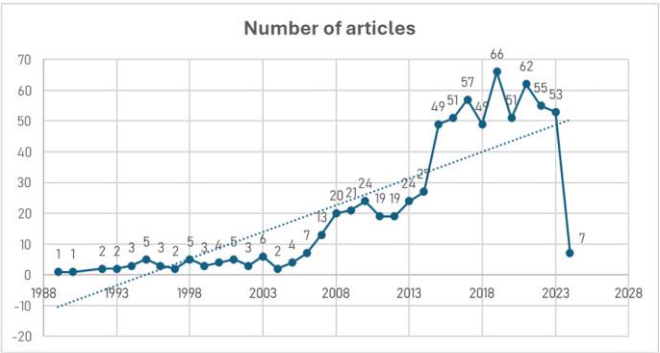

Figure 3. Yearly distribution trends for publishing 725 articles from 1988 through 2024 (Source: Authors' own elaboration)

FINDINGS

Trend of Publication in Time

Figure 3 shows the timeline of published articles on fraction learning from 1988 to 2024. In the late 1980s and early 1990s, there were very few articles indicating that fraction learning was not yet a major focus in education. However, the small increase in publications during this time suggests that fraction learning was beginning to be recognized as an important part of mathematical education.

As we move into the late 1990s and early 2000s, there is a slow but steady rise in research activity. This increase likely reflects broader efforts to improve math education, advances in educational theory and growing awareness of the challenges in teaching and understanding fractions. From 2003 to 2018, there is a noticeable jump in the number of publications, peaking at 66 articles in 2018. This rise indicates a period of intense scholarly interest, which could be due to more funding for STEM education, new teaching strategies, or a global focus on improving math skills (National Mathematics Advisory Panel, 2008).

After peaking in 2018, the number of publications stabilizes in the 50s until 2023. This steady output may indicate a phase where the focus shifted from producing a large number of studies to improving the quality of research and applying what has been learned in educational practices. The sharp drop to just 7 articles in 2024 is significant, but it needs to be understood in context. Since 2024 is the current year and there is often a delay in indexing academic articles, this number likely doesn't represent the full count. As the year progresses,

Table 2. Leading journals publishing on fraction learning

Publication titles	Quartile	IF	Publisher	TP
Journal of Mathematical Behavior	Q3	1	Elsevier Science Inc.	36
Journal for Research in Mathematics Education	Q1	3.5	National Council Teachers Mathematics	35
ZDM Mathematics Education	Q2	2	Springer Heidelberg	31
International Journal of Science and Mathematics Education	Q2	1.9	Springer	29
Journal of Educational Psychology	Q1	5.6	American Psychological Association	27
Journal of Mathematics Teacher Education	Q1	2.1	Springer	23
Educational Studies in Mathematics	Q1	3.4	Springer	21
Learning and Instruction	Q1	4.7	Pergamon-Elsevier Science Ltd.	21
Mathematics	Q1	2.3	MDPI	19
Mathematics Education Research Journal	Q3	1.4	Springer	19
International Journal of Mathematical Education in Science and Technology	Q3	0.7	Taylor & Francis Ltd.	18
Mathematical Thinking and Learning	Q2	2	Taylor & Francis Ltd.	17
School Science and Mathematics	Q3	0.8	Wiley	14
Learning and Individual Differences	Q1	3.8	Elsevier	12
Contemporary Educational Psychology	Q1	3.9	Academic Press Inc.	10

Note. TP: Total publications, representing the cumulative number of published papers from 1989 to 2024; Quartile: Ranking within the subject category as of 2023, with Q1 being the highest (quartiles are calculated from the impact factor [IF], placing journals into four groups: Q1 [top-25%], Q2 [25-50%], Q3 [50-75%], & Q4 [bottom 25%]); IF measures the average number of citations received in 2023 by articles published in the journal during the two preceding years; & All data on IF and quartiles are sourced from journal citation reports provided by Clarivate Analytics

more articles will likely be published and indexed, bringing the total closer to previous years' levels.

Publication Outlets

This study examined 725 papers distributed among 222 distinct publications. According to **Table 2**, the leading journals contributing to research on fraction learning are highlighted. The foremost 15 journals are responsible for 351 publications, accounting for approximately 48.41% of the total. The Journal of Mathematical Behavior is the most prolific, with 36 articles, followed closely by the Journal for Research in Mathematics Education, which has 35 articles. Fraction learning is a key topic in mathematics education and these journals, many of which have high rankings like Q1 and Q2 and notable impact factors, reflect the quality and impact of research in this area.

Figure 4 illustrates that fraction learning is connected not only to mathematics and education but also to fields like psychology and educational research, indicating its multidisciplinary nature. Interestingly, there is limited research on fractions in other areas, such as special education and social sciences. Most research emphasizes the importance of understanding fractions for effective math instruction and overall educational success. However, the broader relevance of fraction learning in different educational contexts remains underexplored, which may explain the lack of studies in certain interdisciplinary areas. Researching fraction learning in diverse educational settings is challenging due to the variety of educational practices and students' baseline math skills (Shin & Bryant, 2015).

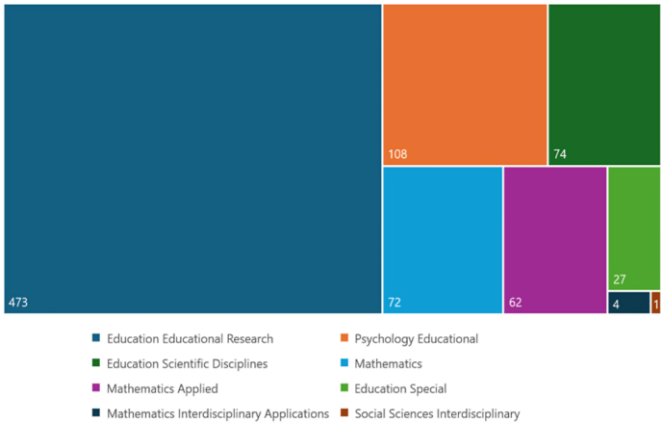

Figure 4. Primary research disciplines in fraction learning across 725 papers (Source: Authors' own elaboration)

Top-Contributing Authors, Institutions, and Countries

Our data set shows that 1,493 authors from 775 organizations across 73 countries have published articles on fraction learning. **Table 3** shows the most prominent author, ranked by the quantity of their published works. Leading the field in terms of published works, Anderson Norton has authored 16 articles, while both Nancy C. Jordan and Wim Van Dooren have contributed 12 articles apiece. In terms of their scholarly impact, Nancy C. Jordan and Wim Van Dooren stand out with citation counts of 560 and 380, respectively, marking their prominence in the area of learning about fractions. Following closely in terms of citations with a total of 378 is Lieven Verschaffel, who is widely recognized for his substantial work on mathematical cognition and education.

Table 3. Leading authors, institutions and countries contributing to fraction learning research

Leading authors	TP	TC	Leading institutions	TP	TC	Leading countries	TP
Norton, Anderson	16	222	University of Delaware	23	783	USA	353
Jordan, Nancy C.	12	560	University of Texas Austin	19	284	Germany	56
Van Dooren, Wim	12	380	Vanderbilt University	16	653	China	44
Verschaffel, Lieven	12	378	Virginia Polytechnic Institute State University	16	224	England	35
Siegler, Robert S.	10	463	University of Missouri Columbia	13	478	Türkiye	30
Van Hoof, Jo	10	293	Florida State University	12	151	Canada	27
Fuchs, Lynn S.	9	535	Carnegie Mellon University	11	1301	Australia	25
Mcmullen, Jake	9	110	Katholieke Univ Leuven	11	405	Taiwan	25
Powell, Sarah R.	8	68	Temple University	11	361	Belgium	21
Prediger, Susanne	8	170	University of Turku	11	146	South Africa	20
Izsak, Andrew	7	168	University of Wisconsin Madison	11	844	Israel	19
Simon, Martin A.	7	39	Beijing Normal University	10	518	Spain	19
Wilkins, Jesse L. M.	7	115	Freiburg University of Education	10	118	France	18
Yang, Der-Ching	7	65	Michigan State University	10	172	Netherlands	16
Copur-Gencturk, Yasemin	6	40	Pennsylvania State University	9	105	Finland	15

Table 3 also presents the most active institutions associated with these scholars. The University of Delaware stands out with 23 publications. The University of Texas at Austin is next with 19 publications, followed by Vanderbilt University with 16 publications. These institutions are located in the USA, revealing a concentration of fraction learning research efforts within this area. This highlights a disparity in academic contributions between the USA and other regions globally. Furthermore, according to **Table 3**, the USA is at the forefront with a total of 353 publications, followed by Germany with 56 articles and China with 44 articles. This data indicates a significant interest in the study of fraction learning in these nations, underscoring their dedication to enhancing math education and the comprehension of fractions.

Keyword Analysis

Hasumi and Chiu (2022) highlights the significance of author keywords in identifying the primary focus areas of scholarly articles. Through the application of a VOS viewer tool, an analysis was conducted to pinpoint dominant themes within the realm of fraction learning studies. This examination unearthed 47 noteworthy keywords across 725 articles, with a threshold of at least 15 occurrences per keyword. **Table 4** lists the top-keywords in fraction learning research. The most frequently used keyword is "fractions," appearing 224 times, showing that it is a central concept in the literature. Other commonly used keywords include "mathematics" (183 occurrences), "knowledge" (144 occurrences) and "students" (88 occurrences). The analysis reveals a diverse range of themes in fraction learning research. The strong focus on "fractions" and "mathematics" highlights the core topics of these studies. The frequent use of "knowledge" and "students" as keywords indicates significant research interest in how students understand and learn fractions.

Table 4. Frequently occurring keywords in fraction learning research

Keyword	Occurrences
Fractions	224
Mathematics	183
Knowledge	144
Students	88
Rational numbers	80
Instruction	68
Individual-differences	58
Children	57
Fraction	44
Achievement	40
Education	37
Performance	37
Whole number	36
Teachers	34
Intervention	31

Figure 5 shows that "fractions" are closely connected with terms like "knowledge," "mathematics," and "instruction." The keyword network also links "fractions" to "rational numbers" and "whole numbers," reflecting both theoretical and numerical aspects of fraction learning. The prominence of keywords like "instruction" and "achievement" suggests a strong focus on teaching methods and their impact on student performance (Ball et al., 2008; Hill et al., 2005). Additionally, keywords like "individual differences" and "performance" point to research on how students vary in their understanding and academic outcomes (Fuchs et al., 2013; Siegler et al., 2012). Another important cluster includes keywords like "teachers" and "education," emphasizing the role of educators in fraction learning, including studies on teacher knowledge and instructional strategies (Ma, 1999; Shulman, 1986). Keywords such as "intervention" and "learning disabilities" highlight the focus on support mechanisms for students who struggle with fractions, addressing educational strategies to help those with learning difficulties (Gersten et al., 2005; Mazzocco et al., 2008).

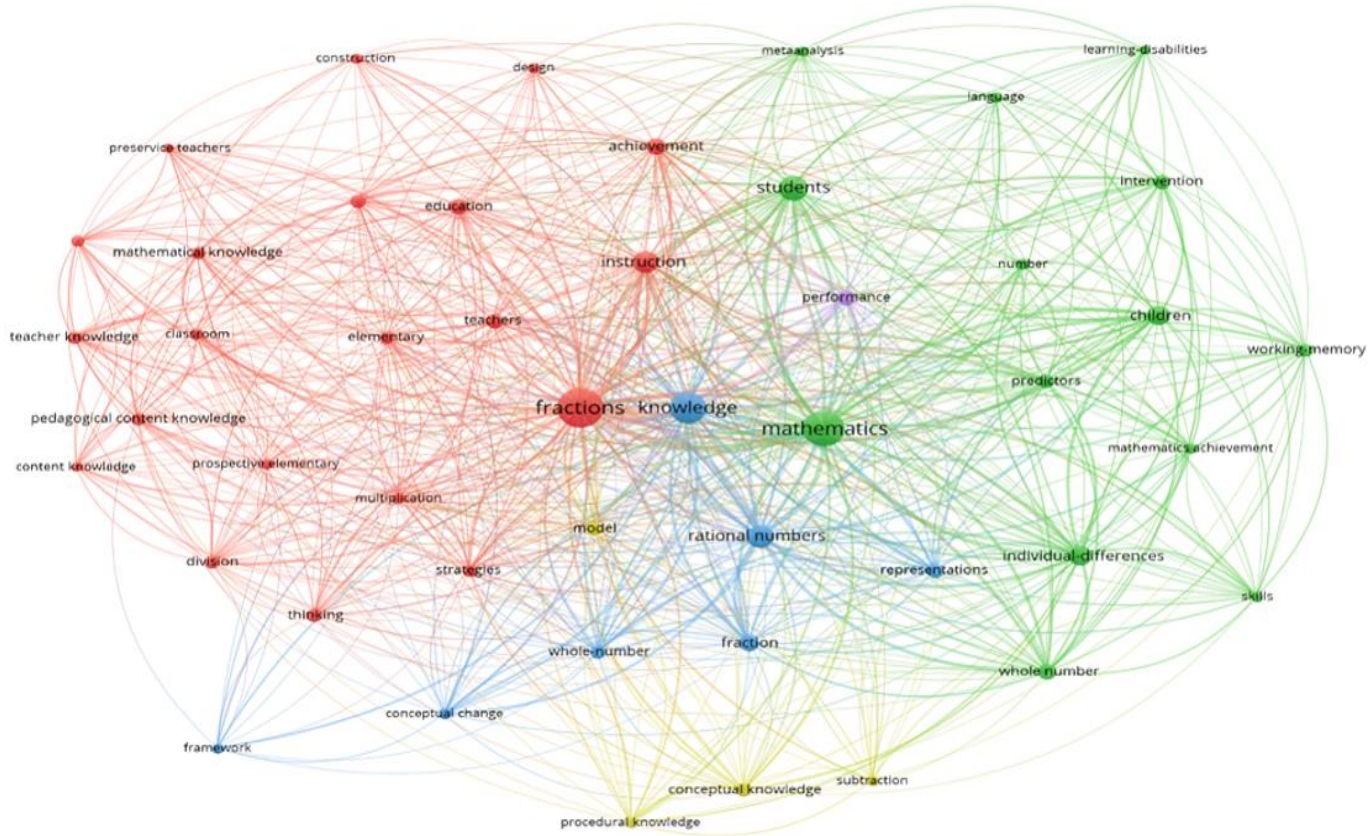

Figure 5. Network of keyword cooccurrence on fraction learning (This figure visualized through VOSviewer: The size of each bubble corresponds to the frequency of the keyword's usage–the larger the bubble, the more frequently the term has been employed) (Source: Authors' own elaboration)

Citation Network Analysis

The measure of citation count serves as an indicator of how many times a document is referenced over the years. Documents that receive a high number of citations are seen as more impactful and significant compared to those with a lesser number of citations. The technique of citation analysis is a critical tool for delineating the impact of scholarly work (Tsay, 2009). In an effort to pinpoint the articles that have had the most impact on the study of fractions, our examination involved a citation network comprised of 725 pieces. From this, it was found that 601 out of the 725 articles had made references to research within the same network.

In **Table 5**, we have cataloged the top-15 articles concerning fraction learning based on their citation frequency, both in local and global contexts. Global citations are the times when an article is referenced by other works across various databases and disciplines. Local citations refer to how often an article is cited by other papers within this specific 725-article network. According to global citations, Hill et al. (2008) are at the top with 890 citations, followed by Rittle-Johnson et al. (2001) with 809 citations and Borko et al. (1992) with 388 citations. In terms of local citations, Hill et al. (2008) also ranks first with 707 citations, followed by Rittle-Johnson et al. (2001) with 589 citations and Borko et al. (1992) with 222 citations. These two articles, by Hill et al. (2008) and Rittle-Johnson et al. (2001), are particularly influential in guiding further research on fraction learning, offering key insights into strategies that improve understanding of fractions.

Table 5. Top-publications on local and global citation count

Article	GC	LC
Hill et al. (2008)	890	707
Rittle-Johnson et al. (2001)	809	589
Borko et al. (1992)	388	222
Kazemi and Stipek (2001)	325	182
Hiebert (1999)	259	127
Booth and Newton (2012)	233	175
Tirosh (2000)	232	163
Fuchs et al. (2013)	228	188
Cramer et al. (2002)	181	117
Hecht and Vagi (2010)	171	140
Mack (1995)	166	121
Fan et al. (2013)	165	133
Resnick et al. (1989)	164	131
Schneider et al. (2009)	156	136
Fuchs et al. (2014)	153	126

Note. GC: Global citations & LC: Local citations

Additionally, **Figure 6** illustrates the central, highly interconnected points in the network that have received a significant number of local citations. Within the context of fraction learning research, articles that garner a large number of local citations are deemed to be highly influential. Again, Hill et al. (2008) and Rittle-Johnson et

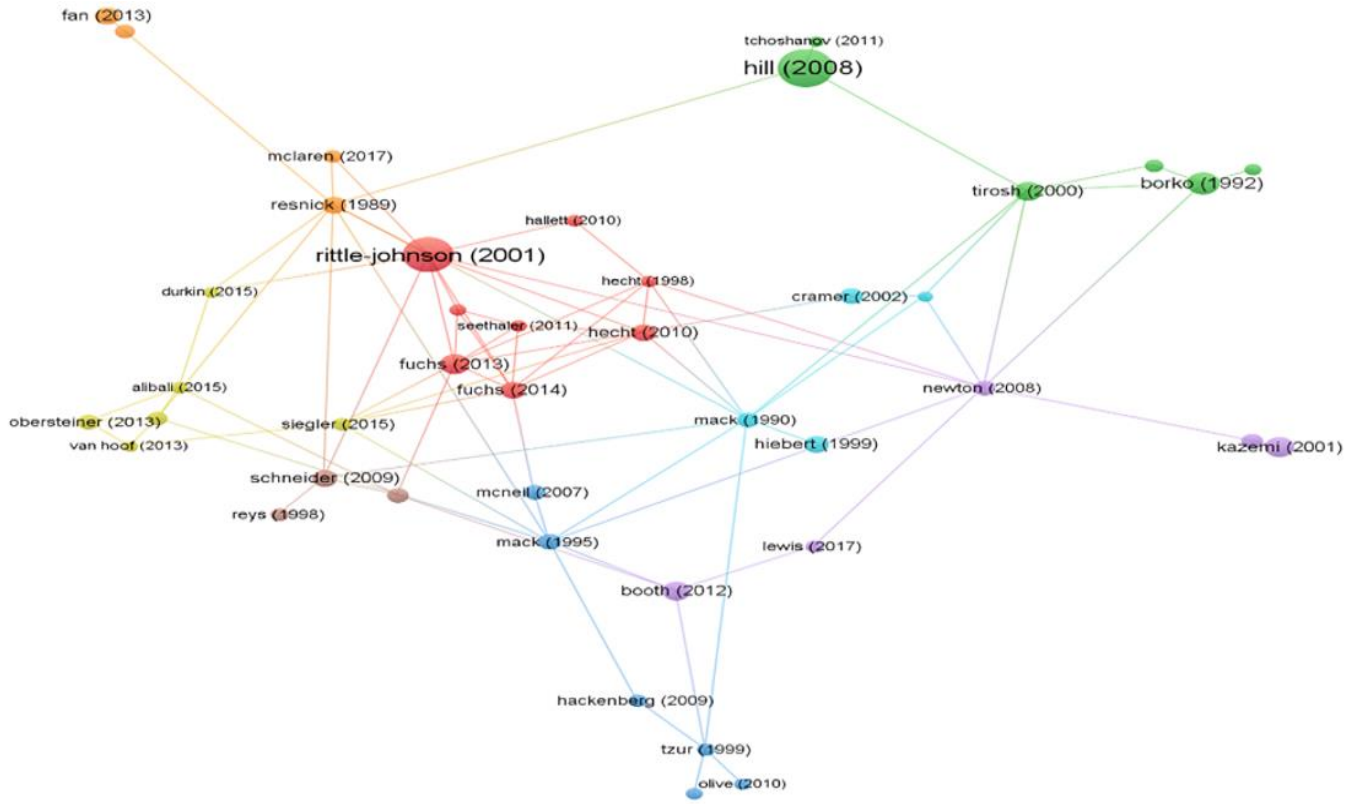

Figure 6. Citation network analysis on fraction learning research (**Figure 6** depicts the citation network in fraction learning research, generated using VOSviewer, with a minimum citation threshold of 50) (Source: Authors' own elaboration)

al. (2001) stand out as major contributors to the field. The network visualization highlights how interconnected these key publications are and their impact on shaping research in fraction learning. The difference between global and local citations suggests that fraction learning has drawn interest from other disciplines as well, reflecting its multidisciplinary nature. This research spans educational psychology, cognitive science and mathematics education. The analysis highlights the importance of foundational works that address both the theoretical and practical aspects of teaching and learning fractions. These significant contributions have influenced subsequent research and educational practices, offering a comprehensive understanding of how students learn fractions and how teachers can effectively support this learning.

Co-Citation Analysis

When two articles are referenced together within a third paper, this is known as co-citation (Boyack & Klavans, 2010). This method is extensively employed in bibliometric studies to reveal the scholarly framework of the most pivotal documents in a specific field of research. The frequency of co-citations of two papers indicates their relevance and connection within the wider research arena (Trujillo & Long, 2018). However, documents that are either too dated and have garnered few citations, or those that are too recent to have made a noticeable impact, are not as effective in mapping out the scholarly terrain (Pilkington & Fitzgerald, 2006). To narrow in on the key publications, our study applied a minimum co-citation threshold of 20 citations. Surwase et al. (2011) recommend a citation threshold ranging from 5 to 100 for articles published over five years ago. In our analysis, from a pool of 725 documents, 99 were found to have been co-cited at least 20 times within the network.

Theme-Based Clustering

Leydesdorff et al. (2017) stated that, within a co-citation network, articles (nodes) can be organized into clusters based on the strength of their connections, with denser connections found within clusters as opposed to between them. Articles grouped within the same cluster exhibit shared themes and have stronger relationships amongst themselves than with articles situated in different clusters. This method of clustering offers a lens through which thematic collections within the co-citation network can be discerned (Mora et al., 2019). Employing VOSviewer for a co-citation analysis on a dataset of 99 documents revealed the formation of three main clusters: cluster 1 containing 41 documents followed by cluster 2 composed of 36 documents and cluster 3 including 22 documents. These clusters were delineated based on the aggregate strength of links indicating the frequency of co-citation between documents, showcasing VOSviewer's utility in clustering and mapping bibliometric data. Articles were then assessed in terms of their link strength within the co-citation network, aiming to pinpoint the most pivotal articles in each cluster. Link strength here acts as a gauge

Table 6. Leading articles in each cluster based on total link strength

Cluster 1 (Cognitive and conceptual understanding of fractions)	Cluster 2 (Developmental and educational aspects of fraction learning)	Cluster 3 (Teacher knowledge and its impact on mathematics teaching)
Addington et al. (2000)	Siegler et al. (2011)	Ma (1999)
Cramer et al. (2002)	Ni and Zhou (2005)	Tirosh (2000)
Behr et al. (1983)	Siegler et al. (2012)	Shulman (1986)
Behr et al. (1992)	National Mathematics Advisory Panel (2008)	Ball et al. (2008)
Mack (1995)	Stafylidou and Vosniadou (2004)	Ball (1990a)
Common Core State Standards Initiative (2010)	Siegler and Pyke (2013)	Newton (2008)
Moss and Case (1999)	Booth and Newton (2012)	Hill et al. (2005)
Lamon (2007)	Fuchs et al. (2013)	Borko et al. (1992)
Steffe (2002)	Rittle-Johnson et al. (2001)	Fischbein et al. (1985)
Tzur (1999)	Bailey et al. (2012)	Simon (1993)
Thompson and Saldanha (2003)	Jordan et al. (2013)	Izsák (2008)
Kieren (1976)	Hecht and Vagi (2010)	Ball (1990b)
Mack (1990)	Siegler et al. (2013)	Toluk-Uçar (2009)
Olive (1999)	Mazzocco and Devlin (2008)	Shulman (1987)
Behr et al. (1984)	Hecht et al. (2003)	Lo and Luo (2012)

of an article's connectedness (via co-citations) with other articles, serving as a measure of its prominence and influence within the network. The leading articles in each cluster, ordered by their total link strength, are itemized in **Table 6**.

Content Analysis

Following a co-citation analysis, an in-depth review of 99 articles segmented into three groups was conducted. Upon close inspection of each group, a prevalent theme emerged.

Cluster 1: Cognitive and conceptual understanding of fractions

Cluster 1 includes 41 documents focusing on how students understand fractions and the mental processes involved in learning them. The research in this cluster looks at how students build their knowledge of fractions and rational numbers, the teaching strategies that support this learning and how educational standards impact it. Key topics from the top-articles include students' misconceptions about fractions, the role of visual aids and the development of conceptual understanding through different teaching methods. For instance, Lamon (2007) emphasizes the importance of understanding proportionality to grasp fraction concepts, stressing the need for a strong theoretical foundation in teaching. Similarly, Thompson and Saldanha (2003) explore how fractions and multiplication are related, showing that students often struggle with fractions because of their prior knowledge of whole numbers. Another significant finding is highlighted in the study of Mack (1995) which reveals that students tend to overapply whole number rules to fractions, leading to common mistakes. This is further supported by Tzur (1999) who examines how children learn about improper fractions and the crucial role teachers play in this learning process.

This cluster uses a variety of research methods, such as experimental designs, longitudinal studies and qualitative analyses. For example, Moss and Case (1999) use a mixed-methods approach to study how children develop an understanding of rational numbers and how experimental curriculums affect learning outcomes. These studies provide valuable insights into how students learn fractions and highlight the importance of aligning educational standards to improve fraction learning (Common Core State Standards Initiative, 2010). Recent developments in this cluster show a growing interest in using technology for teaching fractions and understanding the brain processes behind fraction learning. However, more studies are needed to explore effective ways to support conceptual understanding through various teaching methods, especially in diverse educational settings where resources and strategies may differ.

Cluster 2: Developmental and educational aspects of fraction learning

Cluster 2 consists of 36 documents focusing on how students develop their understanding of fractions over time and the educational methods that support this process. This cluster explores various factors, such as individual differences in learning, predictors of mathematical achievement and interventions aimed at improving fraction learning. Key topics from the top-articles include the importance of early fraction competence, the impact of this knowledge on later math skills and strategies to support struggling learners.

For example, Bailey et al. (2012) highlight that being good at fractions early on is crucial for future success in math, stressing the need for strong fraction instruction from a young age. Another significant study, Fuchs et al. (2013), discusses the importance of targeted interventions for students who have difficulty with fractions, showing that specific teaching strategies can significantly improve their understanding and overall

math performance. Booth and Newton (2012) emphasize how foundational fraction knowledge is for preparing students for algebra, linking early fraction skills to later success in algebra. A variety of methods are employed in the studies within this cluster, including longitudinal studies, experiments and cross-sectional analyses. For instance, Stafylidou and Vosniadou (2004) uses longitudinal data to track students' progress in fraction knowledge and its impact on their broader mathematical abilities. Rittle-Johnson et al. (2001) use experimental methods to study how iterative teaching practices can improve both conceptual and procedural knowledge of fractions.

Collectively, the articles in this cluster make significant contributions to our understanding of the developmental trajectory of fraction learning and the educational practices that best support it. For example, Siegler et al. (2011) provides a comprehensive model that integrates the development of whole number and fraction knowledge, offering insights into how these concepts interact and influence each other over time. Additionally, Siegler et al. (2012) identifies early fraction competence as a key predictor of later success in high school mathematics, highlighting the long-term importance of early fraction education. Research has identified key developmental milestones and effective educational interventions for fraction learning, but there is still a need for longitudinal studies that follow students over time to assess the lasting impact of these interventions. Furthermore, there is a gap in understanding how these strategies can be adapted to better serve diverse student populations, including those with learning disabilities or those in under-resourced schools.

Cluster 3: Teacher knowledge and its impact on mathematics teaching

Cluster 3 includes 22 documents that focus on the knowledge teachers have about fractions and how this knowledge affects their teaching practices and student outcomes in math education. This cluster explores several key areas, including the depth of teachers' understanding of fractions, the role of teacher education programs and the link between teachers' math knowledge and student achievement. The top-articles highlight the challenges teachers face in understanding and teaching fractions and the impact of their knowledge on their students.

For instance, Ball (1990a) discusses the difficulties prospective teachers encounter with division concepts, which are essential for effectively teaching fractions. Similarly, Fischbein et al. (1985) examine how teachers' implicit models influence their problem-solving strategies and teaching methods. Hill et al. (2005), find a strong connection between teachers' mathematical knowledge and their students' academic performance, stressing the importance of teacher education programs that focus on deepening both content knowledge and teaching skills. Newton (2008) identifies gaps in preservice teachers' fraction knowledge and suggests ways to improve teacher preparation programs. This cluster uses various research methods, including qualitative analyses, case studies and mixed methods approaches. For example, Borko et al. (1992) use case studies to explore the challenges faced by new teachers and the support they receive from their mentors. Tirosh (2000) employs qualitative methods to study how teacher education programs can help teachers better understand and address students' misconceptions about fractions.

Key studies in this cluster, such as Ma (1999) provide insights by comparing the mathematical knowledge of teachers in China and the USA, revealing differences in teacher preparation and their impact on student outcomes. Additionally, Ball et al. (2008) discusses the unique nature of the content knowledge required for effective teaching and its implications for teacher education programs. Although the link between teacher knowledge and student outcomes is well-known, more research is needed to understand the long-term effects of teacher education programs on classroom practices and student learning. Additionally, further studies should evaluate the effectiveness of different professional development models and teaching strategies in improving teachers' content knowledge and teaching skills across various educational settings.

Evolution of Clusters

To trace the development of research in fraction learning over time, the evolution of clusters within a co-citation network was examined. **Table 7** presents the publication count within each cluster from 1976 to 2017. Before 2000, research was more focused on the cognitive and conceptual understanding of fractions (cluster 1). This period includes foundational studies aimed at explaining how students grasp fractional concepts and the instructional strategies that improve this understanding. Early research during these years laid the groundwork for understanding the basic cognitive processes involved in fraction learning (Lamon, 2001; National Council of Teachers of Mathematics, 2000). From 2000 onwards, there was a significant increase in publications related to the developmental and educational aspects of fraction learning (cluster 2). This shift signifies a growing interest in exploring individual differences in fraction understanding, developmental predictors of mathematical achievement and effective educational interventions (Bailey et al., 2014; Siegler et al., 2011). The early 2000s saw a marked rise in research focused on identifying the predictors of mathematical success and developing targeted interventions for students struggling with fractions (Jordan et al., 2013).

Table 7. Distribution of publications across clusters (1976-2017)

Year	Cluster 1	Cluster 2	Cluster 3
1976	1		
1978	1		
1983	1		
1984	1		
1985			1
1986	1	1	1
1987	1		1
1988	2		
1989	1	1	
1990	1		2
1991	1	1	
1992	1		2
1993	2		1
1995	1		
1996	1		
1999	4	2	3
2000	3		1
2001	3	1	
2002	2		
2003	2	1	
2004		3	1
2005		1	1
2006	1		
2007	4		
2008		2	4
2009	1		1
2010	3	4	1
2011	1	1	
2012	1	4	1
2013		5	
2014		4	1
2015		4	
2017		1	
Total	41	36	22

Cluster 3, which focuses on teacher knowledge and its impact on mathematics teaching, began to see more publications from the late 1990s, with a significant increase in publications after 2005. This cluster highlights the importance of teacher preparation and professional development in enhancing mathematical instruction and student outcomes (Ball et al., 2008; Hill et al., 2008). Research in this area delves into the depth of teachers' understanding of fractions, the role of teacher education programs and the correlation between teachers' mathematical knowledge and student achievement (Shulman, 1986). The data indicates that the field of fraction learning research has evolved significantly over the past four decades. Initially, the emphasis was on understanding the cognitive foundations of fraction learning. However, over time, the focus has broadened to include developmental, educational and teacher-related aspects. Publications within each of the three clusters have shown a consistent upward trend, demonstrating an increasing awareness of the diverse dimensions of fraction learning and the necessity of detailed research to shape educational strategies. From the mid-2000s onwards, there has been a notable increase in publications, particularly in cluster 2 and cluster 3, which corresponds with a broader educational focus on improving student outcomes through better teaching practices and understanding individual learning differences. The field has seen a diversification of research interests, with significant contributions towards understanding how teacher knowledge impacts student learning and the development of effective instructional strategies.

DISCUSSION

Fraction learning is a crucial part of mathematical education, yet it remains a challenging area for both students and teachers (Siegler et al., 2013). This systematic review, integrated with a bibliometric analysis, provides a comprehensive overview of the evolution and current state of research on fraction learning over the past 35 years. By examining the key themes, methodological approaches and influential works within this domain, significant trends and gaps in literature are highlighted, offering valuable insights for educators, policymakers and researchers.

One notable observation from the analysis is the shift in research focus over time. Initially, studies concentrated primarily on the cognitive and conceptual understanding of fractions (cluster 1). This foundational work was instrumental in identifying the basic cognitive processes and misconceptions encountered by students when learning fractions (Lamon, 2001). These early studies laid the groundwork for understanding how students conceptualize fractions and where they commonly face difficulties, thereby shaping subsequent research in the field. As the field has matured, there has been a marked increase in research addressing the developmental and educational aspects of fraction learning (cluster 2). This includes studies on individual differences, developmental predictors of mathematical achievement and interventions designed to support students' understanding of fractions (Bailey et al., 2012; Jordan et al., 2013). The focus on developmental trajectories and educational interventions reflects a growing recognition of the need to tailor fraction education to meet the diverse needs of learners.

Furthermore, the rise in publications related to teacher knowledge and its impact on mathematics teaching (cluster 3) underscores the recognition that teachers' understanding of fractions plays a pivotal role in student learning outcomes (Ball et al., 2008; Hill et al., 2008). Effective teacher education programs are essential for equipping teachers with the necessary content knowledge and pedagogical skills to teach fractions effectively. This cluster highlights the need for ongoing professional development and support for teachers to ensure they can address students' misconceptions and foster a deep understanding of fractions. Moreover, the link between teacher knowledge and student outcomes

suggests that improving teacher preparation could have a substantial impact on overall mathematics achievement. This is particularly crucial as fractions are foundational for more advanced mathematical concepts (Lee et al., 2023). Therefore, teacher education programs must prioritize deep content knowledge and effective teaching strategies for fractions, incorporating both theoretical understanding and practical application.

Despite the significant advancements in fraction learning research, several critical gaps remain. One of the most pressing issues is the long-term retention of fraction knowledge. Many studies focus on immediate learning outcomes, but there is a lack of research on how well students retain and apply their fraction knowledge over time. Future research should explore longitudinal studies that track students' retention and application of fraction concepts as they progress through their education. Understanding the factors that contribute to long-term retention could inform more effective teaching practices and curricular designs (Barbieri et al., 2020). Additionally, while there is a growing interest in personalized and adaptive learning strategies, more research is needed to determine the effectiveness of these approaches across diverse educational contexts (Koellner et al., 2007). The integration of technology in fraction learning, such as through digital tools and adaptive learning platforms, presents a promising avenue for research. Investigating how these technologies can be tailored to individual learning needs and how they impact long-term learning outcomes would be valuable.

The geographical distribution of research on fraction learning also reveals an imbalance. Much of the research originates from Western countries, particularly the USA, indicating a need for more studies from diverse cultural and educational settings. This would provide a more comprehensive understanding of how different contexts influence fraction learning and help develop strategies that are effective globally. Research in non-Western contexts could uncover unique challenges and opportunities in fraction education, contributing to a more holistic understanding of how students around the world learn fractions.

Limitations and Future Research

While this review provides a comprehensive overview of fraction learning research, it is not without limitations. One limitation is the potential exclusion of relevant studies due to the search criteria used. Despite efforts to ensure the search terms covered a wide range of topics within the field, some pertinent studies might have been excluded because they did not include the related terms used in the search criteria. Additionally, this review relied solely on data from the WoS database, which, while comprehensive, may have limited the breadth of studies included.

Furthermore, while the review's timeline spans from 1989 to 2024, the co-citation analysis concentrated on publications between 1976 and 2017. This restriction may have led to the omission of some of the latest advancements in fraction learning research. Future studies could benefit from broadening the search to include additional databases and refining search criteria to capture a more extensive array of studies. Moreover, expanding the time frame of the co-citation analysis to incorporate more recent developments would provide a more current understanding of the field.

Future research should aim to address these limitations by expanding the search criteria and incorporating additional databases to ensure a more comprehensive inclusion of relevant studies. There is also a need for further investigation into the long-term impact of teacher education programs and the effectiveness of different instructional strategies across various educational settings. Innovative research into personalized learning, the use of technology in teaching fractions and the cognitive processes underlying fraction learning could significantly enhance understanding in this critical area of mathematics education.

CONCLUSION

This systematic review, complemented by bibliometric analysis, provides a thorough examination of the evolution of fraction learning research over the past 35 years. By mapping the intellectual connections among significant works and identifying key trends and gaps, the study offers valuable insights for educators, policymakers and researchers. The findings underscore the importance of a multifaceted approach to improving student outcomes and highlight the need for ongoing research to guide effective teaching practices and educational policies.

To translate these findings into actionable steps, targeted professional development for teachers is essential. Deepening teachers' understanding of fraction concepts and refining their instructional strategies can align their knowledge more closely with students' learning needs, thereby improving outcomes in mathematics. Educational interventions should also be tailored to address individual differences in fraction understanding and provide personalized support for students who struggle with these concepts. Early identification of at-risk students, coupled with targeted interventions, can help build a strong foundation for future mathematical success.

Moreover, ongoing research is crucial to investigate the long-term retention of fraction knowledge and to assess the effectiveness of various instructional approaches across diverse educational settings. Insights from such research can guide the development of more effective teaching practices and curriculum materials, ultimately contributing to better fraction learning

outcomes. The evolution of research in this area reflects the continued importance of refining and adapting educational practices to meet the needs of all learners.

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