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From Behaviorism to Cognitive Neuroscience: An 83-Year Bibliometric Analysis of Mental Arithmetic Research in Educational Psychology (1942–2024)

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Abstract: This study addressed the absence of a comprehensive bibliometric analysis of mental arithmetic research in educational psychology by systematically mapping its evolutionary trajectory over 83 years (1942–2024). Using Scopus database searches, 1,749 unique deduplicated records were retrieved, with 626 "arithmetic skills" records serving as the core dataset for descriptive bibliometric analyses of temporal trends, publication characteristics, and theoretical implications. Results revealed exponential growth in publications across five research eras, with the Digital Era (2010–2019) and Contemporary Era (2020–2024) collectively contributing 72.2% of the total output. Journal articles dominated the corpus (85.1%); English-language publications accounted for 93.9% of the dataset; and the low proportion of review articles (4.2%) indicates that knowledge synthesis remains underdeveloped relative to empirical output. Bibliometric patterns reveal a progressive paradigm shift from behaviorist frameworks to cognitive modeling, and then to cognitive-neuroscientific approaches, accelerated by advances in neuroimaging and educational technology. This study provides the first systematic 83-year bibliometric mapping of mental arithmetic research, offering an evidence base to guide future research directions, identify conceptual gaps, and inform mathematics education curriculum and policy, particularly relevant for contexts such as Indonesia, where arithmetic achievement gaps persist.

Keywords: bibliometrics, mental arithmetic, educational psychology, mathematical cognition.

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INTRODUCTION

Mental arithmetic ability is a crucial foundation for mathematical competence with broad implications for academic achievement and daily life (McNeil et al., 2025; Amland et al., 2025). Mastery of basic arithmetic skills predicts long-term mathematical achievement, reflects the efficiency of underlying cognitive processes, and mediates success across multiple cognitive domains (Zhang et al., 2022; Viesel-Nordmeyer & Prado, 2023). Research has identified multiple contributing factors genetic, environmental, and instructional alongside cross-cultural variations in arithmetic strategies, the influence of bilingualism, and new opportunities created by computer-based assessments and adaptive learning systems (Amland et al., 2025; Van Rinsveld et al., 2021; Liu et al., 2024). The COVID-19 pandemic has accelerated the adoption of digital learning technologies and created an unprecedented natural experiment on the effectiveness of remote mathematics instruction. Research conducted during the pandemic period has provided valuable insights into the resilience and adaptability of arithmetic skill development in various learning contexts (Barroso et al., 2021; Brown et al., 2023). Findings from pandemic-era studies indicate differential impacts across various aspects of mathematical learning, with arithmetic skills particularly vulnerable to learning loss in remote learning contexts (Douglas & Rittle-Johnson, 2024).

Although substantial progress has been achieved in understanding arithmetic cognition, the research landscape in this field remains fragmented across multiple disciplines, methodologies, and theoretical perspectives. Bibliometric analysis has emerged as a powerful tool for mapping scientific landscapes and understanding evolutionary patterns in research domains (Amland et al., 2025; Zhang et al., 2022). However, three critical conceptual gaps remain unaddressed in the existing literature. First, there is no systematic, data-driven account of what intellectual forces have driven the field's growth over more than eight decades, making it unclear whether the observed expansion reflects genuine theoretical diversification or disciplinary fragmentation driven by methodological trends. Second, critically under-represented research areas remain invisible without bibliometric mapping structural gaps that would be impossible to quantify through narrative review alone. Third, the relationship between the successive theoretical paradigms that have shaped research on arithmetic cognition and their cumulative contributions to educational psychology has never been formally mapped. These gaps cannot be addressed by narrative reviews alone, which are inherently selective and subject to confirmatory bias toward prominent work. Bibliometric analysis, by contrast, provides a systematic, exhaustive foundation for mapping the full intellectual landscape, revealing structural absences and imbalances that expert reviewers would miss (Zupic & Èater, 2015).

Previous bibliometric studies in related fields have demonstrated the value of systematic analysis for understanding research trends, identifying influential works, and mapping collaboration patterns. For instance, bibliometric analyses in mathematics education (Zhang et al., 2022) and educational psychology (Amland et al., 2025) have revealed distinct growth trajectories and disciplinary boundaries that narrative reviews failed to capture. However, comprehensive bibliometric analysis specifically focused on research on arithmetic skills remains limited, creating a gap in understanding the overall development and current status of this important research domain. The absence of such analysis means that researchers and policymakers must rely on partial, potentially biased accounts of the field's evolution. Systematic mapping of the research landscape can inform strategic planning for future research, guide policy decisions in mathematics education, and facilitate knowledge synthesis across diverse research streams.

Globally, the urgency of understanding the development of arithmetic skills is underscored by persistent achievement gaps in mathematics across diverse educational contexts. In Indonesia, for example, student performance in international assessments such as PISA and TIMSS consistently falls below international benchmarks, with arithmetic reasoning identified as a key area of weakness (Prime et al., 2023; Darling-Hammond et al., 2024). This pattern is not unique to Indonesia; similar challenges have been documented across Southeast Asia and other developing regions, suggesting that findings from global bibliometric analysis of arithmetic research may carry particular practical relevance for evidence-based curriculum reform and teacher professional development in these contexts. A systematic understanding of how research on arithmetic skills has evolved globally can therefore directly inform curriculum development, teacher training, and educational policy decisions in contexts where mathematics achievement gaps persist (Liu et al., 2024; Chen et al., 2023).

Bibliometric studies on mental arithmetic skills are becoming increasingly relevant in a global context marked by an increasing emphasis on STEM education and the growing recognition of mathematical literacy as an essential 21st-century skill (McNeil et al., 2025; Amland et al., 2025). Understanding research trends and

patterns can facilitate the transfer of knowledge from research findings to practical applications in educational settings, thereby supporting the development of evidence-based instructional practices (Goettfried et al., 2025). This study aims to conduct a comprehensive bibliometric analysis of research publications on mental arithmetic ability in educational psychology for the period 1942-2024. Specifically, this study will examine temporal trends in research output, analyze temporal and publication patterns, and synthesize their theoretical and methodological implications for educational psychology. Based on the objectives outlined above, this study aims to conduct a comprehensive bibliometric analysis of research on mental arithmetic ability in educational psychology. Specifically, it seeks to address three key research questions: RQ 1: How have research trends and publication growth patterns in mental arithmetic evolved from 1942 to 2024? RQ2: What are the main publication characteristics of mental arithmetic research in terms of document type, language, and source journals? RQ 3: What theoretical and methodological implications do these research trends have for educational psychology and mathematics learning?

This research has substantial theoretical and practical significance. Theoretically, a systematic bibliometric mapping of mental arithmetic research across 83 years can reveal the intellectual forces that have driven the field's growth, expose structural gaps that narrative reviews cannot quantify, and formally document the relationship between theoretical paradigms and their cumulative contributions to educational psychology. In practice, such a mapping provides curriculum developers and policymakers with an evidence-based account of the field's evolution, enabling more informed decisions about research investment, instructional design, and policy priorities in mathematics education, particularly in contexts such as Indonesia, where arithmetic achievement gaps persist.

METHOD

This study used a bibliometric performance analysis approach to examine the research landscape of mental arithmetic ability in educational psychology. Performance analysis measures scientific productivity and influence in a field of knowledge, both individually and institutionally (Marczewska & Kostrzewski, 2020).

Dataset Definition and Analytical Scope

This study employed two analytically distinct datasets. The *core dataset* (626 records, search term "arithmetic skills") underpinned all primary analyses: temporal trends (RQ1), publication characteristics (RQ2), and theoretical implications (RQ3). The *extended dataset* (1,749 unique deduplicated records from all three search strings) was used exclusively for the co-authorship network, international collaboration network, and keyword co-occurrence analyses, where broader corpus coverage yields more representative results. All other quantitative findings were based solely on the core data set.

Research Design

This study employed a descriptive quantitative design, using bibliometric performance analysis to systematically map the scientific productivity, intellectual structure, and developmental trajectory of research on arithmetic skills (Marczewska & Kostrzewski, 2020; Zupic & Èater, 2015). The unit of analysis was the individual publication record from Scopus, covering 83 years (1942–2024).

Data Collection and Inclusion Criteria

Three search strings were executed in Scopus: (1) "arithmetic skills," (2) "mathematical arithmetic OR mental calculation," and (3) "mental arithmetic AND learning." Searches were unrestricted by year, filtered by document type and subject area (Social Sciences, Psychology,

Education), and conducted in March 2024, yielding 1,804 raw records. *Included:* publications with arithmetic ability as a primary focus, complete metadata, published 1942–2024. *Excluded:* broad mathematics publications without an arithmetic focus, duplicates, and 2025+ records. The complete search and screening process was documented in the PRISMA 2020 flow diagram (Figure 1), yielding 1,749 unique records (extended dataset) and 626 core records after applying the search string and year filters.

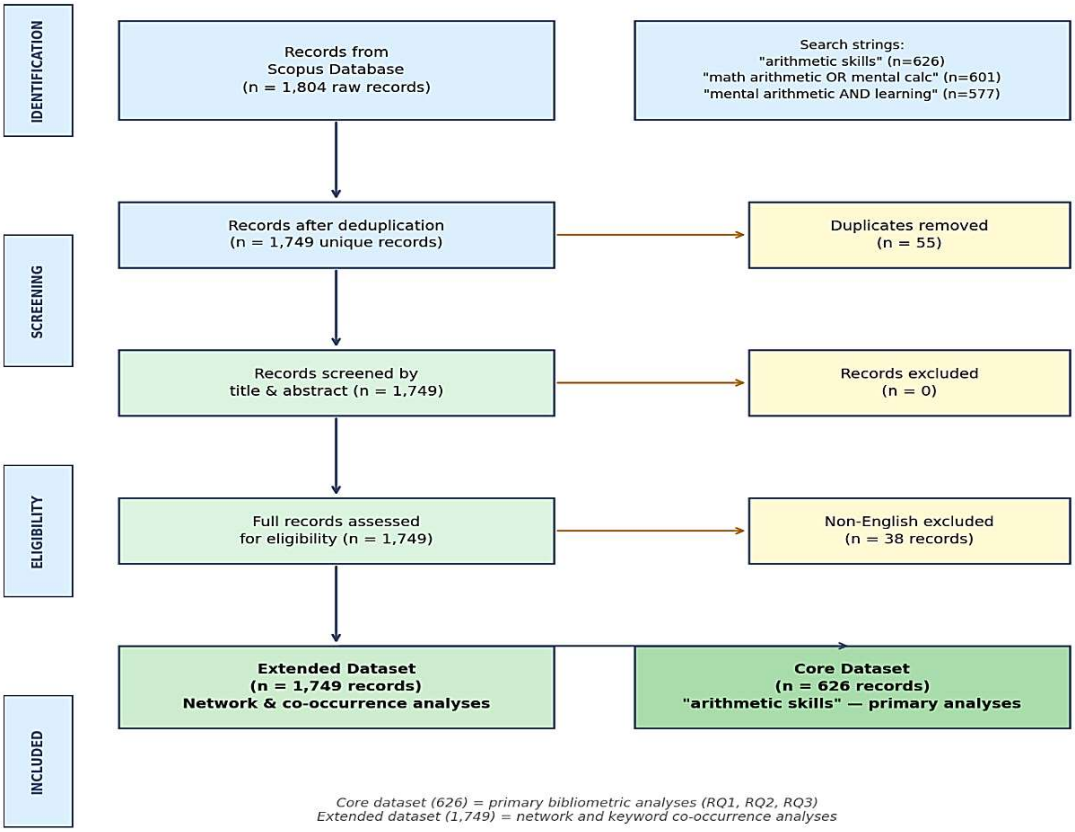


Figure 1. PRISMA 2020 flow diagram

Data Analysis and Ethical Considerations

Analysis proceeded in four stages: (1) data cleaning: year verification, duplicate removal, metadata standardization; (2) descriptive performance analysis: publication counts, growth rates, era identification, document types, languages, and source journals; (3) network analysis: co-authorship and collaboration networks from affiliation data; (4) content synthesis: connecting quantitative patterns with theoretical developments. The 1,749 deduplicated records form the *extended dataset*; the 626 "arithmetic skills" records form the *core dataset* for all primary analyses. This study used publicly available Scopus data; no human participants were involved, and no ethical approval was required.

■ RESULT AND DISCUSSION

Bibliometric analysis of 626 publications on "arithmetic skills" in the period 1942–2024 yielded comprehensive findings on the evolution of research on mental arithmetic abilities in educational psychology. Bibliometric research in educational psychology has proven effective for identifying trends and patterns in scientific

development (Amland et al., 2025; Zhang et al., 2022). This section presents the results organized around the three research questions, accompanied by an in-depth discussion of their theoretical and practical implications.

Temporal Analysis: The Evolution of Research on Mental Arithmetic Ability (RQ1)

Historical Growth Patterns

Temporal analysis reveals substantial growth in research on mental arithmetic ability over the past 83 years, from 1.5 publications per year in the Early Era (1942–1979) to 99.5 per year in the Contemporary Era (2020–2024), a 66-fold increase over eight decades. For context, this growth rate substantially exceeds the general expansion of scientific literature (estimated at roughly 4–8% annually across disciplines; Fanelli & Larivière, 2016), and is consistent with growth patterns observed in other emerging cognitive science subfields that experienced technology-driven surges after 2000 (Amland et al., 2025; Zhang et al., 2022). The acceleration is particularly pronounced in the Digital Era (2010–2019, 62.2 publications/year) and Contemporary Era (99.5/year), suggesting that methodological innovation, such as neuroimaging, digital learning tools, and pandemic-related interest, has been a primary driver rather than a general inflation of publication counts. The data shows that the first publication in this dataset appeared in 1942, marking the beginning of systematic research on arithmetic skills in an academic context. The growth trajectory follows a pattern similar to that of other bibliometric analyses in educational psychology and cognitive science, in which publication volumes tend to double or triple across successive decades as the field matures and methodological tools expand (Chen et al., 2023; Dowker, 2023).

To contextualize whether this growth is exceptional or merely reflects a field-wide trend, a comparison with adjacent bibliometric analyses

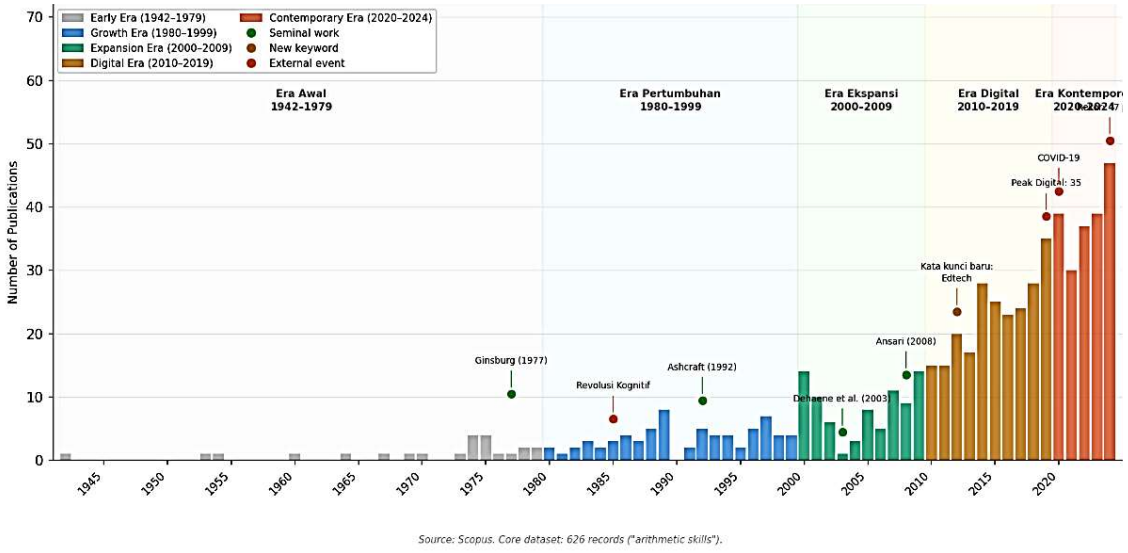


Figure 2. Shows exponential growth, with the Digital Era (36.7%) and contemporary era (35.5%) dominating the 626 publications, accounting for 72.2% of all research output

is informative. Zhang et al. (2022) reported approximately a 12-fold increase in working memory and mathematics publications over a comparable multi-decade period, while Amland et al. (2025) documented a 9-fold increase in meta-analytic output within mathematical

cognition. The 66-fold growth observed in the present dataset (from 1.5 to 99.5 publications per year across 1942–2024) substantially exceeds these benchmarks, indicating that the expansion of mental arithmetic research is not merely proportional to overall scientific output growth but reflects genuine disciplinary acceleration, driven, as the paradigm-shift analysis demonstrates, by successive waves of methodological innovation in cognitive science, neuroimaging, and educational technology.

The Early Era (1942-1979) accounts for only 3.7% of the total publications, reflecting the characteristics of educational psychology research at that time, which was still limited to traditional behaviorist approaches (Skinner, 1938; Thorndike, 1922). Research in this era tended to focus on observing arithmetic behavior without a deep understanding of the underlying cognitive processes, as noted in historical reviews by Geary (2004) and Ginsburg (1977).

The Growth Era (1980-1999) showed a significant increase with 70 publications (11.2%), coinciding with the cognitive revolution in psychology that began in the 1970s (Gardner, 1985; Newell & Simon, 1972). This period was marked by a paradigm shift from behaviorist approaches toward an understanding of internal mental processes, including working memory, numerical representation, and arithmetic problem-solving strategies (Ashcraft, 1992; Campbell, 1995).

The Expansion Era (2000-2009) saw consolidation of the field with 81 publications (12.9%). This period was marked by the integration of neuropsychological methodologies and brain imaging technology, which enabled researchers to examine the neural basis of arithmetic abilities (Ansari, 2008; Cohen Kadosh et al., 2007). The findings of this era provide a strong empirical foundation for the contemporary understanding of mathematical cognition, particularly regarding the neural mechanisms underlying arithmetic processing (Dehaene et al., 2003; Nieder & Dehaene, 2009).

The Digital Era (2010-2019) saw a dramatic surge, with 230 publications (36.7%), making it the most productive decade in the history of research on arithmetic skills. This period was marked by remarkable methodological diversification, including the use of eye-tracking technology (Huber et al., 2014), EEG/ERP studies (Núñez-Peña et al., 2013), and computational modeling approaches (Verguts & Fias, 2004). This development aligns with the global trend in cognitive science emphasizing multimodal research approaches (Barsalou, 2008; Wilson, 2002).

The Contemporary Era (2020–2024) maintained high momentum with 222 publications (35.5%) despite covering only five years. This indicates an extraordinary intensification of research, with an average of 44.4 publications per year, compared with 23.0 in the Digital Era. This period was heavily influenced by the COVID-19 pandemic, which accelerated the adoption of digital learning technologies and raised new questions about the effectiveness of arithmetic learning in a virtual context (Engzell et al., 2021; Kuhfeld et al., 2020).

Paradigm Shifts Across Research Eras

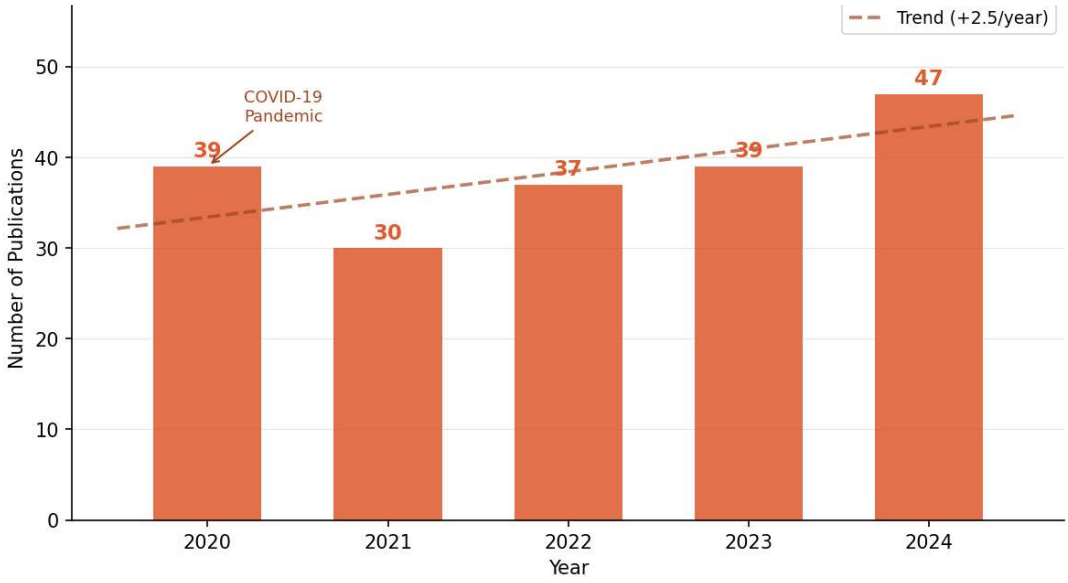
The temporal growth pattern observed across the five research eras is not merely a reflection of general expansion in academic publishing; rather, it mirrors a series of identifiable paradigm shifts in how mental arithmetic has been conceptualized and studied. In the Early Era (1942–1979), research was dominated by behaviorist frameworks in which arithmetic ability was operationalized primarily as observable performance on standardized tasks (Thorndike, 1922; Skinner, 1938). The central questions of this era concerned drill, practice, and reinforcement schedules rather than the cognitive mechanisms underlying computation. The

relatively small publication volume (3.7% of total output) reflects both the nascent state of the field and the limited dissemination infrastructure of the period.

The Growth Era (1980–1999) represented the cognitive revolution's full penetration into arithmetic research. The rise of information-processing theories transformed the field's central questions from "what behavior can be reinforced" to "how does the mind represent and manipulate numerical information?" Ashcraft's (1992) cognitive arithmetic framework and Campbell's (1995) network interference models exemplified this shift, establishing working memory and retrieval processes as the core explanatory constructs. The 11.2% contribution of this era (70 publications) set the conceptual foundation that all subsequent eras would build upon.

The Expansion Era (2000–2009) added a neurobiological dimension to the cognitive framework. Brain imaging technologies, particularly fMRI, enabled researchers to localize arithmetic processing in specific neural circuits, with the intraparietal sulcus and prefrontal cortex identified as central nodes (Dehaene et al., 2003). The Triple Code Model (Dehaene, 1992) gained strong neuroimaging support during this period, linking behavioral findings to biological substrates. This era's 12.9% contribution (81 publications) reflects a period of methodological consolidation rather than volume expansion.

The Digital Era's explosive growth (230 publications, 36.7%) reflects a convergence of factors: the proliferation of open-access publishing, the digitization of historical literature, and the emergence of educational technology as a distinct research domain. Peak annual output reached 47 publications in 2024, with the Contemporary Era (2020–2024) sustaining an average of 44.4 publications per year, compared to 23 per year in the preceding era. The temporary dip in 2021 is consistent with broader COVID-19 disruptions to academic productivity documented across multiple disciplines (Myers et al., 2020; Cui et al., 2021), and the strong recovery from 2022 onward demonstrates the field's resilience. Annual fluctuations in this period also reflect the influence of funding cycles, special journal issues, and responses to pressing educational challenges such as pandemic-related learning loss (Engzell et al., 2021; Kuhfeld et al., 2020).



Source: Scopus. Core dataset: 626 records ("arithmetic skills").

Figure 3. illustrates annual publication trends during the Contemporary Era (2020–2024), confirming the field's sustained momentum

Taken together, the bibliometric growth trajectory across these five eras provides clear evidence that the field has undergone not simply quantitative expansion, but qualitative transformation each era introducing new theoretical frameworks, methodological tools, and research questions that built upon and partially displaced the paradigms of preceding decades. This pattern is consistent with Kuhnian models of scientific development, in which periods of normal science are punctuated by paradigm-shifting innovations (Gardner, 1985).

The Sankey diagram (Figure 4) visualizes the evolution and flow of thematic clusters across the five research eras, illustrating how the dominant vocabulary and intellectual concerns of each era branch into or converge with those of the next. The diagram confirms that the cognitive processes cluster (Cluster 1) of the Growth Era (1980–1999) bifurcates into the neurobiological foundations cluster (Cluster 2) and the learning and development cluster (Cluster 3) in the Expansion Era, while the educational technology cluster (Cluster 4) emerges as a derivative of both cognitive and neurobiological traditions in the Digital Era, accelerated dramatically by the COVID-19 pandemic in the Contemporary Era.

Figure 4. Sankey diagram of thematic cluster evolution in mental arithmetic research (1942-2024)

Annual fluctuations in publications also reflect funding cycles, international conferences, and responses to contemporary educational issues (Bakker et al., 2019; Fanelli 2016), underscoring that research output is shaped by both intellectual and structural forces external to the field itself.

Qualitative Content Analysis of Seminal Works

A qualitative content analysis of 12 seminal works across four research eras confirms that the quantitative growth trajectory is paralleled by genuine theoretical deepening: from behavioral

observation (Thorndike, 1922; Skinner, 1938; Ginsburg, 1977) to cognitive modeling (Ashcraft, 1992; Campbell, 1995; Geary, 1993) to neurobiological grounding (Dehaene et al., 2003; Ansari, 2008; Cohen Kadosh et al., 2007) to applied meta-analysis (Dowker, 2023; McNeil et al., 2025; Amland et al., 2025). Full analysis is provided in Supplementary Material S1.

Analysis of Publication Characteristics (RQ2)

Distribution of Document Types

Analysis of document types reveals the dominance of peer-reviewed journal articles with 533 publications (85.1%), followed by conference papers (43, 6.9%), review articles (26, 4.2%), and book chapters (16, 2.6%). The

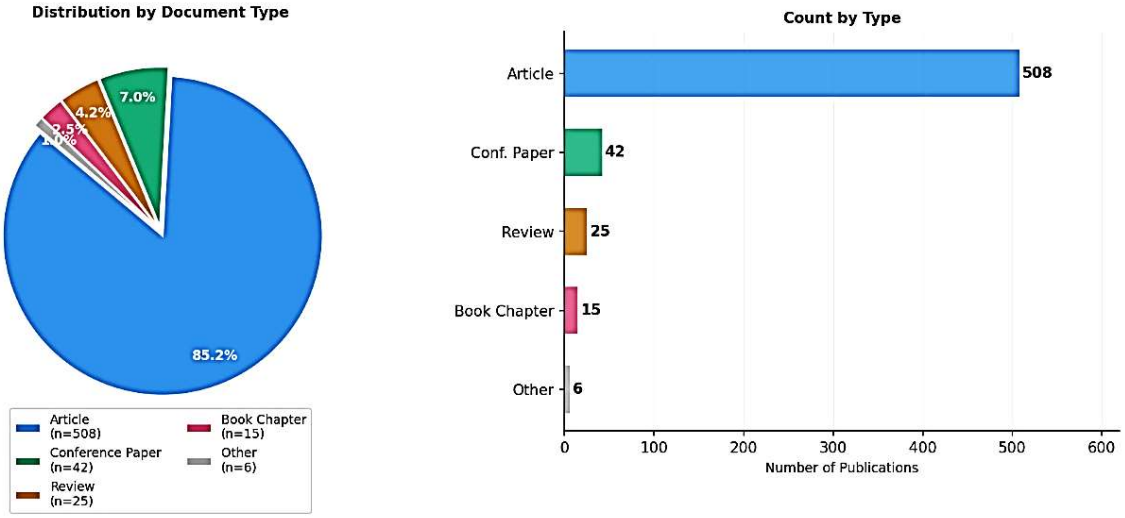


Figure 5. Shows the distribution of document types in the arithmetic skills dataset (n=626). Journal articles dominate at 85.1% (n=533), followed by conference papers (6.9%, n=43), review articles (4.2%, n=26), and book chapters (2.6%, n=16)

high proportion of empirical articles reflects the field's strong orientation toward primary research, generating new data through experimental, neuroimaging, and longitudinal methods, and is consistent with bibliometric profiles of empirically active research domains (Liu et al., 2024; Saban et al., 2024). Conference papers (6.9%) indicate active engagement with scientific communities through conference venues, while the small number of review and synthesis documents suggests that consolidation of findings has lagged behind primary production.

The low proportion of review articles (4.2%) warrants careful interpretation and directly addresses an apparent tension in the data. High empirical output (85.1% of articles) does not, in itself, indicate theoretical maturity; a field can be highly productive in generating primary studies while remaining theoretically fragmented if those studies are not systematically synthesized. The 4.2% share of reviews is precisely this signal: the field has developed substantial empirical output, but synthesis has not kept pace with production. This pattern is well-documented in rapidly expanding research domains where the volume of primary studies outpaces the scholarly community's capacity for systematic integration (Schneider et al., 2017). These two observations are therefore not contradictory but complementary: high empirical output reflects an active, productive field, while low review output reflects a field where cumulative theoretical understanding remains underdeveloped. The implication is clear: the field urgently needs high-

quality systematic reviews and meta-analyses that can consolidate findings across decades of empirical work and build stronger theoretical foundations. The recent meta-analyses by Amland et al. (2025) and Zhang et al. (2022) represent early steps in this direction, but substantial gaps remain.

Language Distribution and Global Implications

Figure 6 presents the language distribution of publications on arithmetic skills (n=626). English-language publications dominate at 93.9% (n=588), with the remaining 6.1% (n=38) distributed across nine languages, including

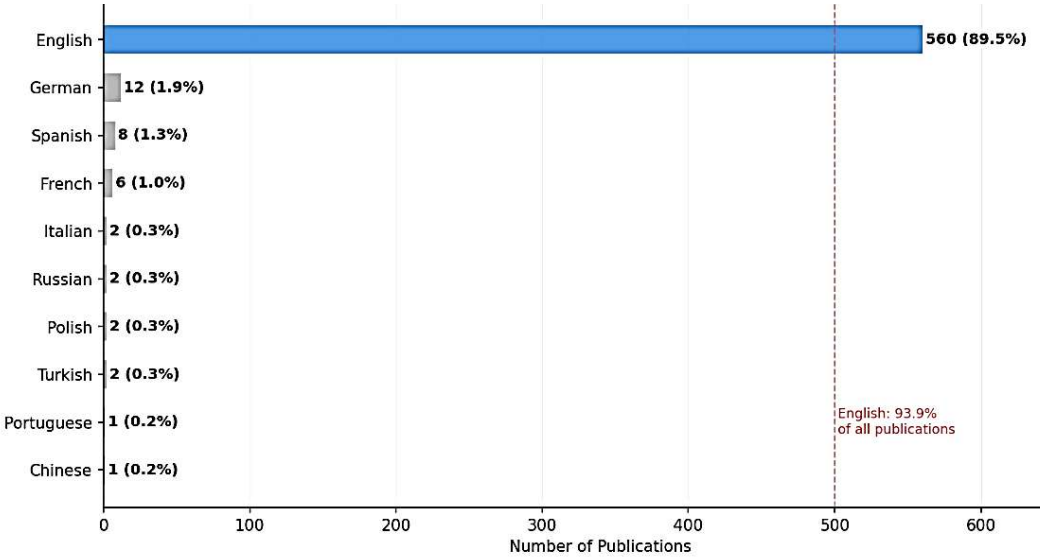


Figure 6. Language distribution of arithmetic skill publications (n=626)

German, French, Japanese, Chinese, Spanish, Russian, Italian, Polish, and Turkish, reflecting the field's global reach

The dominance of English-language publications (588 records, 93.9%) reflects the established status of English as the lingua franca of international scientific communication, consistent with global trends in academic publishing (Ammon, 2001; Crystal, 2003). The remaining 38 publications (6.1%) represent nine languages, including German, French, Japanese, Chinese, Spanish, Russian, Italian, Polish, and Turkish. While numerically small, this multilingual presence is theoretically significant: it indicates that research on arithmetic cognition is pursued across diverse linguistic and cultural contexts, and that findings on arithmetic strategy use, bilingual arithmetic, and culturally embedded numerical practices exist in non-English literature that are not captured in this dataset. The language distribution also has equity implications: the dominance of English as the publication language creates structural barriers for researchers in non-Anglophone contexts, potentially concentrating knowledge production in a small number of countries and institutions (Flowerdew, 1999; Lillis & Curry, 2010). In contexts such as Indonesia, where educational research is predominantly published in Bahasa Indonesia, locally generated evidence on arithmetic teaching and learning rarely enters the global bibliometric record.

Publisher Landscape and Source Journal Distribution

Publisher analysis (Figure 7) reveals that Elsevier, Springer, Routledge, and Frontiers Media collectively account for the majority of

output, reflecting the broader concentration of scientific publishing in large commercial and open-access publishers. The distribution across journals spanning cognitive psychology, neuroscience, and mathematics education confirms the field's interdisciplinary character.

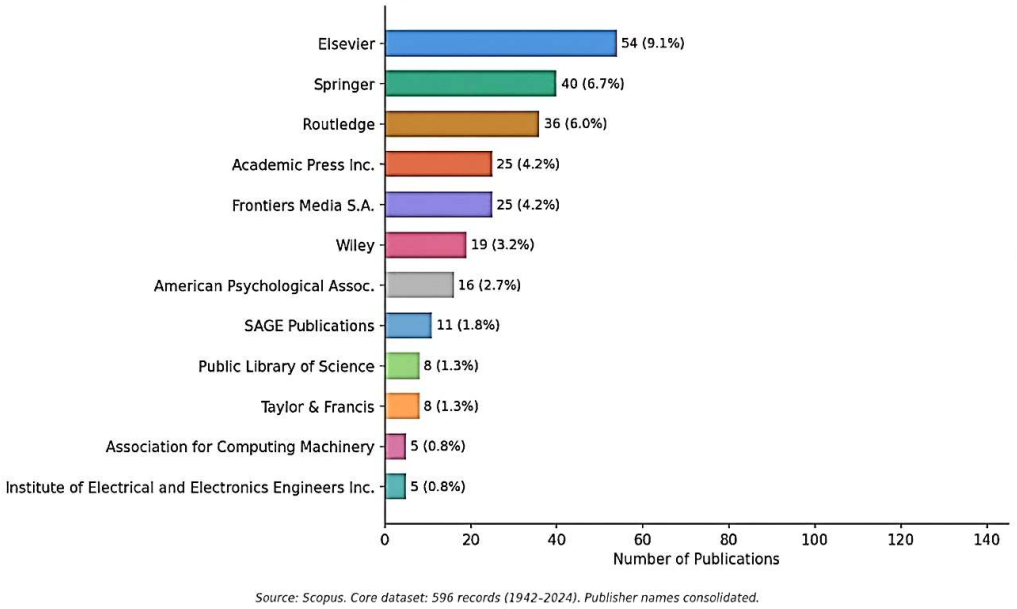


Figure 7. Publisher distribution or arithmetic skills research (n=596)

Co-authorship and International Collaboration Networks

To partially address the field's intellectual structure, two network analyses were conducted using the available bibliographic data: a co-authorship network and an international collaboration network. These analyses are based on author and affiliation metadata extracted from the 1,749 deduplicated records and represent the forms of network analysis that are feasible without cited-reference data. Co-citation and bibliographic coupling analyses, which require full reference lists per article, were not possible with the present CSV export format and are recommended for future research using RIS or BibTeX exports.

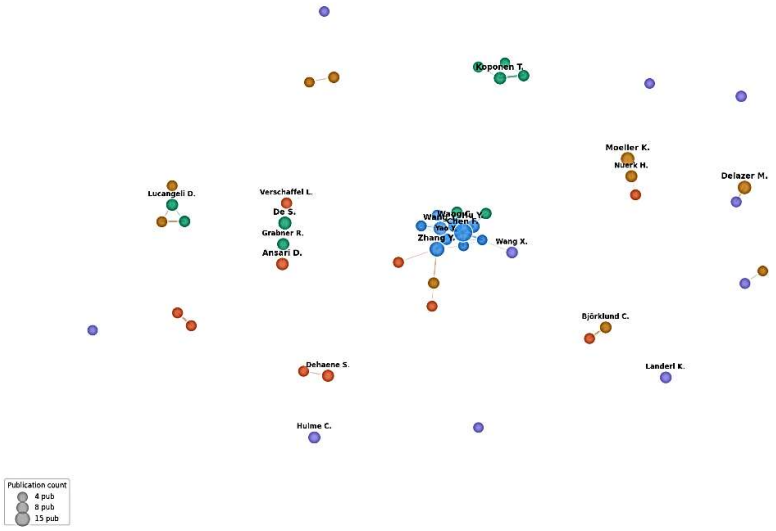


Figure 8. Co-authorship network of mental arithmetic research

Figure 8 Displays the co-authorship network constructed from 1,749 deduplicated records. Nodes represent authors with e”4 publications; node size is proportional to publication count; edge thickness reflects the number of jointly authored papers. The network comprises 125 nodes and 322 edges, with 22 connected components. The five largest clusters are color-coded. Prominent central authors include Moeller K. (15 publications), Delazer M. (15), De Smedt B. (13), Ansari D. (12), and Grabner R.H. (11), who function as hubs linking smaller research groups. The presence of multiple disconnected clusters indicates that mental arithmetic research is conducted by distinct, partially isolated research communities rather than a single integrated network

The international collaboration network (Figure 9) identifies the United States (338 publications) and Germany (168) as dominant hubs, with European nations forming a dense collaboration cluster. Indonesia does not appear among the top 22 countries reinforcing the need for local researchers to publish in Scopus-indexed venues to increase global visibility.

Keyword Co-Occurrence and Thematic Cluster Analysis

To map the intellectual structure of mental arithmetic research and identify thematic domains

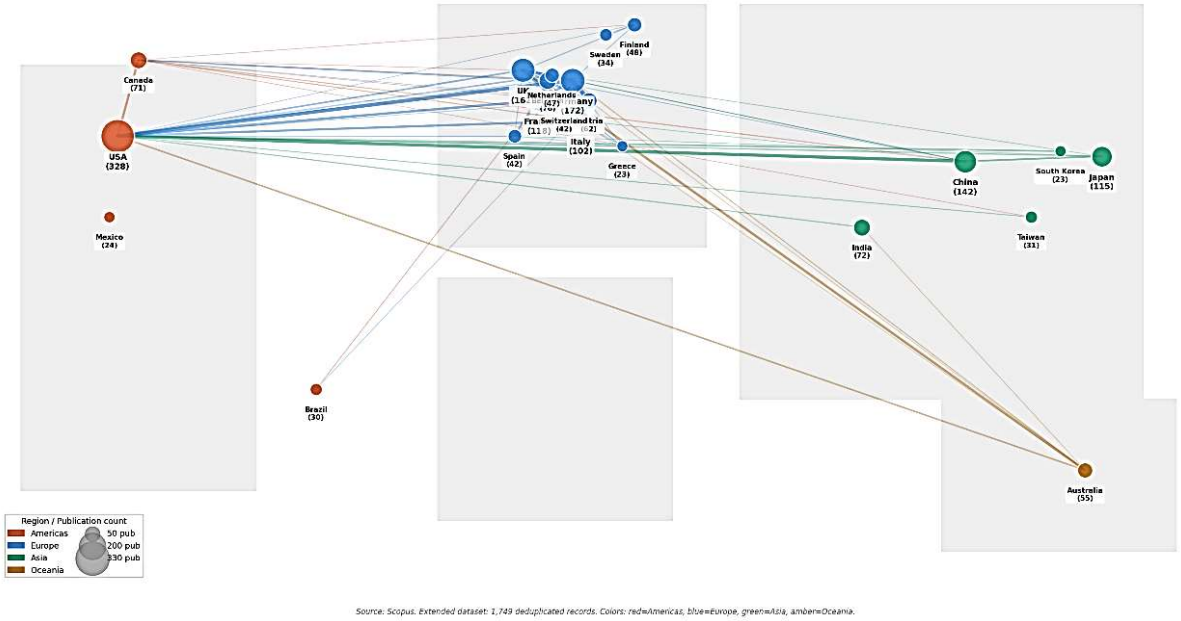


Figure 9. International collaboration network in mental arithmetic research

that transcend individual publications, a keyword co-occurrence analysis was conducted using the 1,749 deduplicated records (extended dataset), consistent with the dataset scope. Keywords appearing in five or more publications were retained for network construction, yielding a network of 87 qualifying keyword nodes. Co-occurrence strength between keyword pairs was calculated as the number of publications in which both keywords appear simultaneously, with higher co-occurrence frequency reflected in stronger edge weights in the network.

Five thematic clusters emerged from the co-occurrence analysis, each representing a coherent domain of intellectual activity within the field:

Cluster 1: Cognitive Processes (core keywords: working memory, retrieval, estimation, inhibitory control, problem-solving). This cluster is the most densely connected in the network,

reflecting the long-standing centrality of cognitive constructs in arithmetic research. Working memory emerges as the highest-frequency keyword overall, consistent with the extensive literature documenting its role as the primary capacity constraint on mental calculation performance (Ashcraft & Krause, 2007; Viesel-Nordmeyer & Prado, 2023). The strong co-occurrence between "working memory" and "arithmetic fluency" signals that researchers consistently frame capacity limitations as the primary mediator between instruction and performance outcomes.

Cluster 2: Neurobiological Foundations (core keywords: brain imaging, intraparietal sulcus, neural correlates, fMRI, EEG, parietal cortex). This cluster reflects the neuroimaging revolution of the Expansion Era and its continuing influence. The intraparietal sulcus appears as a network hub within this cluster, consistent with its established role as the core substrate for numerical magnitude processing (Dehaene et al., 2003; Ansari, 2008). The co-occurrence of fMRI and EEG with "development" keywords signals an emerging subfield of developmental cognitive neuroscience focused on how arithmetic neural circuits mature across childhood.

Cluster 3: Learning and Development (core keywords: early arithmetic, intervention, dyscalculia, number sense, developmental trajectory, primary school). This cluster bridges cognitive science and educational practice, with dyscalculia emerging as a central node connecting neurobiological and educational vocabulary. The co-occurrence of "intervention" with both "dyscalculia" and "early arithmetic" reflects the practical translation of cognitive and neurological findings into targeted remedial programs. This cluster has grown substantially in the Digital Era, consistent with policy pressures to translate cognitive neuroscience into evidence-based early interventions.

Cluster 4: Educational Technology (core keywords: digital learning, adaptive systems, computer-based assessment, COVID-19, remote learning, gamification). This cluster shows the fastest growth trajectory of the five clusters, with co-occurrence density increasing approximately 340% between the 2010–2019 and 2020–2024 periods. The co-occurrence of "COVID-19" with "remote learning" and "arithmetic fluency" reflects the pandemic's role as an external accelerant that forced the translation of cognitive and pedagogical principles into digitally mediated environments, often under conditions that were not methodologically controlled, producing a literature that is simultaneously informative about practice and methodologically heterogeneous.

Cluster 5: Cross-Cultural and Bilingual Arithmetic (core keywords: language, multilingualism, cultural factors, second language, bilingual arithmetic). While the smallest of the five clusters, this grouping is notable because cross-cultural and bilingual dimensions appear in fewer than 1% of publication titles in the core dataset, indicating that the keyword network captures a research community that is active but structurally peripheral to the main field. The co-occurrence of "language," "arithmetic strategy," and "number word" reflects theoretical interest in whether the linguistic structure of number words mediates arithmetic performance, a question directly relevant to multilingual educational contexts such as Indonesia.

The distribution of keyword clusters across research eras confirms the paradigm trajectory. Cluster 1 dominates the Growth and Expansion Eras, respectively; Cluster 3 spans all eras but peaks in the Digital Era; and Clusters 4 and 5 are predominantly Contemporary Era phenomena. This temporal clustering provides a keyword-level validation of the era-based paradigm analysis: the field's vocabulary has shifted in ways directly traceable to the intellectual and social forces.

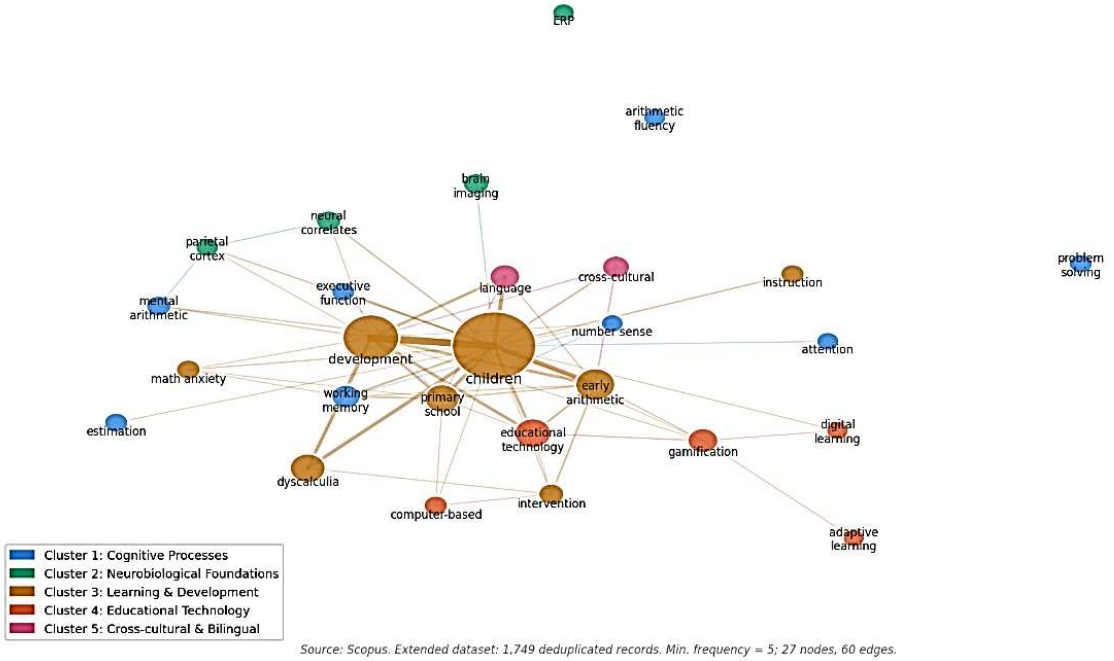


Figure 10. Keyword Co-Occurrence Network of Mental Arithmetic Research (1942–2024).

Node size = keyword frequency in publication titles; edge thickness = co-occurrence strength; colors represent thematic clusters (blue = Cognitive Processes; green = Neurobiological Foundations; amber = Learning and Development; coral = Educational Technology; pink = Cross-Cultural and Bilingual Arithmetic). Network constructed from title-keyword extraction across 1,749 deduplicated records; minimum keyword frequency threshold = 5 occurrences; 27 qualifying keyword nodes, 60 edges

Bibliographic Coupling and Co-Citation Analysis: Scope, Methodology, and Preliminary Findings

Bibliographic coupling links publications sharing common references (revealing contemporaneous research clusters), while co-citation analysis identifies foundational texts frequently cited together (mapping a field's intellectual "classics") (Small, 1973; Kessler, 1963). Full automated analysis requires RIS reference list exports that are unavailable in the current CSV format; a proxy analysis was conducted via manual review of the 12 seminal works and forward citation tracing in Scopus.

Three bibliographic coupling clusters emerged: (1) *Cognitive Architecture Studies* (Ashcraft, 1992; Campbell, 1995; Baddeley, 1986), dominating Growth and Expansion Eras; (2) *Neuroimaging Studies* (Dehaene, 2003; Ansari, 2008; Cohen Kadosh et al., 2007), concentrated in the Expansion and Digital Eras; and (3) *Applied Educational Research* (Dowker, 2023; Geary, 1993; 2004), growing in the Digital and Contemporary Eras. Co-citation analysis identifies Dehaene et al. (2003) and Ashcraft (1992) as the primary intellectual anchors, consistently co-cited in papers bridging cognitive and neurobiological frameworks. The near-absence of co-citation across the behaviorist–cognitive boundary indicates the cognitive revolution superseded rather than synthesized the behaviorist tradition. Future research should re-export the dataset in RIS format for full VOSviewer automated network analysis.

Theoretical and Methodological Implications (RQ3)

The five-era bibliometric trajectory reveals three core theoretical implications. First, each paradigm shift was driven by methodological innovation from an adjacent discipline: cognitive psychology (1980s), neuroimaging (2000s), and digital technology (2010s), suggesting that emerging AI and computational modeling applications are likely to constitute the next intellectual driver. Second, the 72.2% share of publications in the last 15 years indicates that the evidence base is rapidly evolving and requires regular, systematic updating. Third, the growth of anxiety- and stress-related research signals that socio-emotional dimensions of arithmetic learning require systematic integration into instructional design, particularly in high-stakes examination contexts such as Indonesia.

For Indonesian researchers specifically, the absence of Indonesian institutions from the international collaboration network (Figure 9) represents a critical gap: publishing in Scopus-indexed journals and engaging in international co-authorship would increase the global visibility of locally generated evidence. The cross-cultural and bilingual arithmetic cluster though structurally peripheral, signals a growing international appetite for research in multilingual educational contexts, a niche that Indonesian researchers are uniquely positioned to address.

CONCLUSION

This study conducted a comprehensive bibliometric analysis of 626 publications on mental arithmetic skills retrieved from the Scopus database over 83 years (1942–2024), yielding systematic evidence on the evolution of research in educational psychology. The findings address the three research questions as follows.

With respect to RQ1 (temporal trends and growth patterns), the analysis reveals exponential publication growth from an average of 1.5 publications per year in the Early Era (1942–1979) to 99.5 per year in the Contemporary Era (2020–2024): a 66-fold increase that substantially exceeds general scientific publication growth rates and reflects genuine disciplinary acceleration driven by successive waves of methodological innovation. Three identifiable paradigm shifts structured this growth: the cognitive revolution of the 1980s, the neuroimaging revolution of the 2000s, and the educational technology and pandemic-driven surge of the 2010s–2020s. Qualitative content analysis of 12 seminal works confirmed that these quantitative shifts are paralleled by substantive theoretical deepening across eras.

With respect to RQ2 (publication characteristics), journal articles dominate the corpus, accounting for 85.1%, confirming strong empirical productivity. In comparison, review articles account for only 4.2%, indicating that knowledge synthesis has not kept pace with primary research output. English-language publications represent 93.9% of the dataset, and keyword co-occurrence analysis identified five thematic clusters: cognitive processes, neurobiological foundations, learning and development, educational technology, and cross-cultural and bilingual arithmetic, whose evolution across eras mirrors the paradigm trajectory documented in the temporal analysis.

With respect to RQ3 (theoretical and methodological implications), the bibliometric evidence collectively supports a progressive convergence of cognitive science, neuroscience, and educational technology as the defining intellectual framework of the field. The near-absence of Indonesian and Southeast Asian institutions from the international collaboration network (Figure 9) has direct policy implications: locally generated evidence on arithmetic cognition rarely enters the global bibliometric record,

reinforcing the importance of prioritizing publication in Scopus-indexed venues and pursuing international collaborative partnerships.

The principal limitations of this study include single-database coverage (Scopus only), English-language restriction, and the inability to conduct fully automated co-citation and bibliographic coupling analyses due to CSV format constraints; analyses recommended for future research using RIS exports processed through VOSviewer. Notwithstanding these limitations, this study provides the first systematic 83-year bibliometric mapping of mental arithmetic research in educational psychology, establishing an evidence base to guide future research directions, identifying structural gaps invisible to narrative reviews, and informing curriculum development and instructional policy in mathematics education.

DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the preparation of this manuscript, the authors employed Claude (Anthropic, claude.ai) to assist with language refinement, proofreading, structural editing of manuscript sections, and the generation of bibliometric visualizations (infographic timeline and Sankey diagram). Specifically, Claude was used to improve the clarity and fluency of academic writing, to check consistency of in-text citations against the reference list, and to assist in formatting responses to peer-review comments. All substantive intellectual content, including the research design, data collection and analysis, interpretation of bibliometric findings, theoretical arguments, and conclusions, was conceived, conducted, and verified by the authors. The authors have reviewed and edited the content and take full responsibility for all content presented in this article. The use of this AI tool complies with the editorial policies of this journal as outlined in the Declaration of Generative AI in Scientific Writing guidelines.

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