



# Mapping Minds: A Comprehensive Review of Metacognition and Executive Function in Elementary Science Learning

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**Abstract:** This study aims to comprehensively review the development and research trends of metacognition and executive function in elementary science education. The research employed a comprehensive literature review approach to map the evolution, key themes, and future directions in this field. Articles were retrieved from the Scopus and Web of Science databases using the keywords “metacognition,” “executive function,” and “elementary science education,” covering the years 2015-2025. The selection and analysis followed the PRISMA Guidelines, while bibliometric mapping was conducted using VOSviewer software. The findings indicate that metacognition occupies a central position in the global research network and is strongly associated with self-regulation, motivation, and executive function. Three major clusters emerged: (1) theoretical and cognitive foundations of learning, (2) pedagogical and reflective practices in science classrooms, and (3) cross-cultural and contextual applications. The trend shows a shift from conceptual analyses to technology-enhanced and inquiry-based implementations. It can be concluded that strengthening metacognitive-executive abilities promotes students’ critical thinking, cognitive flexibility, and self-regulation, which are essential for 21st-century science education.

**Keywords:** Comprehensive review; Executive function; Metacognition; Science education

## Introduction

One of the essential 21st-century competencies is metacognition, which enables learners to become autonomous, reflective, and innovative in managing their own learning processes (Hendriani et al., 2021). Metacognition refers to an individual’s awareness and regulation of cognitive activities, encompassing the ability to plan, monitor, and evaluate problem-solving strategies across different tasks (Eberhart, Murayama, et al., 2025; Pascual et al., 2019).

In science education, where reasoning and inquiry are central, metacognition supports students in

developing comprehension, analytical reasoning, and reflective evaluation of the reflective evaluation of their thought processes. Students with higher metacognitive ability demonstrate stronger problem-solving, better learning strategies, and greater independence in monitoring their understanding (Rozy et al., 2025).

Complementary to metacognition are executive functions (EF), including working memory, inhibitory control, and cognitive flexibility, which are crucial in sustaining attention and managing complex reasoning during scientific investigations (Braund & DeLuca, 2018; Drexler & Zelazo, 2025; Schneider & Lockl, 2009; Siregar, 2021). Working memory helps store and retrieve

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relevant information, while inhibition interacts dynamically with metacognition to facilitate higher-order thinking and inquiry performance in science learning (Ilahi et al., 2024; Nurdiyanti & Wajdi, 2023).

Despite these theoretical linkages, empirical studies in elementary science education rarely integrate metacognitive and EF constructs within the same framework (Wang et al., 2021). Many focus on one aspect only, leading to fragmented findings and limited classroom application (Malawau, 2023; Marulis et al., 2021; Murisqa et al., 2024). Moreover, the diversity of science domains (e.g., biology, physics, and chemistry) and assessment instruments ranging from conceptual understanding to inquiry-based tasks makes it difficult to compare results or synthesize evidence systematically (Aliyah et al., 2023; Granato et al., 2025; Kubota et al., 2023; Malawau, 2023).

Prior reviews and meta-analyses often emphasize specific interventions or isolated skills, overlooking how metacognition and EF jointly contribute to inquiry, reasoning, and reflective practice (Schäfer et al., 2024; Vandenbroucke et al., 2018; Korzeniowski et al., 2020). This situation reveals a critical research gap: the lack of an integrated and comprehensive synthesis of how metacognition and EF are conceptualized, implemented, and measured in the context of elementary science education (Amundsen et al., 2020; Devy et al., 2022). Addressing this gap is essential to understanding the cognitive mechanisms underlying effective and self-regulatory capacities (Berninger et al., 2017; Cirino et al., 2019; Eberhart, Schäfer, et al., 2025; Finch et al., 2022). The study by Kubota et al. (2023) demonstrates that teaching metacognition and executive functions to elementary school students produces inconsistent results with negligible effects on academic outcomes.

Therefore, this study conducts a comprehensive bibliometric literature review to (1) map the research landscape, themes, and collaboration networks on metacognition and EF in elementary science education, (2) identify dominant pedagogical approaches and assessment trends, and (3) determine the conceptual interconnections that can guide more integrated, reflective, and evidence-based science learning practices.

The novelty of this study lies in combining bibliometric mapping and conceptual synthesis to provide an integrative understanding of metacognitive and executive functions, an area previously examined in isolation. This research is important because it not only clarifies the current state of global scholarship but also offers insights into how metacognitive-executive learning can enhance students' inquiry, reasoning, and reflective abilities in 21st-century science education.

## Method

This comprehensive review adopted the PRISMA 2020 and PRISMA-S protocols to ensure transparency and rigor in reporting the literature search and selection process (Page et al., 2021). The methodological framework was adapted from the Campbell and Cochrane (2019) educational review model, focusing on the systematic identification, screening, and synthesis of relevant studies. The review combined systematic review procedures, bibliometric mapping, and thematic synthesis to provide a holistic overview of the research landscape on metacognition and executive function in elementary science education. Similar methodological approaches have been implemented in prior educational bibliometric studies (Chen et al., 2025; Pascual et al., 2019; Thi-Nga et al., 2024).

### Data Collection

Data were collected from two international databases: Scopus and Web of Science (WoS), covering the publication period 2015-2025. Both databases were selected due to their reliability and extensive indexing of peer-reviewed educational research. The Boolean search string used was “metacognition” AND “executive function” AND (“elementary school” OR “primary education”) AND (“science learning” OR “science education”).

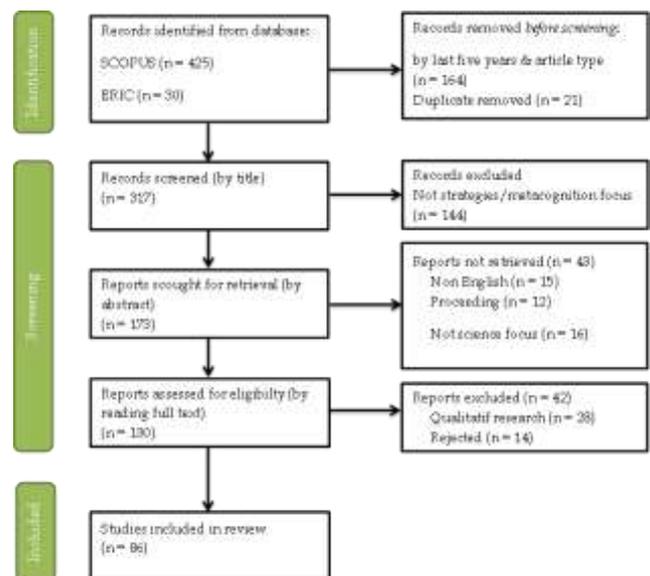


Figure 1. Data selection with PRISMA

Only peer-reviewed journal articles written in English or Indonesian were included. Duplicate records were removed prior to screening. The searchflow followed three PRISMA stages: identification, screening, and inclusion, as illustrated in figure 1. The search strategy was informed by bibliometric procedures in prior reviews (Chen et al., 2025), which demonstrated

the advantages of dual-database integration for enhancing coverage and citation accuracy.

#### *Inclusion Criteria*

The inclusion criteria were as follows: studies explicitly addressing metacognition and/or executive function within elementary science education contexts; peer-reviewed journal articles with empirical or conceptual approaches; articles written in English or Indonesian and available in full text; and studies reporting on students' reasoning, inquiry, or conceptual understanding outcomes.

#### *Data Coding*

All included articles were coded for both bibliographic metadata and substantive content. Metadata variables included author names and co-authorship relationships; publication year and source title; country of origin and institutional affiliation; keywords and citation counts. Thematic coding involved categorizing disciplinary focus (biology, physics, chemistry, general science); cognitive construct type (metacognition, executive function, or integrated approaches); research designs and sample characteristics; and reported learning outcomes, such as inquiry ability, reasoning, or conceptual understanding. Coding procedures followed standards used in educational review studies (Thi-Nga et al., 2024).

#### *Data Analysis*

Bibliometric and thematic analyses were performed using VOSviewer (Bulut, 2025). This software enables the visualization of bibliometric metadata to identify co-occurrence networks and thematic clusters (van Eck & Waltman, 2010). The analyses generated three main visualizations: network visualization, illustrating clusters of co-authorship, co-citation, and keyword co-occurrence; overlay visualization, showing the chronological evolution of research topics; and density visualization, identifying areas of high research concentration.

#### *Publication Bias*

To minimize publication bias, several steps were undertaken: only peer-reviewed journal articles indexed in Scopus and WoS were analyzed, ensuring publication quality; both open-access and subscription-based sources were included to balance accessibility; studies with positive, null, or negative findings were retained to prevent selective bias; and exclusion of gray literature (e.g., theses, reports) maintained methodological consistency. This approach aligns with prior meta-analytic recommendations (Pascual et al., 2019). Emphasizing comprehensive coverage and minimized bias through transparent selection and documentation.

## **Result and Discussion**

The researcher employed a deductive approach in presenting the results, moving from general bibliometric patterns to specific insights such as publication distribution, citation trends, country collaborations, and keyword co-occurrences. As emphasized by Esrozlu & Karakus (2019), a deductive presentation allows readers to follow the analytical progression from overarching trends to detailed interpretations. Bibliometric visualization techniques were used in conjunction with the bibliometric analysis strategy.

Through this approach, research trends and publication characteristics were statistically examined (McBurney & Novak, 2002). To illustrate the structural development of this research domain, several visualization methods were utilized (Garfield, 2009). The data were analyzed and visualized using VOSviewer (van Eck & Waltman, 2010, 2014a, 2014b, 2017), generating maps of bibliographic coupling among sources, authors, institutions, and nations, as well as co-occurrence occurrence networks of author keywords.

The network visualization revealed a clustering pattern dominated by the term's "metacognition," "executive function," "self-regulation," "mindfulness," and "inquiry learning." A noticeable trend shows a gradual shift from research focusing primarily on academic performance and self-regulated learning toward investigations integrating digital tools, inquiry-based science learning, and reflective pedagogy. The acronym IDL, frequently appearing in the 2023–2025 data range, refers to inquiry-driven learning, an instructional approach that combines technology-supported exploration and student-centered investigation, rather than an unrelated or speculative construct.

In the overlay visualization, colors ranging from dark to light blue represent variations in research frequency and collaboration intensity. Darker blue areas indicate regions or topics with limited research attention, suggesting potential opportunities for further exploration—particularly on gender-related differences, cultural contexts, and socio-emotional factors in elementary science learning. Lighter yellow nodes highlight emerging keywords and recent research topics, including AI-based feedback, digital scaffolding, and mindfulness training.

The density visualization reinforces this trend, showing a growing concentration of studies linking metacognition, executive function, and mindfulness. In the context of elementary school students, mindfulness is increasingly discussed as a cognitive-affective skill that supports attention regulation, self-monitoring, and emotional stability during inquiry-based activities. This suggests that cultivating mindfulness may enhance

metacognitive awareness and executive control, leading to improved reasoning and reflective learning performance. These findings align with recent empirical evidence showing the relationship between mindfulness and cognitive flexibility in school-age learners (Pascual et al., 2019; Qu et al., 2022; Siburian & Mardiyanti, 2023).

Geographic visualization shows that research productivity remains concentrated in developed countries notably the United States, United Kingdom, and the Netherlands, reflecting established funding and research infrastructures. However, emerging collaborations from Asia, particularly Indonesia, Malaysia, and South Korea, indicate a promising expansion of metacognitive and executive function studies in developing educational contexts. This aligns with broader regional initiatives encouraging technology-enhanced and reflective learning frameworks in Southeast Asian curricula (Thi-Nga et al., 2024).

The co-authorship network further indicates limited inter-institutional collaboration across continents, implying that future research could benefit international partnerships that integrate diverse cultural and pedagogical perspectives. These potential expansions can help address the darker-blue research gaps observed in the maps, especially concerning culturally responsive metacognitive interventions and gender-inclusive inquiry learning.

Figures and tables accompanying this section (see Figure 2–4) display clear, digitally generated maps rather than scanned images. Figure 2 illustrates the co-occurrence network of author keywords, Figure 3 presents the overlay map highlighting temporal topic evolution, and Figure 4 shows the country collaboration density map. Each visualization was produced directly from Scopus and WoS metadata using VOSviewer, ensuring data integrity and transparency.

Overall, the findings demonstrate that the research landscape has evolved toward integrating metacognitive–executive learning frameworks supported by technology, teacher professional development, and affective education. This progression marks a transition from cognitive theory to whole-person learning, emphasizing both intellectual and emotional growth in young learners.

*Trends in Publications*

Sorting the number of publications by the year of release provides an illustration of the publication trends. The trends in publications of inclusive education for kids from 2016 to 2025 are shown in Table 1. Table 1 displays publication records and publishing percentages by year of publication. The findings indicate that the quantity of publications fluctuates from year to year, with 2020 to 2025 seeing the largest number of articles, with 2016

seeing the fewest. To concentrate on current trends in this discipline, publications published before 2020 were not included in this analysis. Prior to 2020, there weren't many publications, and they weren't evenly distributed among years, but some of them had a lot of citations. The impact of more recent articles would have been masked if these publications had not been disregarded.

**Table 1.** Records of Publications and Percentages

Publication Years	Publication Records	% of 502
2016	28	5.57
2017	32	7.37
2018	36	7.17
2019	38	7.56
2020	43	8.56
2021	45	8.96
2022	52	10.35
2023	69	13.74
2024	73	14.54
2025	86	17.23

*Research Concentration*

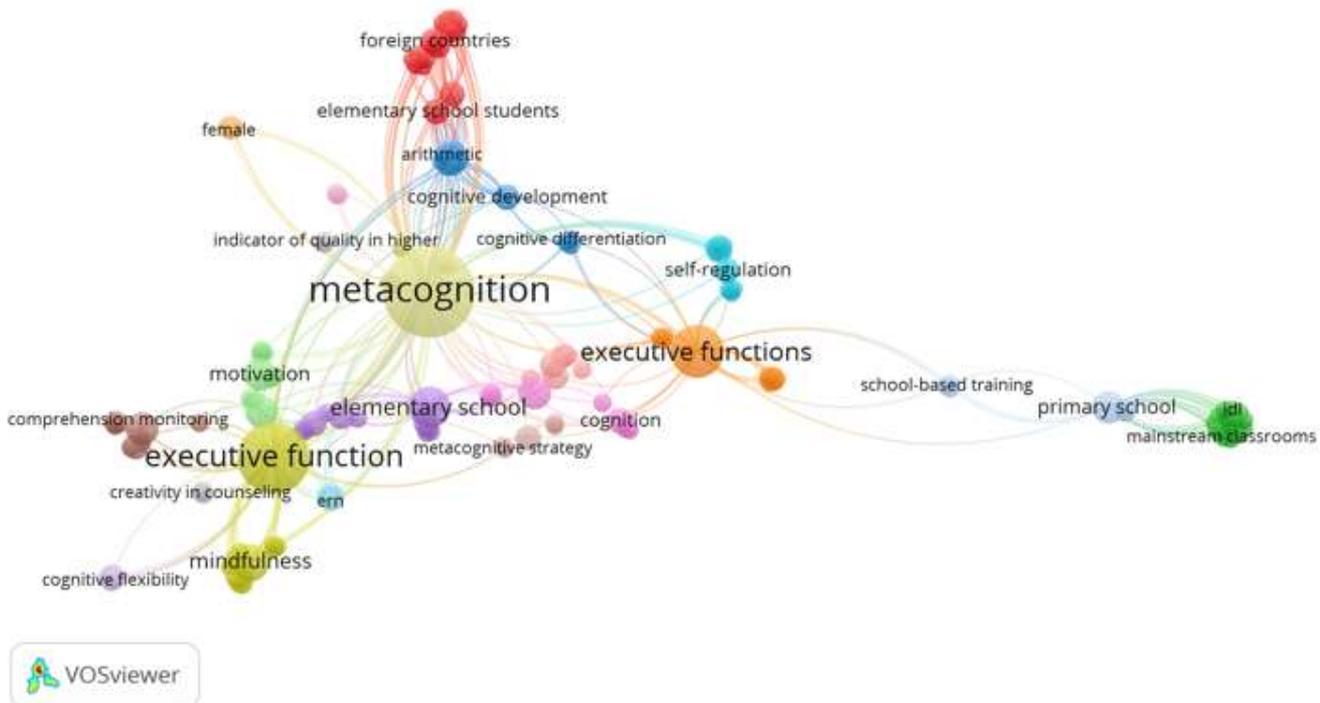
The conceptual landscape of research on executive function and metacognition in the setting of elementary education is displayed in the VOSviewer visualization. Figure 2 illustrates the intimate connections between several fundamental ideas that together constitute a body of knowledge spanning the domains of pedagogy, cognitive science, and educational psychology. The map's colors correspond to theme clusters, which organize research topics according to citations and semantic proximity.

Cluster 1: The Scientific Center of Gravity: Metacognition. Since yellow predominates in the map's center, "metacognition" is the node that appears most frequently and centrally in the literature. This node is linked to ideas like executive function, self-regulation, and cognitive development, indicating that academics consider metacognition that is, an individual's awareness and control over their own thought processes to be a crucial skill in contemporary learning. The context of "elementary school students" is also strongly indicated by this focus, indicating that a large body of research examines how children's reflective skills evolve in primary school. This cluster, in theory, shows how knowledge-based learning gives way to thinking-based learning.

Cluster 2: Self-regulation and executive function A network of ideas focused on "executive functions," self-control, and intellect symbolized by orange. The dynamics of mental control—how pupils organize, track, and modify their learning behavior—are demonstrated by this cluster. The relationship between academic achievement and executive function, as well as how these functions aid in

problem-solving and decision-making, are the main topics of research in this cluster. The existence of phrases like "school-based training" suggests that research is

now more focused on real-world implementation in educational settings.



**Figure 2.** Research focus

Cluster 3: Training Based in Schools and the Primary School Context— 10, Nodes like "primary school," "school-based training," and "mainstream classrooms" are indicated by blue. This cluster highlights that research continues beyond the level of cognitive concepts and continues into real-world applications. Researchers examine the ways in which School-based training initiatives can enhance students' executive functioning skills and promote metacognitive awareness. This emphasis shows how pedagogical and psychological approaches can work together to create a learning environment in schools where kids can develop their capacity for reflective thought.

Cluster 4: Cognitive Flexibility, Motivation, and Mindfulness Concepts like "mindfulness," "motivation," and "cognitive flexibility" are all represented with green. Affective subtleties are introduced into the cognitive discourse by this cluster. Motivation is a key component in making sure that this thought process is ongoing, and the mindfulness technique is regarded to be a means of assisting pupils in being more profoundly conscious of their thoughts. The relationship between metacognition and cognitive flexibility suggests that effective learning involves both "what students think" and "how they adjust their thinking" in response to the learning context.

Cluster 5: Cross-cultural and Social Context Nodes like "foreign countries," "female," and "arithmetic" are indicated by the color red. The sociocultural aspect of new research is shown in this cluster. To comprehend how cognitive and metacognitive functions evolve in many educational contexts, researchers are starting to take note of contextual differences, such as gender and cultural surroundings. This cross-cultural approach deepens our understanding of how executive functions and reflective learning are not universal and might vary depending on national educational systems, customs, and values.

All things considered, this map shows that research on executive function and metacognition has shifted globally in the direction of applied, contextual, and integrative approaches. Because these clusters are closely related, researchers are now trying to understand how kids learn holistically by combining cognitive, affective, and social factors. In other words, research now addresses "how students perceive, regulate, and direct their thoughts in the learning process" in addition to "how they think." This method offers a solid basis for the creation of metacognitive learning models in elementary schools—models that help students build their reflective, resilient, and autonomous character in addition to teaching higher-order thinking abilities.

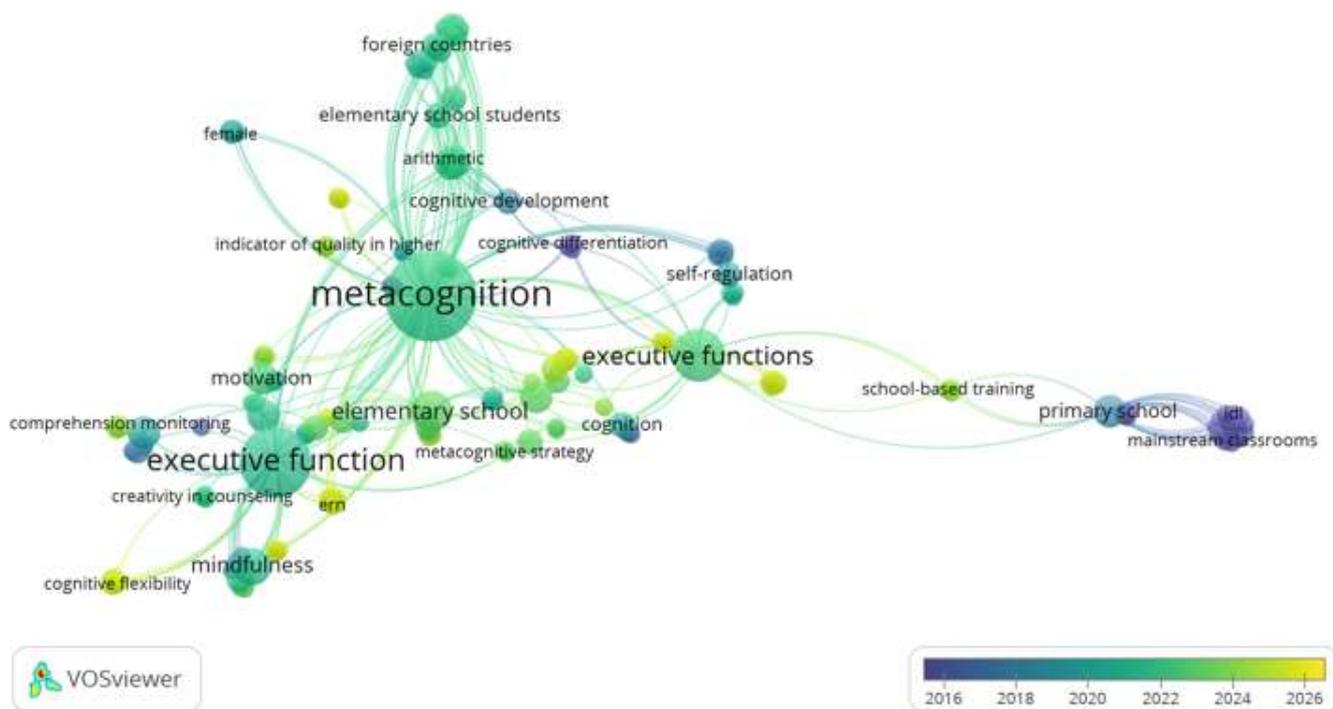


Figure 3. Research novelty

The findings of Figure 3, overlay mapping, demonstrate that, between 2016 and the present, there has been a notable thematic evolution in the study themes related to executive function and metacognition. Bright yellow denotes more recent study directions (2023–2025), whereas dark blue to light green colors represent subjects that were previously examined (2016–2021). We can see where new advancements are happening and how the focus of study has changed thanks to this color pattern.

**Early Wave: Theoretical and Cognitive Foundations (2016–2020).** Research mostly concentrated on fundamental ideas like "metacognition," "cognitive development," and "elementary school students" throughout the early period (shown in dark blue to greenish blue). These investigations examined the connection between children's cognitive development and thinking awareness, which are still conceptual in character. During this time, a lot of research focused on the relationship between metacognition and learning techniques and academic achievement, but it did not yet address contextual factors like the learning environment or school-based interventions.

**Second Wave: Self-regulation and executive function integration (2020–2023).** Research started to move toward the areas of "executive function," "self-regulation," and "mindfulness" as the green period began. During this stage, scientists started fusing neuropsychological data with cognitive theory. To explain how youngsters not only think but also manage and assess their thoughts, a cross-disciplinary method

was developed. The primary breakthrough at this point was the realization that executive functions and metacognition support one another in self-regulation-oriented learning rather than operating independently.

**Current Trends (2023–2025): School-Based Learning and Contextual Implementation.** The most recent path of this research is shown by the yellow color on nodes like "school-based training," "primary school," and "mainstream classrooms." This stage signifies a change from theoretical to applied research, with an emphasis on the direct application of executive functions and metacognition in the context of primary schools.

Highlights of recent research include the use of metacognition and executive function-based teacher training to increase the effectiveness of instruction, the incorporation of mindfulness learning to help students focus and regulate their emotions, and technology-based adaptive learning designs that track students' cognitive flexibility and reflective skills in real time. This pattern suggests the rise of a new paradigm, according to which metacognition is a competency that can be taught, cultivated, and assessed through actual classroom instruction.

Recent studies indicate a shift in emphasis from contextual application toward a deeper focus on cognitive concepts. The relationship between metacognition and academic achievement is no longer the sole concern of researchers; instead, contemporary investigations are exploring how school-based interventions and teacher training programs can cultivate students' awareness of their own thinking

processes. These efforts reflect an emerging pedagogical paradigm that integrates executive functions and metacognition within a single, cohesive learning framework.

Within this framework, executive functions serve as the mechanisms of cognitive control, while metacognition operates as the regulator of thinking awareness. Together, they form a mutually supportive system that bridges cognitive and affective dimensions of learning, aligning with the growing movement toward more humanistic education. Prominence emphasizes the importance of psychological well-being alongside cognitive development.

At the same time, the integration of digital tools and technological advancements has opened new directions in metacognitive research. Emerging studies, particularly those projected toward 2025, suggest the potential for AI-based feedback systems and digital scaffolding to enhance students' reflective thinking and self-monitoring abilities. Although still limited in number, these innovations signal a promising future where technology not only supports cognitive excellence

but also nurtures learners' emotional and reflective capacities in a balanced, holistic manner.

All things considered, the study represented in this map is innovative because it shifts the paradigm of metacognition and executive function research from theory to real-world classroom implementation. The new method frames schools as settings that promote self-regulation, teachers as agents of thinking awareness, and students as reflective learners. The development of learning models based on metacognition and executive function that are focused on children's mental health and character is made possible by this line of inquiry.

The "Density Visualization" in Figure 4 is a graphic that illustrates the state of research on executive function and metacognition in relation to learning in elementary and primary schools. The map's colors reflect the degree of topic occurrence and interrelationships: blue denotes places with low density or weak relationships, green denotes areas with moderate density, and yellow denotes the most often occurring and interconnected locations.

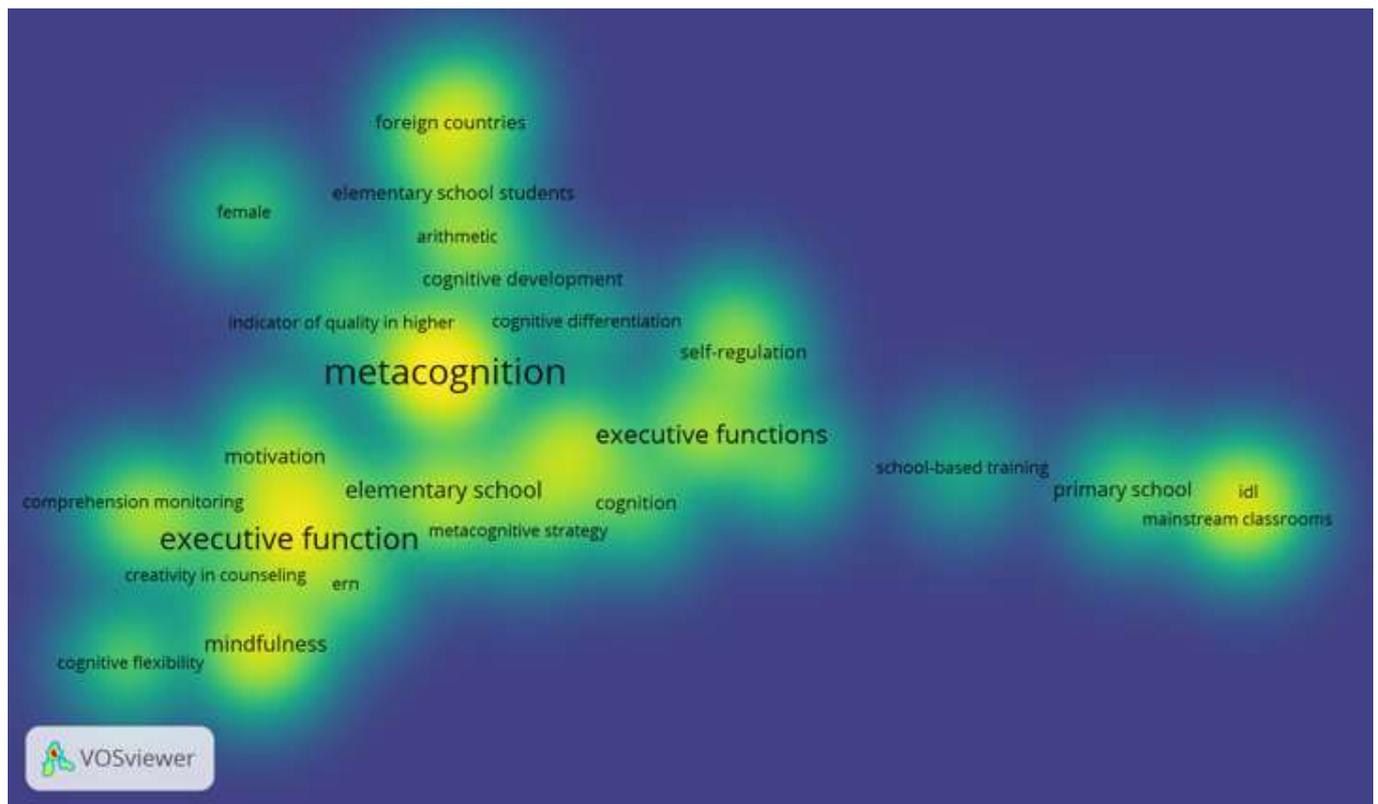


Figure 4. Density visualization

The most prevalent node, "metacognition," is highlighted by the bright yellow core and is closely related to several cognitive and educational ideas. This demonstrates that metacognition, which is frequently linked to subjects like executive function, self-regulation, and cognitive growth, is the primary focus of

the literature. This link supports the idea that metacognition is a higher-order thinking ability that helps with organizing, observing, and managing the learning process, particularly for primary school students.

Metacognition and executive function are closely related, as seen in the green-yellow area next to the center. These two ideas make up a significant cluster in the study, which reflects an emphasis on cognitive self-regulation processes (e.g., cognitive flexibility, working memory, and inhibitory control). Concepts like cognitive differentiation and self-regulation highlight that children's cognitive development is viewed as the outcome of their capacity to control and reflect on their own thought processes, in addition to the acquisition of knowledge.

The study application area in the context of elementary education is depicted on the right side of the map, which has green to blue hues. Metacognition and executive functions are frequently examined within the framework of elementary school learning, as demonstrated by terms like "elementary school," "primary school," and "school-based training." A change in emphasis from theory to learning practice—specifically, how teachers might promote metacognitive skills through self-regulated learning and classroom training—is shown using terminology like mainstream classrooms and IDL, which may be short for personalized learning.

Terms like "motivation," "awareness," and "comprehension monitoring" indicate clusters in the lower left section that connect metacognition to the reflective and affective facets of learning. This points to a more integrative research tendency, which holds that metacognition is not just cognitive in nature but also connected to emotion and attention regulation, both of which are critical for effective learning.

The existence of comparative and demographic features in the literature is indicated by terms like "foreign countries" and "female," which are situated in a dimmer area (light blue-green). Some research looks at gender-based disparities or analyzes how metacognitive methods are applied in different nations. This area contributes to the global understanding of the role of metacognition in primary schools, although it is less dense than the main cluster.

All things considered, this density map demonstrates how, throughout the past five years, research has positioned metacognition at the forefront of scientific discussions encompassing executive function, self-regulation, and elementary school pedagogical applications. These two ideas are the primary theoretical pillars for describing how infants develop thinking awareness and the capacity to regulate their learning processes, as indicated by the progressively brighter colors surrounding the terms "metacognition" and "executive function." Future studies seem to be taking a more comprehensive approach, combining school-based interventions, motivation, and mindfulness to improve

the development of metacognitive abilities at the primary school level.

#### *Results of Bibliometric Analysis Thematic Synthesis*

A conceptual map of research on metacognition and executive function in the setting of primary education was formed by a number of major topics that emerged from the bibliometric analysis results. These themes arose from the density of research as seen in the density map, the intensity of temporal correlations in the overlay visualization, and the relationships between keywords in the network visualization. Three main, related themes that characterize the trajectory of worldwide research progress are derived from this synthesis of the analysis results.

#### *Theme 1: Fortifying Theoretical and Cognitive Bases*

This topic emphasizes how self-regulation, executive function, and metacognition are closely related and serve as the foundation for higher-order cognitive abilities. This cluster's research focuses on how kids comprehend, keep an eye on, and manage their thought processes throughout educational events. While executive function serves as a regulatory mechanism that aids pupils in organizing, remembering, and modifying their learning processes, metacognition is theoretically defined as awareness of thinking. This theme highlights that the key pillars of successful learning in early infancy are developing introspective skills and cognitive self-control.

#### *Theme 2: Interventions in Schools and Pedagogical Methods*

The utilization of executive function and metacognition ideas in learning activities is the second theme. The introduction of new trends that result in reflective and self-aware learning methodologies is indicated by keywords like "mindfulness," "school-based training," and "primary education." Through problem-solving, self-reflection, and exploratory activities, teachers serve as facilitators, helping students to consider how they think. This theme's research highlights how crucial it is to have a learning environment in primary schools that encourages self-regulated learning and contextual cognitive training.

#### *Theme 3: Implementation Context and Global Research Direction*

The third element emphasizes how environment and cultural variations affect how metacognitive techniques are applied across nations. Research is becoming more aware of the diversity of social, cultural, and educational systems, as evidenced by keywords like "foreign nations," "elementary school pupils," and "mainstream classes." Nonetheless, developed nations continue to dominate most studies, creating chances for

studies in Asia and Indonesia to offer fresh viewpoints. Therefore, this theme offers the opportunity for innovation in attempts to use cross-cultural and glocalized education approaches to adapt executive functions and metacognitive theory to local situations.

From conceptual underpinnings to instructional approaches and cross-context adaptation, the three themes work in concert to provide a distinct research growth path. With an emphasis on fostering reflective, regulatory, and character-oriented learning, current trends indicate a move away from theoretical research and toward practical classroom implementations.

The merger of locally based methods with reflective learning technology that comprehensively support students' executive functions and metacognitive skills offers the possibility for innovation. Three chances for novelty (research novelty) arise from the synthesis of bibliometric results, and they include the following: the study of executive functions as mediators between metacognition and learning outcomes in science or math, the incorporation of metacognition and executive functions in reflective technology-based learning in elementary schools, and the modification of cross-cultural and glocalized pedagogy approaches to foster critical thinking within the framework of local Indonesian culture.

## Conclusion

This bibliometric review reveals that global research on metacognition and executive function in elementary science education has evolved from theoretical and cognitive foundations toward school-based reflective pedagogical approaches and cross-cultural implementation contexts. These three interconnected themes demonstrate how the field has progressively moved from conceptual analyses to applied reflective practices that link cognition, self-regulation, and classroom inquiry. The findings highlight a growing convergence between metacognitive awareness and executive control, indicating that these constructs function as complementary mechanisms in fostering students' reasoning and reflective learning. Emerging studies also point to the integration of digital scaffolding and mindfulness-based strategies that enhance students' attention regulation, self-monitoring, and reflective awareness within inquiry-based science learning. Future research should continue to expand the cross-cultural scope of this field by exploring how technology-supported and reflective pedagogical frameworks can be adapted to diverse educational contexts. Overall, this study underscores the importance of developing critical thinking, cognitive flexibility, and self-regulation among

elementary school learners to meet the cognitive and reflective demands of 21st-century science education.

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## Author Contributions

Conceptualization, methodology, formal analysis, investigation, resources, data curation, and original draft writing: R.P.; validation, review and editing, and visualization: M. N. and D.R. All authors have read and approved the published version of the manuscript.

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## Conflicts of Interest

The authors declare no conflict of interest.

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