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Derleme Makalesi * Review Article

An Examination of Computational Thinking in Mathematics Education through Bibliometric and Content Analysis

Matematik Eğitiminde Bilgi İşlemsel Düşünmenin Bibliyometrik ve İçerik Analizi ile İncelenmesi

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Abstract: The importance of computational thinking in the 21st century has been widely acknowledged, with its incorporation into school curricula around the world. However, there is no consensus on the content of computational thinking, which has led to a growing interest in the field. This has necessitated the need for review studies that are expected to provide a clear explanation of the literature and trends in the field. In this context, this study aimed to examine the studies on computational thinking in mathematics education in two dimensions. First, bibliometric analysis was used to provide a general framework of the field. To this end, the Web of Science database was searched, and 194 publications were included in the analysis. The 10 most cited articles were then selected from these publications and content analyzed in terms of their methodological approaches, aims, and results. Through these analyses, research trends were identified. The results of the bibliometric analysis revealed the most frequently used keywords, the most productive countries, the most influential authors, and articles. The results of the content analysis indicate that the most cited articles address the integration of computational thinking into mathematics education in theoretical and applied contexts. It is anticipated that the findings will inform future studies.

Keywords: Computational thinking, mathematics education, Bibliometric analysis.

Öz: Bilgi işlem düşünme, 21. yüzyılın gerekli bir becerisi olarak kabul edilmektedir. İçeriği konusunda tam bir fikir birliği olmamasına rağmen, dünya genelinde okul müfredatlarına dahil edilmektedir. Bu artan ilgi, literatürü ve alandaki trendleri açık bir şekilde açıklaması beklenen derleme çalışmalarına olan ihtiyacı doğurmuştur. Bu bağlamda bu çalışma, matematik eğitiminde bilgi işlemsel düşünme üzerine yapılan çalışmaları iki boyutta incelemeyi amaçlamıştır. İlk olarak, bibliyometrik analiz kullanılarak alanın genel bir çerçevesini sunmak hedeflenmiştir. Bu doğrultuda, Web of Science veritabanı taranmış ve 194 yayın analiz kapsamına alınmıştır. Ardından, bu yayınlar arasından en çok atıf alan 10 makale seçilerek, metodolojik yaklaşımları, amaçları ve sonuçları açısından içerik analizi yapılmıştır. Bu analizler aracılığıyla araştırma eğilimleri belirlenmeye çalışılmıştır. Bibliyometrik analiz sonuçları, en sık kullanılan anahtar kelimeleri, en üretken ülkeleri, en etkili yazarları ve makaleleri ortaya koymuştur. İçerik analizi sonuçlarına göre, en çok atıf alan makaleler, teorik ve uygulamalı bağlamda bilgi işlem düşünmenin matematik eğitimine en etkili şekilde nasıl entegre edilebileceğine yönelik araştırmaları içermektedir. Elde edilen bulguların gelecekte yapılacak olan çalışmalar için yol gösterici olacağı düşünülmektedir.

Anahtar Kelimeler: Bilgi işlemsel düşünme, matematik eğitimi, bibliyometrik analiz.

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INTRODUCTION

Computational thinking (CT) has gained considerable traction recently (Wing, 2008). Yet, its origins can be traced back to the early 1980s, when Papert first proposed the integration of CT skills into K-12 education. Papert (1996) stated that using the computer as a tool in mathematics enables effective solutions. In addition to this idea, Wing (2006) argued that CT is a fundamental skill not only for computer scientists but for all individuals. She emphasized the importance of integrating CT into every child's analytical abilities, alongside reading, writing, and arithmetic. CT is defined as the ability to solve problems, to design systems, and to understand human behavior based on different computer concepts and processes (Wing, 2008). In another study, Wing (2011) defines CT as "the mental activity involved in formulating a problem to admit a computational solution. The solution can be carried out by a human or machine, or more generally, by combinations of humans and machines." The term "problem" in this context encompasses not only well-defined problems but also complex software problems, whose solutions are often large and complex. According to the Wing, CT encompasses the design and analysis of problems and their solutions, which are broadly interpreted. Similarly, Barr, Harrison, and Conery (2011) stated that CT is a process of problem-solving that involves formulating problems in a way that enables the use of computers and tools, identifying, analyzing, and implementing possible solutions to achieve efficient results. A prevalent viewpoint is that mathematical thinking and CT are viewed as problem-solving tools (ISTE, 2011).To summarize, the definition of CT has evolved in parallel with the rapid advancement of technology. Initially, CT was defined solely as the solving of problems through computer usage. However, over time, this definition has expanded to include the involvement of both computers and humans in thinking computationally, and addressing complex real-world problems among others in the problem-solving process. This raises the question: What is the relationship between CT and mathematics? Does the problem-solving process employed by both disciplines share a common foundation?

Although CT is linked to all disciplines of science, technology, mathematics, and engineering (STEM) education, its closest relationship is with mathematics (Baldwin, Walker, & Henderson, 2013). The CT in mathematical education provides students with a more realistic understanding of the professional and real-world applications of mathematics. This is achieved by allowing students to engage with mathematical concepts through the use of computational tools (Ng and Cui, 2021).

How CT can be integrated into the mathematics education? CT can facilitate the expansion of central processes within mathematics by restructuring how problems are both formulated and solved. In terms of contextualization, this perspective situates mathematics as a context for CT. Consequently, both mathematical objects (resulting from horizontal mathematization) and mathematical activities (in the process of vertical mathematization) can serve as starting points for CT (Kallia et al., 2021). When considered in the context of problem-solving, CT is a methodical approach to solving problems, involving the use of abstraction, decomposition, algorithmic design, evaluation, and generalizations (Selby and Woollard (2013: p. 5). In their study, Kalelioğlu, Gülbahar, and Kukul (2016) developed a framework for CT as a problem-solving process. This framework encompasses the following components:

- *Identifying the problem:* abstraction, decomposition
- *Gathering, representing, and analyzing data:* data collection, analysis, pattern recognition, conceptualizing, data representation
- *Generating, selecting, and planning solutions:* mathematical reasoning, building algorithms, and procedures, parallelization
- *Implementing solutions:* automation, modeling, and simulations
- *Assessing solutions and continuing for improvement*: testing, debugging and generalization

This kind of matching between the problem-solving process in mathematics and the components of CT is thought to facilitate the integration of CT into mathematics classes. Indeed, there are studies in the literature that explore how to integrate CT into mathematics education and investigate its impact on learning mathematics. Weintrop et al. (2016) conducted a study on defining CT and integrating it into mathematics and science education. In their study, they proposed a classification that categorizes CT for mathematics and science into four main categories: data applications, modeling and simulation applications, computational problem-solving applications, and systems thinking applications. This classification offers a response to the challenge of defining CT. In a similar vein, Gadanidis, Hughes, Minniti, and White (2017) examined the potential benefits of integrating CT into mathematics education, to provide students with enhanced learning environments. Similarly, Miller (2019) conducted a six-week teaching experiment to investigate the impact of coding activities on the mathematical skills of second-grade students. The study aimed to determine whether coding could enhance students' abilities to identify mathematical patterns and structures. The study's findings indicated that students demonstrated enhanced abilities to identify patterns and structures following instruction through coding. Some studies have also examined the use of sub-dimensions of CT in Mathematics Education (ME). For instance, Rich and Yadav (2020) proposed a framework focusing on the abstraction component of CT in elementary mathematics education. This framework suggests that levels of abstraction will assist elementary school students in solving verbal problems. Borkulo et al. (2021) observed that algorithmic thinking and generalization are two fundamental elements that are frequently underrepresented in traditional mathematics classes. Consequently, the researchers investigated the potential for addressing algorithmic thinking and generalization elements in 12th-grade mathematics classes through the use of GeoGebra software. The study resulted in the formulation of strategies for educators interested in integrating CT elements into mathematics lessons.

Several reviews have been conducted on the use of CT in ME. Nordby, Bjerke, and Mifsud (2022) conducted a systematic review examining studies on CT and mathematics learning in elementary school classrooms. This study synthesized ten studies conducted between 2000 and 2021, evaluating articles in terms of robotic coding activities and activities focusing on communication, exploration, creativity, and participation. Isharyadi and Juan (2023) examined 24 studies published in Scopus between 2018 and 2022 to investigate the benefits and challenges of CT in ME. Similarly, Barcelos (2018) conducted a review of 42 articles from the ACM, IEEE, and Google Scholar databases with the same objective. Montuori, Gambarota, Altoe, and Arfe (2024) conducted a systematic review of findings from 11 experimental studies published between 2006 and 2022. The objective was to explore the effects of coding and programming interventions on children's basic and executive functions, including inhibition, working memory, cognitive flexibility, planning, and problem-solving. Similarly, Refvik and Bjerke (2022) conducted a content analysis of seven studies examining the relationship between CT and problem-solving in elementary and middle school mathematics education contexts. Adanır (2023) conducted a bibliometric and content analysis on 156 studies scanned in WoS, with a focus on CT at early childhood and elementary school levels. The study concluded that robotics, block-based, unplugged, STEM, and gamified activities are prominent in the teaching of CT skills at the kindergarten through fifth-grade levels. Wu and Yang (2022) review studies synthesize the literature on how CT and mathematical thinking (MT) are integrated into mathematics education research with a focus on tasks. A review of 28 relevant articles in the Web of Science Core Collection database The findings of the study indicate that CT develops mathematical concepts and skills, and there exists a reciprocal relationship between CT and mathematical thinking (MT). In this relationship, CT is involved in problem-solving processes, while MT is engaged in the debugging phase of the process.

In the context of research reviews, the most commonly encountered methods include meta-synthesis, meta-analysis, and bibliometric analysis. In contrast, meta-synthesis studies are conducted with qualitative research, while meta-analysis studies involve quantitative research. In contrast, bibliometric studies encompass all studies conducted within the relevant field. Bibliometric analysis is used for purposes such as identifying general trends related to the researched topic, detecting collaborations between countries and authors, and determining the most frequently used keywords. According to Donthu et al. (2021), the data that play a central role in bibliometric analysis are typically large-scale (e.g., in the hundreds or even thousands) and objective in nature (e.g., the number of citations and publications, the frequency of keywords and topics). However, the interpretation of this data often relies on both objective (e.g., performance analysis) and subjective (e.g., thematic analysis) evaluations. These evaluations are based on informed techniques and procedures. Consequently, the integration of bibliometric and content analysis methodologies offers a comprehensive qualitative insight into the subject matter, encompassing not only the specific topics, concepts, and methodologies, but also reflecting the overarching perspective. This enhances the value of the study.This study aims to collate existing research on CT in ME, identify core themes, provide an overview, and offer insights for future studies. By this purpose, this study conducted bibliometric and content analyses of studies about CT in ME, as retrieved from the Web of Science database. The bibliometric analysis identified global publications' networks, citations, trends, and other relevant factors related to the research topic. The content analysis evaluated the methodological approaches, topics, and findings of the top 10 most cited articles. In this context, the research questions are formulated as follows:

1. How are the articles on CT in ME and their citation data distributed over the years?

2. What is the numerical distribution of the types and languages of publications related to CT in ME?

3. What bibliometric features are present in the literature on CT in ME, including the most frequently occurring keywords, the most productive countries, the most influential authors, and the most frequently published and cited journals?

4. What are the key topics, methodologies, samples, mathematics subject matter, data collection tools, and significant implications in the most cited articles on CT in ME?

METHOD

This study employs a systematic review methodology, integrating bibliometric analysis and content analysis. Initially, a bibliometric analysis of research on CT in ME was conducted, providing a comprehensive overview. Subsequently, the selected articles underwent content analysis, with the results presented to the reader.

Article selection process

The Web of Science (WoS) was utilized as the data source for this study due to its inclusion of high-quality publications. A search was conducted on June 13, 2024, using the keywords ("comput* think*") AND ("math* course" OR "math* educat*" OR "teach* math*" OR "learn* math*" OR "math* curriculum" OR "math* instruct*" OR "math* teacher educat*" OR "math* teach*" OR "math* learn*" OR "asses* in math* educat*" OR "math* pedagogy" OR "math* teach* practice*"). All searches were performed in the topic section of WoS. The search resulted in 194 publications. No exclusion/inclusion criteria were applied in this phase as the aim was to provide a general overview of CT in ME. Furthermore, a content analysis was conducted on the ten most cited articles obtained by filtering.

Data analysis

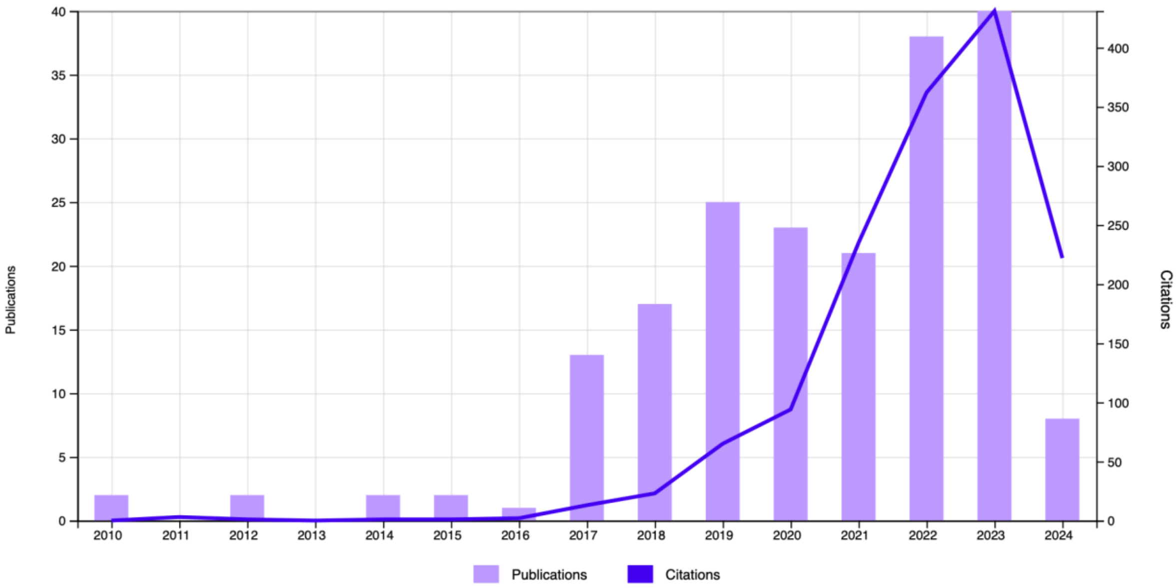
Descriptive statistics, bibliometric mapping, and content analysis were employed to analyze the data. Descriptive statistics presented the distribution of publications and citations by year, as well as the types and languages of publications. Bibliometric mapping, as defined by Haddow (2013: 219), is "a quantitative method applied to a body of literature to gain insight into the patterns, trends, and networks of communication occurring within the literature." In this manner, the publications were analyzed according to the following categories: occurring keywords, productive countries, influential authors, and the most frequently published and cited journals. Bibliometric mapping was conducted using the VOSViewer software version 1.6.19. VOSViewer is a software application utilized for the creation and visualization of bibliometric networks. Following the exclusion of 10 review articles from 194 publications, the 10 most frequently cited articles among the remaining publications were subjected to a content analysis. The content analysis encompassed the examination of the topic, methods, sample, mathematics subject matter, data collection tools, and findings of these articles.

FINDINGS

The findings of the bibliometric and content analyses are presented in two sections.

Findings of bibliometric analysis

Descriptive statistics, including the distribution of publications and citations by year, and the types and languages of publications, were obtained from the Web of Science (WoS). The distribution of studies and citations over the years is shown in Figure 1.



Note. Because this research was conducted before the end of 2024, the data for 2024 appear to be lower.

Figure 1. *The distribution of publications and citations by year*

Although the history of CT is much older, Figure 1 illustrates that studies of CT in ME commenced in 2010. Despite the low number of studies and citations linking CT to mathematics between 2010 and 2016, it can be observed that there has been an increase since 2017. The highest number of publications was reached in 2023. In conclusion, it can be stated that studies dealing with CT in ME are among the most popular topics in recent years. Table 1 presents the frequency data on the types and languages of the publications on CT in ME.

Table 1. *Document type and language*

Document Type	f	Language	f
Article	122	English	181
Proceeding Paper	56	Spanish	8
Review Article	10	Portuguese	5
Book Chapters	2		
Editorial Material	3		
Meeting Abstract	1		
Total	**194**	**Total**	**194**

Table 1 reveals that when the publications are analyzed according to document type, 122 of the 194 documents are articles, 56 are proceeding papers, 10 are review articles, 2 are book chapters, 3 are editorial materials, and 1 is a meeting abstract. Additionally, Table 1 indicates that the majority of the publications on this subject are in English.

Frequently occurring keywords

To ascertain the keywords that authors most frequently utilize, the co-occurrences of author keywords were subjected to analysis. Given that the authors employed a total of 524 keywords, the minimum number of occurrences for each keyword was adjusted to 5. Consequently, five clusters comprising 20 keywords were identified (see Table 2).

Table 2. *The most frequently occurring keywords*

Clusters	Items
1	Abstraction (f:5), Algorithmic thinking (f:5), CT (f:115), Computer Science Education (f: 5), Problem Solving (f: 9), Stem(f:11)
2	Constructionism (f: 10), Mathematics Education (f: 48), Problem-Solving (f: 5), Programming (f: 22), Robotics (f: 7), Stem Education (f: 5)
3	Coding (f: 11), Early Childhood Education (f: 5), Primary Education (f: 6), Primary School (f: 5)
4	Mathematics (f: 26), Scratch (f: 12), Technology (f: 7)
5	Mathematical Thinking (f: 7)

Table 2 indicates that the most frequently used keywords are CT (f: 115), mathematics education (f: 48), and programming (f: 22). Furthermore, it has been observed that similar keywords are used for the same concept, such as problem-solving and problem-solving, or primary school and primary education. About CT, the keywords abstraction, algorithmic thinking, and computer science education are predominantly used. In the dimension of mathematics education, the keywords problem solving, mathematical thinking, and mathematics education are frequently utilized. Concerning the technological dimension, the keywords programming, robotics, and Scratch are most commonly employed.

Figure 2 shows the network between keywords and their distribution over the years. In this visualization, the overlay visualization of the Vos Viewer program is preferred and how the keywords change over the years is examined. Mathematics, constructionism, STEM, and abstraction are the keywords used in 2020, and in 2021-2022 they start to be used together with keywords such as scratch, coding, programming, and CT. More recently, terms such as elementary school, early childhood, problem-solving, and STEM education have become popular.

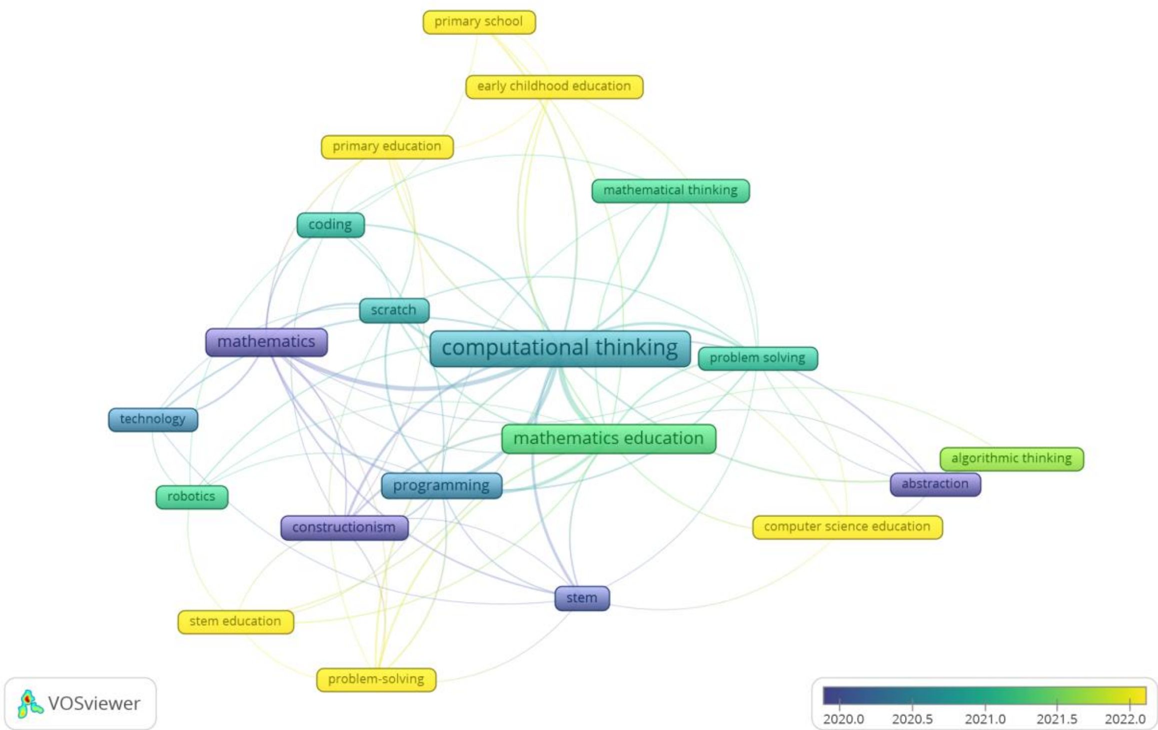


Figure 2. *The most frequently occurring keywords*

Productive countries

The minimum number of documents belonging to an author is set at five, and the minimum number of citations is set at two. The eleven most productive countries are identified according to these criteria. The results of the analysis are presented in Table 3, which shows that the United States of America (USA) is the country with the highest number of publications and citations. The next most productive countries are Canada, China, Spain, and Brazil, with 19, 18, 16, and 15 publications, respectively. Turkey contributed six documents. Table 3 shows the number of articles and citations for these countries. Analyzing the network between the countries shown in Figure 3, the country with the highest number of collaborations is the United States of America with seven countries. Canada collaborated with six countries, while China collaborated with three countries.

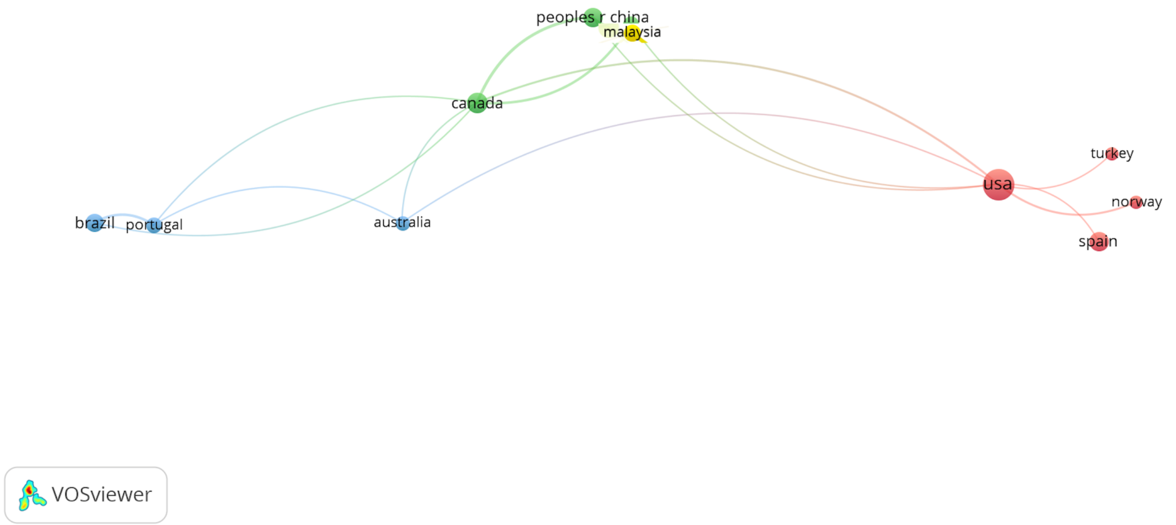


Figure 3. *The most productive countries*

Table 3. *Number of articles in top countries*

Countries	Number of publications	Number of citations
USA	59	671
Canada	19	118
China	18	230
Spain	16	112
Brazil	15	52
Sweden	9	50
Malaysia	9	24
Portugal	9	4
Australia	7	47
Turkey	6	63
Norway	6	53

Influential authors

A co-citation analysis was conducted to identify the most cited authors on CT in ME. The results of the analysis are presented in Figure 4. The most influential authors were Jeannetta M. Wing (citation: 152), David Weintrop (citation: 78), Seymour Papert (citation: 73), Shuchi Grover (citation: 67), Elise Lockwood (citation: 66), and Aman Yadav (citation: 59). As illustrated in Figure 4, the data set comprises three clusters, designated as green, blue, and red. This implies that researchers affiliated with the same cluster are collectively represented in the bibliographies of studies conducted within the related field.

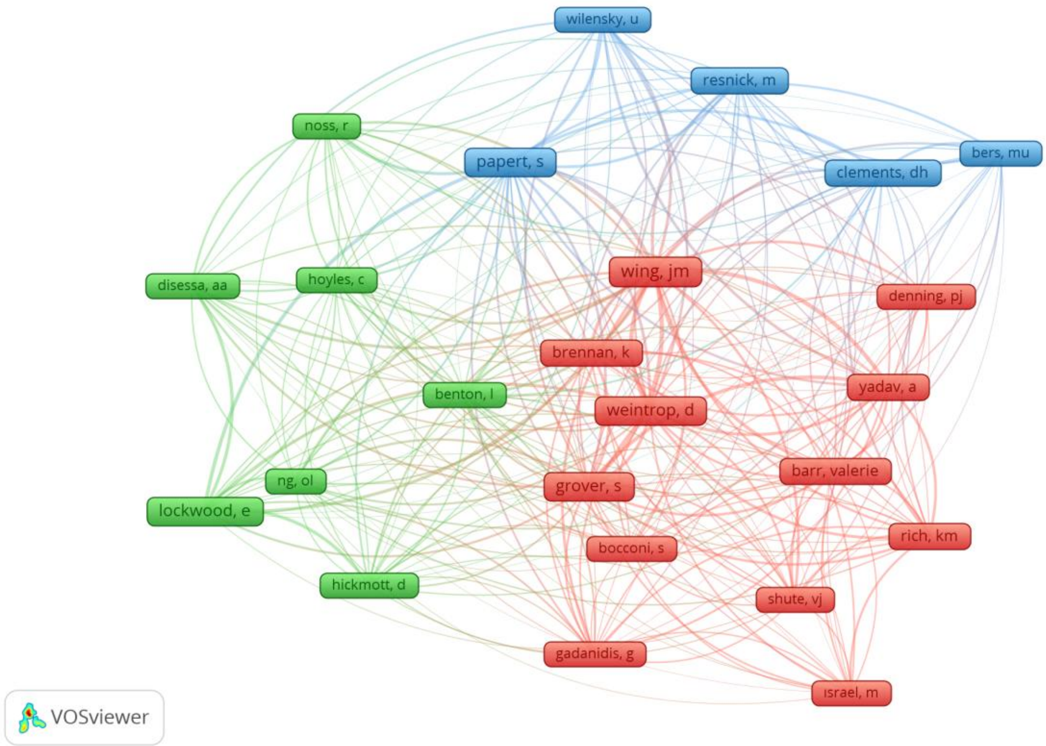


Figure 4. *Co-cited authors*

Most published and cited journals

Table 4 presents the number of publications and citations of the journals. Upon examination of Table 4, it becomes evident that the most frequently cited journals are Mathematical Thinking and Learning (6 documents, 125 citations), Journal of Mathematical Behavior (6 documents, 69 citations), ZDM-Mathematics Education (6 documents, 63 citations), and Mathematics (5 documents, 33 citations). Even though the Education Sciences journal published the highest number of documents on this topic, it received only 13 citations.

Table 4. *Most published and cited journals*

Journal Name	Number of Publications	Number of Citations
Mathematical Thinking and Learning	6	125
ZDM-Mathematics Education	6	63
Journal of Mathematical Behavior	6	69
Education and Information Technology	4	16
Education Sciences	8	13
Sustainability	4	6
Mathematics	5	33

Findings of content analysis

The ten most cited articles in the Web of Science (WoS) have been subjected to content analysis. To exclude review articles from the analysis, 194 articles were initially selected. After applying the review article exclusion criteria, the number of articles was reduced to 184. Upon examination of the top 10 most cited articles from the 184 articles in question, it was determined that one article was not pertinent to the subject matter and was therefore removed. Ten articles were subjected to content analysis. The titles, authors, publication years, journals, and citation counts of the top 10 most cited articles are presented in Table 5.

Table 5. *The ten most frequently cited publications*

No	Title-Author-Year	Source	Total Citation
A1	Computational thinking and mathematics using Scratch: an experiment with sixth-grade students (Rodriguez-Martinez, Conzales-Calero and Saez-Lopez, 2020).	Interactive Learning Environments	85
A2	Computational thinking from a disciplinary perspective: Integrating computational thinking in K-12 science, technology, engineering, and mathematics education (Lee vd., 2020)	Journal of Science Education and Technology	68
A3	Introducing computational thinking to young learners: Practicing computational perspectives through embodiment in mathematics education (Sung, Ahn and Black, 2017)	Tech Know Learn	63
A4	Computational Literacy and "The Big Picture" Concerning Computers in Mathematics Education (diSessa, 2018)	Mathematical Thinking and Learning	43
A5	Reflective abstraction in computational thinking (Cetin and Dubinsky (2017)	Journal of Mathematical Behavior	34
A6	Cultivating computational thinking practices and mathematical habits of mind in Lattice Land (Pei, Weintrop and Wilensky, 2018)	Mathematical Thinking and Learning	33
A7	STEM education in the primary years to support mathematical thinking: using coding to identify mathematical structures and patterns (Miller, 2019)	ZDM	33
A8	Artificial intelligence, Computational thinking, and mathematics education (Gadanidis, 2017)	The International Journal of Information and Learning Technology	32
A9	The Interplay between Mathematics and CT in Primary School Students' Mathematical Problem-solving within a Programming Environment (Cui and Ng, 2021)	Journal of Educational Computing Research	27
A10	Examining primary students' mathematical problem-solving in a programming context: towards computationally enhanced mathematics education (Ng and Cui, 2021)	ZDM	27

The content analysis initially classified the ten most frequently cited articles according to their research focus. The articles A2, A4, A5, and A8 are theoretical papers that were conducted in the field of CT in ME. Table 6 provides an overview of the topics addressed in these articles.

Table 6. *Topics of theoretical articles*

Article No	Topic
A2	A disciplinary perspective on CT (CT), with a focus on integrating CT into science, technology, engineering, and mathematics (STEM) education at the K-12 level
A4	The organization of learning activities in the context of computational literacy, social change, and the emergence of new literacy, CT, STEM, and technology.
A5	To construct a theoretical bridge between CT and APOS theory, demonstrating how reflective abstraction can be applied in the context of CT.
A8	Initial investigation into the convergence of augmented reality, CT, and mathematics education, emphasizing their three shared characteristics: agency, modeling, and abstraction.

Upon examination of Table 6, it becomes evident that articles A2 and A4 investigate the relationship between CT and STEM. Article A5 relates the abstraction component of CT to APOS theory, while article A8 is a theoretical study that integrates augmented reality, CT, and ME. The methodological information for the remaining six articles is presented in Table 7.

Table 7. *Methodological of the reviewed articles*

No	Method	Sample	Data Collection Tools	Subject
A1	Quantitative	Grade 6	CT test (Roman Gonzales et al. 2017 Mathematical knowledge test- González-Calero, Martínez, and Sotos (2016). Scratch	Problem solving (concepts of the greatest common divisor (GCD) and the least common multiple (LCM)
A3	Quantitative	Kindergarden and Grade 1	Paper-based pre-tests, post-tests, and delayed tests Scratch	Number line estimation, counting, addition, subtraction, and numerical magnitude comparison
A6	Qualitative	High School	Pre- and post-semi-structured interviews Lattice Land	Geometrical concepts
A7	Mixed method	Grade 2	Pre and post testing of patterning and coding, The intervention Scratch	Mathematical patterns and structures
A9	Qualitative	Grade 5-6	Arduino	Problem solving
A10	Design-based research	Grade 5-6	Digital making tasks Arduino	Variables, algebraic thinking, modeling, and problem decomposition

Table 8. *Important conclusions and topic of the reviewed articles*

No	Important conclusion	Topic
A1	A notable enhancement was observed in the students who solved linear combination (LCM) and greatest common divisor (GCD) problems with Scratch. However, no discernible difference was found in the control group.	The impact of programming activities with Scratch on students' acquisition of mathematical concepts and CT.
A3	Efficacy in enhancing students' numerical skills, magnitude comparisons, and applied number line estimations, as evidenced by the results of the post-test and delayed tests.	The impact of varying degrees of embodiment and computational perspective-taking practices on students' academic performance in mathematics and computer programming.
A6	Students employ mathematical habits of mind and CT practices to investigate and comprehend fundamental geometric concepts.	The development of a computational learning environment designed to support the development of mathematical habits of mind and to promote CT practices in mathematics classrooms.
A7	Integrating coding into mathematics education can enhance students' comprehension and performance in mathematics, as well as foster more sophisticated mathematical reasoning.	To examine how mathematical knowledge and thinking skills can be enhanced through students' participation in coding lessons.
A9	Discrepancies between mathematical reasoning and programming abilities contribute to these difficulties. This study provides support for the integration of CT into mathematics education.	The challenges encountered by primary school students when attempting to solve problems using block-based programming.
A10	Problem-based digital construction tasks support students' modeling, algorithmic thinking, testing, and debugging practices. Additionally, the study emphasized the effective integration of computer science and mathematics, highlighting the interconnectedness of reasoning and problem-solving skills between the two disciplines.	Provide evidence for integrating computer science concepts into mathematics education settings and provide evidence for combining mathematical content and problem-solving practices in a programming context.

Table 7 reveals that the most frequently cited studies, A1 and A3, are quantitative studies that investigate the effectiveness of the Scratch program in problem-solving. Study A6 employed a qualitative methodology, utilizing semi-structured interviews with high school students to investigate their conceptual understanding of geometrical principles. Study A7 employed a mixed-method approach to examine whether second-grade students demonstrated enhanced proficiency in mathematical patterns and structures with the use of Scratch. Finally, articles A9 and A10 examined the efficacy of fifth- and sixth-grade students in problem-solving using the Arduino program. Table 8 provides an overview of the topics and conclusions addressed in these articles.

As indicated in Table 8, the implementation of Scratch-based instruction in articles A1 and A3 resulted in a notable disparity in the performance of the experimental group students. In article A6, a CT-based instructional model was designed to support the development of mathematical habits of mind. The results of the study showed that students used mathematical habits of mind and CT practices in basic geometric concepts. Article A7 examined the impact of coding instruction on students' mathematical knowledge and thinking skills. According to the results of the study, it was emphasized that including coding in mathematics education improves students' performance and enhances mathematical thinking skills. The difficulties encountered by elementary school students when attempting to solve problems with the Arduino program were examined in the A9 article. This study has been instructive in the integration of CT into mathematics courses. The objective of the A10 article was to integrate mathematical content and problem-solving practices within the context of programming. The findings of the study highlighted the interrelationship between reasoning and problem-solving abilities across the two disciplines.

DISCUSSION

This study conducted a bibliometric and content analysis of the literature on CT in ME. This study identified the place of CT in ME, research trends, and prolific authors. It has been determined that studies on CT in mathematics education have started to be conducted since 2010. Although the origins of CT are older, Wing's (2011) change in the definition of CT has led to an increase in studies on the association of CT with other disciplines. CT studies, which did not receive the expected attention between 2010 and 2016, have shown an increase in the number of publications and citations since 2017. The increase in the number of publications and citations, especially since 2020, is an indication that this topic is becoming increasingly popular. This trend reveals the increasing importance and impact of CT in ME.

The analysis shows that a large proportion of publications related to CT in mathematics education consist of research articles. These are followed by proceedings and review articles. The increasing interest in CT in ME in recent years is related to the fact that this is a new area open to research. This may explain the high number of research articles. VOSviewer analysis revealed that the most frequently used keywords were CT, mathematics education, and programming. This finding aligns with the study of Isharyadi and Juandi (2023), which examined publications searched in the Scopus database between 2018 and 2022. In their study, it was determined that the most frequently used keywords were CT, mathematics education, and programming. This study also revealed that there have been changes in keywords over the years. Initially, as CT was newly associated with mathematics education, the keywords mathematical thinking, problem solving, and coding were used. However, in recent years, as CT has gained a foothold in mathematics education, the keywords elementary school, early childhood, and STEM education have come to the fore. The reason for this situation is that initially, CT and mathematics education were associated with each other, and then after the relationship was found to be high, the issues of the most effective integration of CT in mathematics classrooms, especially in classrooms with young children, came to the forefront. This is important for researchers as it shows the popular topics and emerging fields of recent years.

The bibliometric analysis identified the United States of America (USA) as the most productive country. This country has the highest number of publications and the highest number of citations. One reason may be that Jeannette M. Wing, one of the pioneers of CT, is a professor of computer science at Columbia University, and she and her team publish more collaboratively. Another reason is that technologically advanced countries such as the US, Canada and China are pioneers in combining computer science with interdisciplinary courses. The advanced level of technology and education in these countries supports the application of CT in various disciplines. The fact that CT is a new field of study in mathematics education may explain the low number of publications per country. It is also noteworthy that although the number of publications in Turkey and Norway is low, the number of citations to these publications is high. This may indicate that the studies in these countries are pioneering and that these studies are important and are referenced by other researchers.

It is not surprising that Jeannetta M. Wing ranks first among the most influential authors. In her work, Wing (2011) opened the door to combining CT with disciplines other than computer science by stating that in problem solving, "The solution can be realized by humans or machines, or more generally, by combinations of humans and machines." For this reason, it is natural to find Wing frequently in CT documents in mathematics education. Other influential authors, such as David Weintrop, Seymour Papert, Shuchi Grover, Elise Lockwood, and Aman Yadav, are also highly ranked. These authors have conducted pioneering research investigating the implications of CT in various disciplines. The results obtained in the content analysis section of the study also support this finding. Their work has contributed to the evolution of CT in education and computer science and has laid the foundation for future research in this field. The main journals that have made significant contributions to CT in ME are Mathematical Thinking and Learning, ZDM-Mathematics Education, and Journal of Mathematical Behavior. Many of the top 10 most cited articles used in the content analysis were published in these journals, indicating that they are the leading journals in the field. Researchers may consider examining the publications of these journals if they wish to examine the role of CT in ME. For researchers interested in submitting articles to these journals, it is recommended that these journals be among the priority choices.

Following the bibliometric analysis, the ten most frequently cited articles were subjected to content analysis. The content analysis revealed that four of the ten articles addressed CT in ME from a theoretical perspective. While CT and mathematics education are well-established topics, the combination of these two fields has only begun to be explored since the 2010s. Consequently, studies have been conducted to define and theoretically frame this field. Some of these studies include investigations that establish links between CT and STEM (diSessa, 2018; Lee et al., 2020), integrate CT with APOS theory (Çetin & Dubinsky, 2017), and finally, CT-enhanced reality-mathematics education (Gadanidis, 2017). These studies underscore common features such as agency, modeling, and abstraction.

In the most frequently cited articles, students were typically presented with mathematical problems or activities and asked to solve these problems in a digital environment using a programming language (Cui & Ng, 2021; Miller, 2019; Ng & Cui, 2021; Rodriguez-Martinez et al., 2020; Sung et al., 2017). This approach permitted the investigation of the influence of programming education on the mathematical problem-solving process, and it identified advantages and disadvantages for students, findings that are supported by evidence. Moreover, these studies have furnished data on the optimal manner of integrating CT into the problem-solving process. These studies were frequently conducted with younger age groups of students. Block-based coding tools, such as Scratch and Arduino, were preferred over other options to attract students in this age group, as they provide a permanent and effective learning environment through gamified educational activities. Moreover, these tools facilitated the development of mathematical thinking skills in students (Miller, 2019; Rodriguez-Martinez et al., 2020).

CONCLUSION AND LIMITATIONS

This study concluded with significant findings that can guide researchers on future avenues of study within the context of CT in ME. Moreover, this indicates that CT in ME is a vast area with extensive opportunities for exploration. A keyword and thematic analysis of the literature on CT in ME reveals that the topics studied in this field have undergone significant changes over time. The current studies focus on the linkage of CT and mathematics education with a third variable and the assessment of its applicability in the classroom. In light of the growing number of publications and citations over time, it is reasonable to anticipate an expansion in the number of countries, institutions, and authors who prioritize this topic. In light of these findings, it is recommended that researchers collaborate more extensively to investigate the untapped potential of CT in ME. For practitioners, given that CT fosters skills such as problem-solving, algorithmic thinking, and logical reasoning in mathematics, it is recommended to integrate CT into classroom teaching activities. This approach is likely to enhance students' motivation and make the learning process more enjoyable.

One of the limitations of this study is that the bibliometric analysis was limited to WoS (Web of Science). The inclusion of other databases would enable the study to be repeated and analyzed in more depth. A second limitation is that only the 10 most cited articles were analyzed in the content analysis. Given the limitations and existing gaps in the literature, it is recommended that a bibliometric analysis of publications in different databases, such as Scopus, be conducted, as well as a content analysis of additional studies.

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