

Fostering K-12 Students' Computational Thinking Skills Using Collaborative Technology-rich Learning Environments: A Systematic Review

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Abstract: In today's technology-driven society, mastering Computational Thinking (CT) skills is crucial for students. To develop these skills, leveraging collaborative technology-rich environments (TREs) can be an effective approach. Examples of those TREs include block-based programming learning environments, immersive digital games, and robotic toolkits. In this systematic review, following PRISMA, we identified 56 studies from the literature. We investigated how collaboration within TREs influences the development of CT skills among K-12 students. The findings underscore the value of collaborative learning environments within TREs for effectively fostering students' CT skills, emphasizing the importance of creating impactful learning environments that prioritize collaboration in CT skill development.

Keywords: Computational Thinking, Collaboration, K-12, Systematic Review

Introduction

Computational thinking (CT) has been defined in various ways, with some emphasizing cognitive skills and others focusing on more tangible skills. For instance, Shute et al. (2017) and Wing (2008) relate CT to a range of problem-solving and analytical skills that enable individuals to break down complex problems into smaller, more manageable parts. Similarly, Wing (2006, p. 33) describes CT as "solving problems, designing systems, and understanding human behavior by drawing on the concepts fundamental to computer science." These definitions highlight the cognitive aspects of CT, such as problem-solving and analytical thinking. On the other hand, some researchers describe CT as encompassing more concrete skills. Grover and Pea (2013) propose that CT includes various sub-skills, such as algorithmic thinking, pattern recognition, abstraction, and decomposition. These skills are more closely tied to the practical application of computational concepts. Furthermore, Denner et al. (2012) suggest that CT is a comprehensive skill set composed of three fundamental elements: programming, documenting and understanding software, and designing for usability. This definition emphasizes the importance of hands-on experience with programming and software development in developing CT skills.

In this paper, we refer to CT as a combination of cognitive and practical skills. We recognize the importance of problem-solving and analytical abilities in breaking down complex problems, as well as the value of hands-on experience with programming and software development in fostering CT. By considering both the cognitive and practical aspects of CT, we aim to provide a more comprehensive understanding of this critical skill set and its potential applications in various domains.

In the modern era of technology, CT competency is an essential life skill that should be taught in early education. (Wing, 2006; Yadav et al., 2017). Studies indicate that proficiency in CT correlates with both academic achievement and career advancement (Hurt et al., 2023; Israel-Fishelson et al., 2021). Various interventions have been implemented to enhance CT skills among learners (Tang et al., 2020). For instance, robotic tools like Lego robotics (Leonard et al., 2023), online games (Sun et al., 2023; Cheng et al., 2022), unplugged activities such as card games (Guimarães et al., 2020), and storytelling (Chen et al., 2023) have been employed to enhance CT skills.

Collaboration during learning activities is effective in promoting CT skills among K-12 students (e.g., Lin et al, 2022; Standl, 2016). Collaborative learning involves a group of learners working together to achieve a mutual goal and through that collaboration improve their knowledge and skills (Hmelo-Silver, 2004). Collaborative learning enables students to exchange ideas and ask questions, fostering a dynamic environment for knowledge sharing and inquiry (Laal & Laal, 2012). The effectiveness of collaborative learning in promoting CT skills could be due to providing opportunities for peer learning and receiving feedback (Shahin et al., 2022), and engaging students in problem-solving, critical thinking, and effective communication (Ardito et al., 2020).

Advances in technology have created new opportunities for collaborative learning in technology-rich environments (TREs) (Barfurth, 1995). TREs refer to classrooms or digital learning environments where technology is extensively used to support and enhance the learning process (Shute et al., 2016). TREs that are designed to promote CT skills do that through interactive and immersive learning experiences (Zhao &

Shute, 2019). For example, digital educational games and other virtual learning environments that promote CT skills provide a safe and supportive space to practice and experiment with CT skills (e.g., De Jesús & Silveira, 2021; Galdo et al., 2022; Zhao & Shute, 2019). Therefore, integrating collaborative learning in TREs can be a powerful way to promote CT skills among K-12 students (Turchi et al., 2019).

Multiple empirical, design-based studies have been conducted to examine the effectiveness of collaborative learning in TREs (e.g., Wen et al., 202; Latulipe & De Jaeger, 2022). However, to our knowledge, there is no systematic review of the studies focusing on TREs that facilitate K-12 students' CT through collaboration. In this systematic review, we synthesize the existing literature on collaborative learning of CT skills in TREs, identify gaps in the current literature, and provide suggestions for future studies. The findings will be valuable for educators and researchers interested in promoting CT skills in collaborative TREs. The research questions guiding this review are as follows:

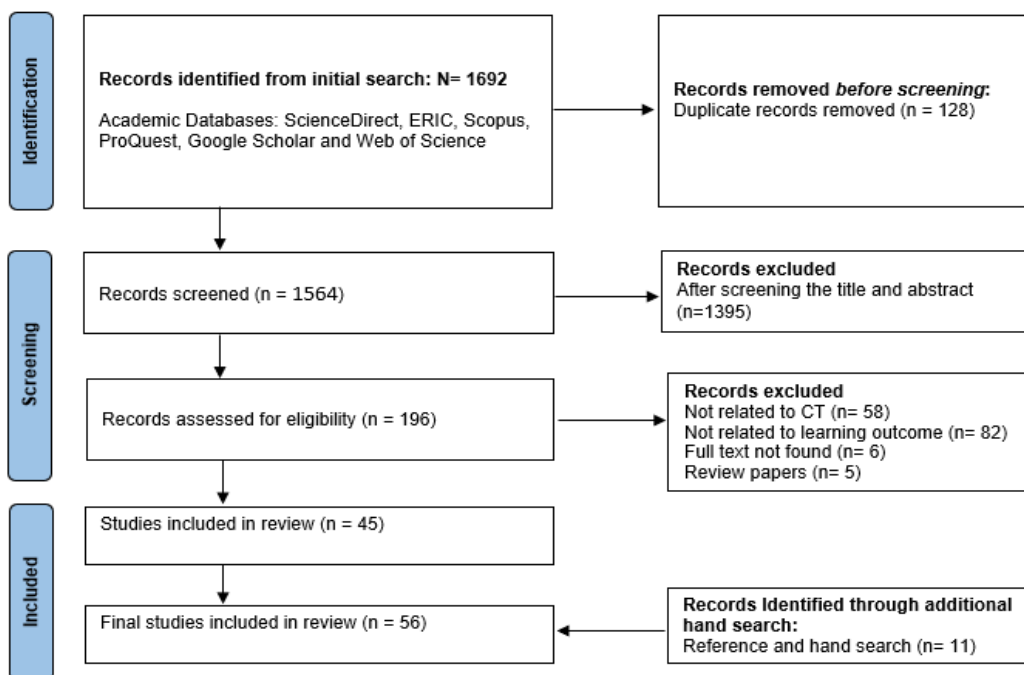
1. What types of collaborative TREs are used to promote students' CT skills in K-12?
2. What CT topics are being taught and promoted in those TREs?
3. What are the effects of collaboration in TREs on K-12 students' CT skills?
4. What are the learning theories implemented in the collaborative TREs to promote students' CT skills in K-12?

Method

To address our research questions, we conducted a systematic review using the updated PRISMA (Page et al., 2021) guidelines. A comprehensive search of relevant databases including ScienceDirect, ERIC, Scopus, ProQuest, Google Scholar, and Web of Science was conducted to identify studies on collaborative TREs and their effectiveness in promoting K-12 students' CT skills. Using several search strings (e.g., (Collaboration OR collaborative learning OR collaborative) AND ("computational thinking" OR game OR digital OR coding OR programming OR "blocked-based programming") AND (K-12)), we searched in the mentioned databases. To avoid publication bias and ensure a comprehensive review of the literature, our inclusion criteria included all types of manuscripts (e.g., peer-reviewed or non-peer-reviewed) meeting the specified criteria: studies (1) published between 2006-2022 (inclusive). We chose this timeframe because following Janette Wing's seminal paper in 2006, interest in CT began to grow in academic settings; (2) written in English; (3) focused on enhancing CT in collaborative TREs; and (4) in K-12 education context. The exclusion criteria were: (1) studies before 2006; (2) not in English; (3) students with disabilities or adult learners; and (4) low-quality articles. Following the inclusion/exclusion criteria, we included 56 studies for review (see Figure 1).

Figure 1

PRISMA Flow Diagram Detailing the Steps in the Identification and Screening of Sources



Two researchers independently screened abstracts and full texts for review eligibility and then resolved any conflicts through discussion to reach a mutual agreement. To extract the data, we created a spreadsheet to collect and summarize the key features per study (e.g., title, manuscript type, field of study, research method, name of the learning environment, target audience, sample size, and learning theories). Subsequently, both researchers individually extracted data from each study through several rounds and reconciled any differences. This process yielded 56 studies, with 11 studies included through hand search.

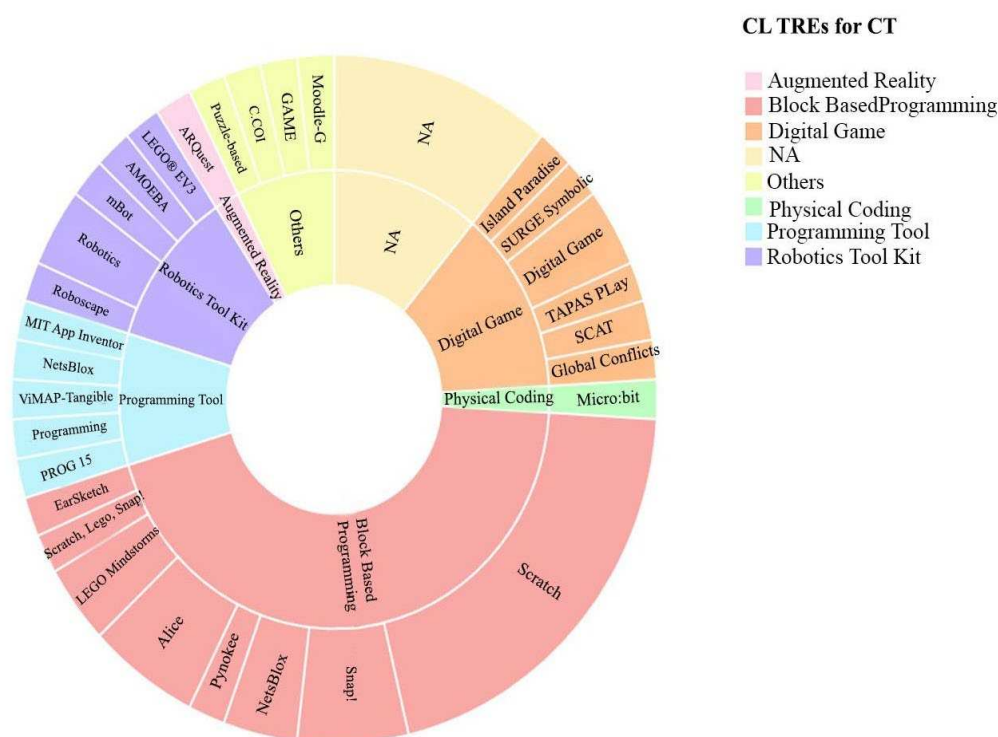
Results

The 56 studies were from a diverse set of manuscript types (38 journal articles; 6 conference papers; 9 proceedings; 2 symposiums; 1 dissertations). These studies included participants ranging from 3rd to 12th grade. Moreover, the studies selected in this review originated from various fields of study such as computer science ($n = 27$), educational technology ($n = 11$), learning sciences ($n = 17$), and mathematics education ($n = 1$). Furthermore, among the studies in educational technology ($n = 7$) and learning sciences ($n = 6$), there was a notable focus on primary students, indicating a growing interest in understanding their learning dynamics. In contrast, within the field of computer science, only 4 studies specifically targeted primary education, suggesting a relatively lesser emphasis on this demographic.

Regarding RQ1, we encountered a rich diversity of environments used within the scope of these studies. Among the various TREs, digital games ($n = 6$), block-based programming environments ($n = 22$), robotics toolkits ($n = 6$), and Programming tools ($n = 5$) stood out prominently. Each of these settings contributed uniquely to the educational landscape, offering distinctive learning opportunities and experiences. Notably, block-based programming learning environments (e.g., Scratch [13 studies used Scratch]) emerged as a leading example. The prevalence and influence of Scratch in facilitating learning experiences highlight the significance and impact of block-based programming environments in educational research (see Figure 2).

Figure 2

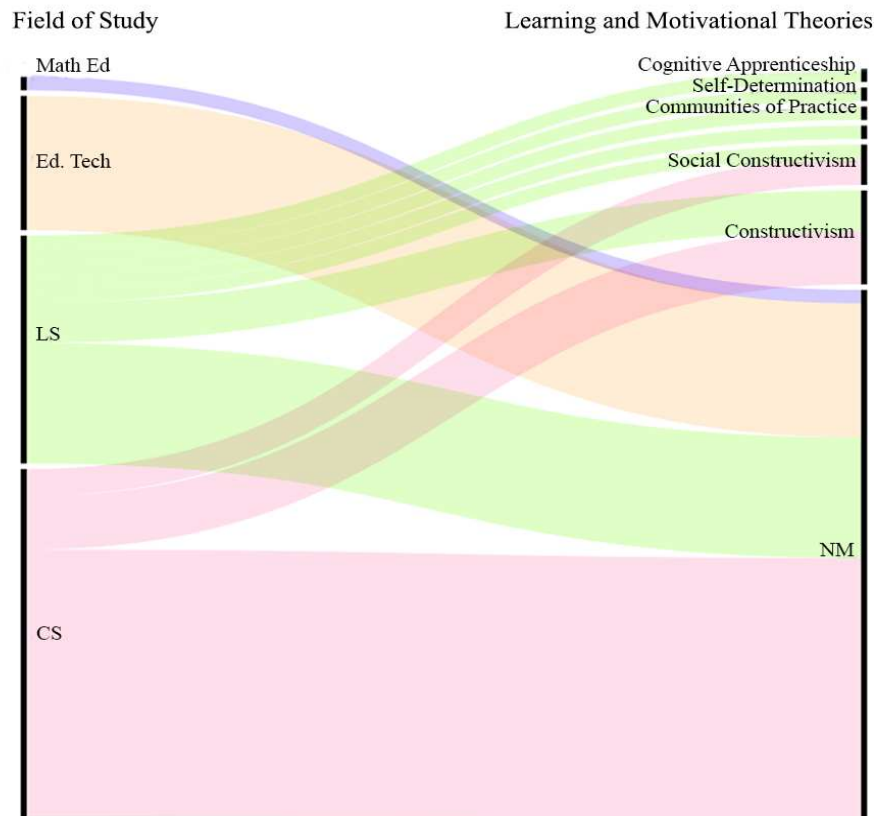
Sunburst diagram showing types of TREs used for CT skills in K-12



Regarding RQ2 (CT topics and learning objectives are being taught and promoted in TREs), we found that the primary focus across the majority of papers centered on (a) Enhancing Programming as a part of CT skills ($n = 28$); (b) CT skills ($n = 13$) without explicitly stating which concepts were targeted; (c) Specific area of CT skills ($n = 15$), the remaining papers distinctly address specific areas of CT skills, highlighting concepts like Conditional ($n = 3$), Abstraction ($n = 3$), Algorithm ($n = 7$), Planning ($n = 2$).

Regarding RQ3 (the learning and motivational theories implemented in TREs for collaborative CT skills learning on K-12 students), we have identified the following trends in the literature: (a) Not mentioned explicitly (n = 42) this was the most common category, including papers that did not explicitly mention any learning theory; (b) Constructivism (n = 8) papers referenced constructivism as their underlying learning theory; (c) Social Constructivism (n = 3) papers emphasized social constructivism as their theoretical framework; (d) Cognitive Apprenticeship (n = 1) this paper specifically mentioned cognitive apprenticeship as its guiding theory; (e) Self-determination (n = 1) this paper was grounded in self-determination theory; and (f) Communities of Practice (n = 1) this paper was based on the concept of communities of practice (see Figure 3).

Figure 3
Learning and Motivational Theories Implemented in TREs



Regarding RQ4 (the effects of collaboration in TREs on K-12 students' CT skills), we've identified the following trends in the literature: (a) Moderate positive effects (n = 17) studies reported that collaborative learning (CL) in TREs have a moderate positive impact on computational thinking (CT); (b) Large positive effects (n = 18) studies reported a large positive link between CL and CT and programming skills in TREs (c) No Significant Effects: 8 studies, suggesting that CL in TREs might not have a clear impact on CT and programming skills; Finally, (d) Negative Effects: 2 studies reported some possible downsides of CL in TREs on CT and programming skills. A closer look at the results related to RQ4 helps us understand the different outcomes linked to CL in TREs and how to incorporate collaboration in TREs to successfully enhance CT and programming skills—this will be the focus of our future work related to this systematic review.

Discussion

In this systematic review, we investigated 56 studies that leveraged collaboration within TREs to foster the development of computational thinking skills among K-12 students. Our analysis revealed that these studies targeted a broad range of audiences, and originated from different academic disciplines. The findings suggest the use of various digital platforms to facilitate collaborative learning of CT skills, including digital games, block-based programming environments, programming tools, and robotic toolkits. Each of these platforms offers unique and interactive opportunities for students to engage collaboratively with CT concepts. Notably, the prevalence of block-based programming platforms indicates their widespread utilization by researchers

as effective tools for collaborative CT skill development. The prevalence of block-based programming platforms may be attributed to their user-friendly nature, capacity to reduce entry barriers to programming, visually appealing interface, and their facilitation of collaborative learning, creativity, and skill development in computational thinking for K-12 students (João et al., 2019).

The majority of papers did not deeply explore the CT skills or specific concepts within CT, given its multifaceted nature. This finding highlights a need for more explicit definitions and focus on particular areas of CT skills. Addressing this gap by specifying targeted concepts could improve pedagogical strategies within TREs, enabling more effective integration of CT skills into educational frameworks.

Additionally, including a diverse age range of participants demonstrates the adaptability and scalability of collaborative TREs as a platform for fostering CT skills. The studies' origins spanned multiple academic disciplines, including computer science, educational technology, and learning sciences. This diversity emphasizes the pivotal role of collaborative digital environments in promoting CT skills, fostering cross-disciplinary collaborations, and contributing to comprehensive educational advancements. The prominence of computer science in this context creates exciting opportunities for interdisciplinary research, allowing for the integration of pedagogical approaches, learning theories, and technological innovations to optimize the enhancement of computational thinking skills among K-12 students.

Our investigation into the learning theories utilized by researchers has uncovered a noticeable gap in the adoption of a theoretical framework across numerous studies, 42 out of the total did not explicitly mention or incorporate any learning theory. The absence of a clear learning theory within these studies can give rise to several challenges in educational research, including the lack of a theoretical framework, difficulties in interpretation, and limited generalizability. Moreover, it is worth highlighting that a significant proportion of papers in the computer science field did not mention any specific learning theory. This indicates a potential area of improvement for researchers in this domain. It is worth noting that constructivism was the most dominant theoretical perspective within those limited studies that explicitly employ a learning theory. Our analysis has shed light on various learning approaches aligned with constructivism, including game-based learning, collaborative learning, and problem-based learning. Careful examination of these approaches can provide valuable insights into the pedagogical principles that contribute to the effectiveness of collaborative CT skill development.

Limitations

We faced several limitations in conducting this review. First, the review was limited to studies published in English, potentially excluding relevant research conducted in other languages. Second, the lack of a universally accepted definition for CT poses a challenge in comparing and synthesizing findings across studies. Third, the included studies employed various assessment methods, which may lead to different interpretations of results and make it difficult to draw definitive conclusions. And, future research would benefit from a more standardized approach to defining and assessing CT skills.

Future directions and conclusion

This research aims to synthesize findings on fostering K-12 students' computational thinking skills using collaborative TREs. As our review continues, we will address our last research question related to the specific design elements that enhance students' CT skills in collaborative TREs. This upcoming research intends to deepen our understanding of how particular collaborative aspects within digital settings continuously influence and improve the development of CT skills among K-12 students. Additionally, we plan to refine our focus to emphasize conceptual insights over empirical findings, thereby enhancing the overall coherence and relevance of our work.

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