A Systematic Review of Computational Thinking Assessment in the Context of 21st Century Skills

Jing Han(✉)

The University of Hongkong, Hongkong, China
jing.han0610@gmail.com

Abstract. Computational thinking (CT) is a vital component in the development of STEM and 21st-century skills. In order to integrate CT into the current curriculum, it is crucial to assess CT skills, which can provide valuable insights for teaching practices and future research. The purpose of this review is to examine recent studies on the assessment of CT skills and determine the necessity for the creation of a CT assessment system. The report includes detailed figures and tables to support the findings, as well as implications for educators, CT framework developers, and empirical researchers. By analyzing the current state of CT assessment, this review aims to contribute to the ongoing conversation on how to effectively integrate CT into educational programs.

Keywords: Computational thinking · Assessment · 21st-century skills · Systematic review

1 Introduction

The origin of the term "computational thinking" dates back to Papert's 1980 article, referring to children's enhancement of thinking and knowledge acquired when using computers to do programming. Wing then developed the definition of CT as an approach that "involves solving problems, designing systems, and understanding human behaviour, by drawing on the concepts fundamental to computer science" (2006, p. 33). Based on this, researchers in recent decades establish three types of definitions for computational thinking skills. Aho (2012) advocates a generic definition of CT skill together with the strategy of problem-solving. This is further developed by Roman-Gonzalez (2017) that CT is an essential cognitive process for problem-solving and enables a new literacy. In order to represent a more detailed landscape of CT skills, the International Society for Technology in Education (ISTE) and the Computer Science Teacher Association (CSTA) elaborate on different operational branches of CT, characterized by the following skills: problem identification and formulation, logic organization and analysis of data, representation in an abstract way of thinking (through simulations and models, etc.), automating solutions in programming, evaluating the efficiency of solutions iteratively, migration and transformation of the problem-solving process to other cases (2011). These operational definitions lead CT skills to the realm of K12 education. Some researchers then explore a more micro-educational definition for the cultivation of CT

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on an exact educational site (classroom, etc.). One of the most frequently cited frameworks is the 3-D framework by Brennan, Balch, and Chung (2014), embracing the CT concepts, practices and perspectives.

It is clear that CT plays a crucial role in STEM education and 21st-century skills development. By incorporating CT into educational curricula, students can develop the skills necessary to navigate a rapidly changing technological landscape and become more critical and analytical thinkers (Chan, Looi & Sumintono, 2021; Aydeniz, 2018; Mueller et al., 2017). Additionally, the assessment of CT skills can provide valuable insights into the effectiveness of different teaching techniques and curricula, as well as the relationships between CT and other factors such as creativity, motivation, and engagement (Zapata-Caceres, Martin-Barroso & Roman-Gonzalez, 2021; Guggemos, Seufert & Roman-Gonzalez, 2022).

There are a variety of CT learning tools available for educators to use in the classroom, including robotics, programming media (Scratch, Blue Ant Code (BAC), Makey Makey, etc.), unplugged activities (storytelling, animations, games, pretend play, etc.), and ethics lessons (Perez-Marin, Hijon-Neira, Bacelo & Pizarro, 2020; Zapata-Caceres, Martin-Barroso & Roman-Gonzalez, 2021; Li, Xie, Vongkulluksn, Stein & Zhang, 2021; Oliveira, Correia & Bittencourt, 2021; Hollenstein, Thurnheer & Vogt, 2022). CT assessment can assist instructors in the selection of CT teaching techniques, tools and curriculum design, according to different learning stages and demographic characteristics of the students. In addition, the evaluation of CT skills enables a more comprehensive understanding of its relationships with other factors, such as creativity, engagement, motivation and gender (Kirwan, Costello & Donlon, 2022). The research design can include a reliable and valid CT assessment scale to explore the predictability or relevance of CT to other 21st century skills and pedagogical or social elements.

Given the importance of CT and CT assessment mentioned above, the objective of this review is to gain a better comprehension of CT assessment in the context of 21st-century skills via a systematic examination of previous research. The research question is as follows: how to assess CT in the context of 21st-century skills, as suggested by the empirical evidence?

The rest of this essay consists of five parts. The next section is the introduction of conceptual frameworks for CT assessment. The methodology section describes how this systematic review identifies, screens, and excludes articles. Results are displayed in terms of the characteristics of the selected papers and their matchup with Brennan and Resnick's (2012) framework. Then, a summarization of the findings and major contributions of this paper will be discussed. Finally, the research gaps in both theoretical and empirical aspects are explored to render insights for further research.

2 Conceptual Framework

The current evaluation frameworks for CT are based on different definitions and levels of CT learning. In their research, Roman-Gonzalez, Moreno-Leon, and Robles have identified seven types of CT assessment tools, which include CT diagnostic, CT summative, CT formative-iterative, CT data-mining, CT skill-transfer, CT perceptions-attitude, and CT vocabulary assessment (p. 7, 2019). Meanwhile, Tang, Yin, Lin, Hadad, and Zhai

have simplified the seven types of CT evaluation into four categories, namely traditional test, portfolio, survey, and interview. However, there is a lack of research that has focused on the reliability and validity of CT assessment tools. In addition, the psychological construct of these methods is poorly defined (Chan, Looi & Sumintono, 2021; Zapata-Caceres, Martin-Barroso & Roman-Gonzalez, 2021).

In this case, the Computational Thinking test (CTt) distinguishes itself by taking the psychometric viewpoint into consideration (Tang et al., 2020). Since Roman-Gonzalez's proposal of CTt, this CT diagnostic scale has been widely validated by several empirical studies via data analysis like the Rasch model (Chan, Looi & Sumintono, 2021). CTt is based on Brennan and Resnick's 2012 3-D CT dimensions model, with 28 items testing the CT concepts, practices and perspectives of learners. Originally, CTt aims at students between 10 and 16 years old. Some studies expand the age scope down to primary school in early stages (6–10) and up to higher education (over 18). This shows that the 3-D CT dimensions model has the potential to be adapted to all learning stages, including K-12 and college learning. Thus, the 3-D CT model is chosen as the guiding framework of this systematic review.

The 3-D CT model is composed of three layers, namely CT concepts, CT practices, and CT perspectives. The CT concepts layer encompasses the programming concepts utilized by learners, such as "sequences, loops, events, parallelism, conditionals, operators, and data." On the other hand, the CT practices layer pertains to the problem-solving behaviors of programmers, including "experimenting and iterating, testing and debugging, reusing and remixing, abstracting, and modularizing." Lastly, the CT perspectives layer indicates how learners perceive themselves and others in a digital world through "expressing, connecting, and questioning" (Brennan & Resnick, pp. 1–25, 2012). This essay aims to evaluate the selected papers using the 3-D CT model as a framework.

3 Methodology

The systematic literature review, as shown in Fig. 1, was conducted following Vojíř and Rusek's framework, which involves four stages: identification, screening, eligibility, and inclusion (2019).

To address our research question, we conducted an electronic search using the Web of Science, a highly regarded and comprehensive database in the field of computer science learning. The Boolean logic of the initial search was constructed in this way: ((computational thinking) AND (assess* OR evaluat* OR test OR exam* OR scale OR measure* OR instrument*) AND (21st-century skills) AND (educat* OR teach* OR learn* OR school)). This search yielded 91 results, which we then filtered by removing duplicates and results that were only in abstract or clinical trial form, resulting in 88 relevant items. Figure 2 displays the distribution of publications from 2014 to 2021, with more than five articles published annually since 2017. Our search was limited to the period between 2017 and July 2022, and we excluded studies written in languages other than English. Ultimately, we downloaded and analyzed 68 studies.

To select papers relevant to this study, the screening and eligibility stages were executed on the basis of inclusion criteria and exclusion criteria mentioned in Table 1.

The objective of this systematic review is to identify practical methods for assessing critical thinking (CT) that can be used by both educational practitioners and researchers.

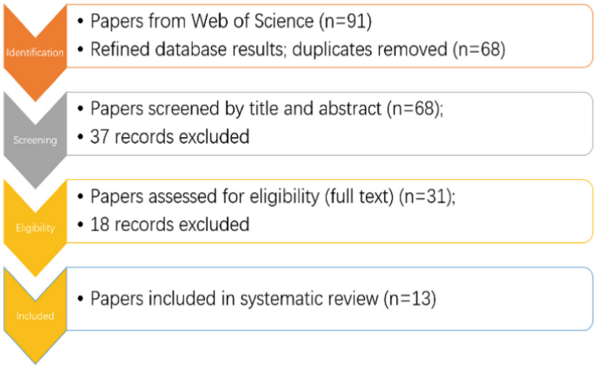

Fig. 1. Paper selection process.

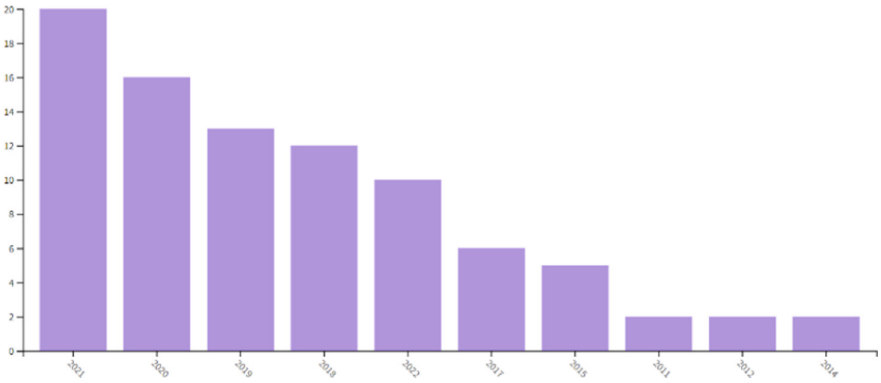

Fig. 2. Years of Publication.

Table 1. Inclusion and Exclusion Criteria.

Inclusion criteria	Exclusion criteria
Empirical studies	Theoretical study, such as literature review, the conceptualization of CT, research proposal, etc.
Assessment of CT skills	Studies focus on other skills, with CT skills as predictive factors or dependent variables.
All age phases	Studies in the context of the 21st century, not specifically about 21st-century skills.
	Studies targeting at teacher training in CT lessons.

The review aims to provide a comprehensive understanding of CT assessment by including all age groups. This wide age range will enable the development of a systematic framework for CT skill development across different learning stages, taking into account

the characteristics of each stage, the transitions between stages, and the coherence of the CT learning system. The review will prioritize the evaluation of CT and exclude studies that focus on other educational factors such as self-efficacy, engagement, or creativity. By doing so, the review will provide valuable insights into CT assessment that can inform effective teaching and learning practices.

During the screening process, the titles and abstracts of the papers were scrutinized based on predetermined inclusion and exclusion criteria to weed out any irrelevant articles, resulting in 31 articles being retained. Subsequently, a thorough analysis of the full content was conducted, which led to the inclusion of 13 eligible records in this systematic review.

4 Results

In this section, we present the findings of our analysis on the distribution of studies and their correlation with the 3-D CT model. Figure 3 illustrates that the number of published papers has been steadily increasing from 2018 to 2021, highlighting the growing interest in CT assessment.

Based on the data presented in Fig. 4, it can be observed that Asia has the highest research productivity, accounting for 53.8% of the publications. Europe comes in second place with 38.5%. Moreover, China has the highest number of publications on CT assessment, making it the most productive country in this field.

This comprehensive review examines the evaluation of critical thinking (CT) across all educational levels. Primary schools appear to be the primary setting for CT assessment, while CT skill development was initially aimed at K-12 learners. As a result, the majority of articles in this review focus on CT in elementary education.

Based on the data presented in Fig. 5, it can be observed that the evaluation of critical thinking skills in primary school students is the most researched and cited topic, indicating that the education sector is currently the primary focus of CT assessment research.

The sample size of the selected articles shown in Fig. 6 is all over 30, suggesting a sizable design of data sources (Fig. 7).

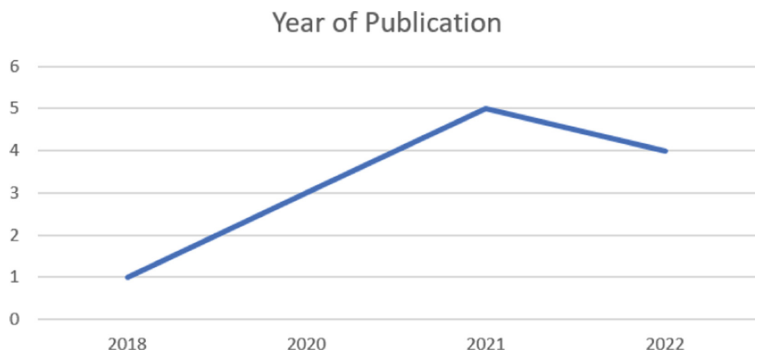

Fig. 3. Year of Publication

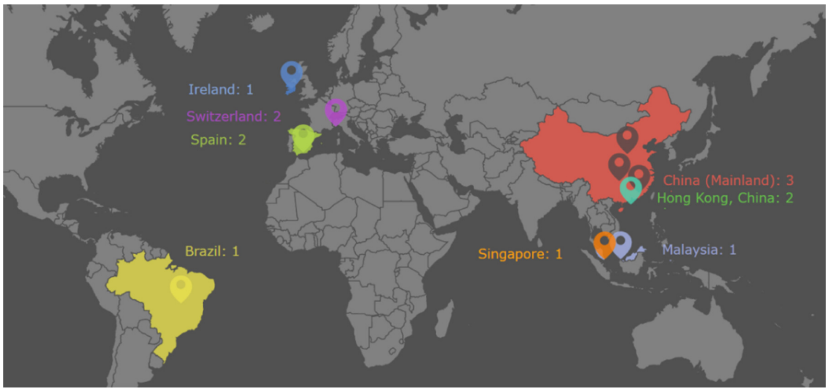

Fig. 4. Locality of Published Papers

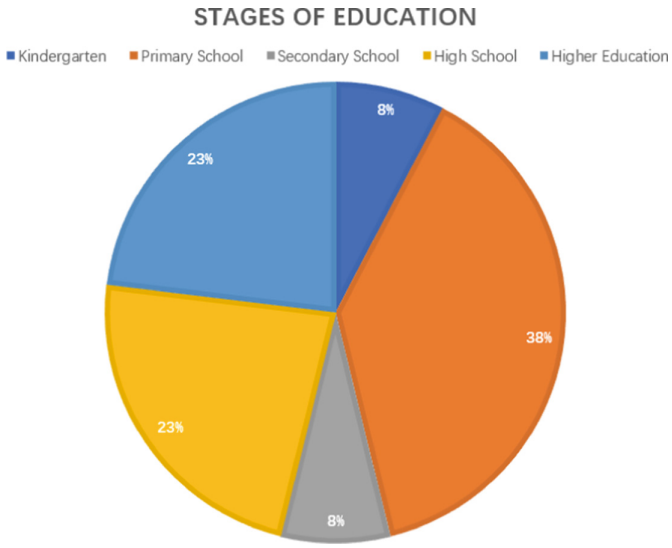

Fig. 5. Stages of Education

The majority of the studies chosen for analysis require a time frame ranging from 2 to 5 months in order to evaluate the cognitive thinking (CT) abilities of participants. However, there are two studies that focus solely on testing learners at a specific point in time, which is within one week. In addition, there are two longitudinal studies that build upon previous research conducted on the same group of individuals.

Based on the findings presented in Fig. 8, it can be observed that the studies on assessing CT skills primarily utilized quantitative and mixed research methodologies. The majority of the selected articles employed quantitative techniques to evaluate CT skills, and the sources of data used were largely objective, such as pre-and post-tests, CT scales, and various surveys. However, some studies also gathered subjective data through

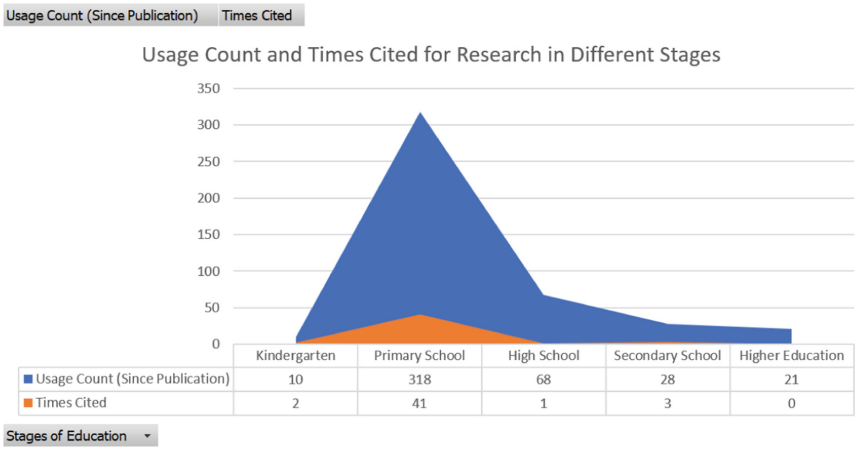

Fig. 6. Usage Count and Times Cited

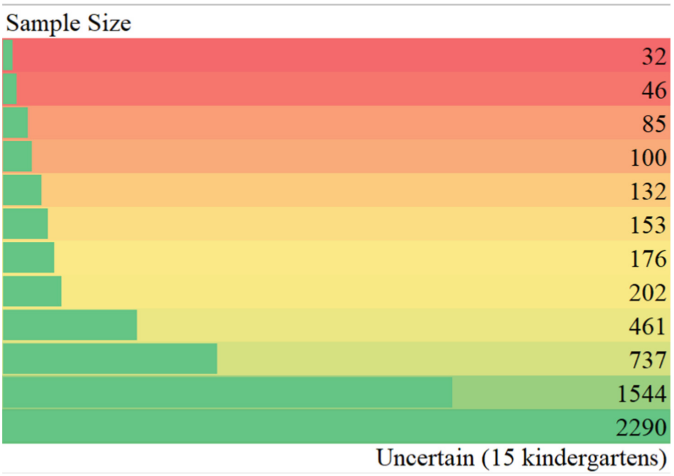

Fig. 7. Sample Size

self-rating tests, observation, or interviews. Three articles introduced a prototype of a CT assessment system, which utilized mixed methodologies to obtain both objective and subjective data. These instruments assessed various dimensions of CT skills, and some triangulated with one another to validate the outcomes (Figs. 9, 10 and 11).

According to the Venn diagram below, not all research examined all the skills in Brennan and Resnick's (2012) 3-D CT model. 7 studies cover all three aspects of the framework, including CT concepts, CT practices and CT perspectives. 5 out of 13 studies directly cite this framework as the guiding structure. Another 2 studies are able to align with these three dimensions in the 3-D CT model, despite using or combining other frameworks (ISTE or Selby's five intended CT constructs).

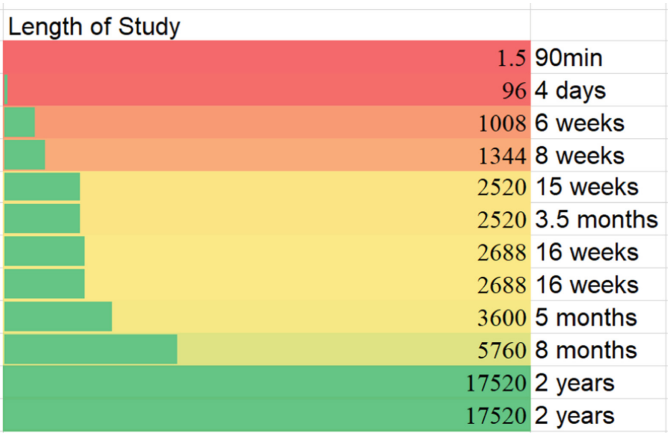

Fig. 8. Length of Study

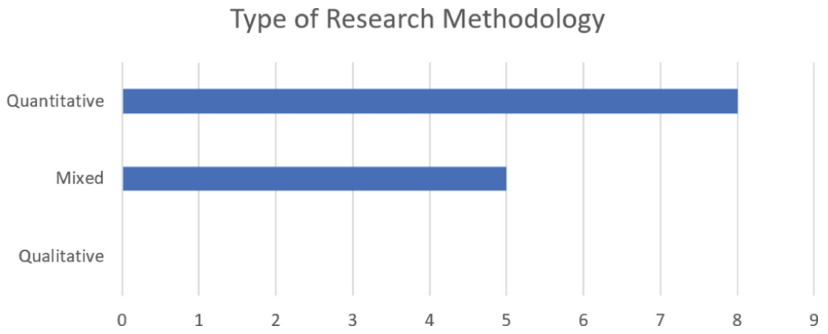

Fig. 9. Type of Research Methodology

A study on the development of CT disposition only assesses the CT concepts and CT perspectives. 23% of the articles focus mostly on CT concepts and CT practices while ignoring the evaluation of computational perspectives. Among the three dimensions, CT practices and CT concepts are more frequently identified than CT perspectives. This echoes the research findings by Zapata-Caceres, Martin-Barroso and Roman-Gonzalez (2021), who point out that the studies on CT perspectives are still insufficient (Fig. 12).

5 Discussions and Future Research

Based on the results, this systematic review discovers several research gaps. Firstly, most of the selected papers tend to assess CT skills in a research setting, instead of a pedagogical environment. Thus, some scholars are concerned about the transferability of these CT assessment tools to the classroom, carried out by educational practitioners rather than researchers (Tang et al., 2020). Worse still, many platforms for CT skills evaluation are not freely available, such as Alice's 3D virtual world, BAC, ICILS, Fairy Assessment and Basic Programming Abilities (Fields et al., 2018; Guggemos, Seufert &

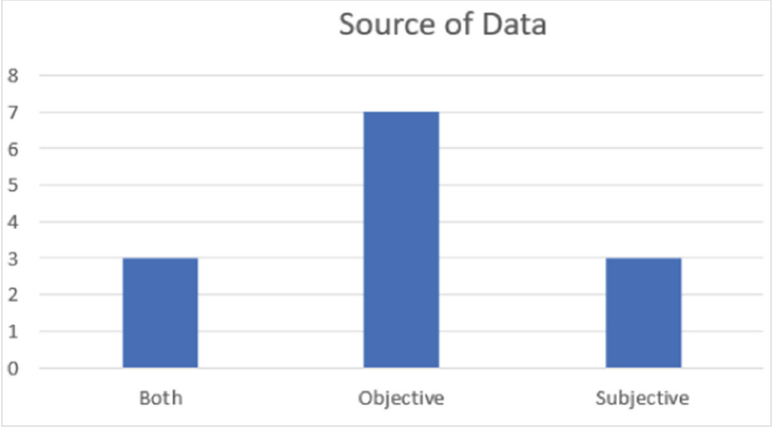

Fig. 10. Source of Data

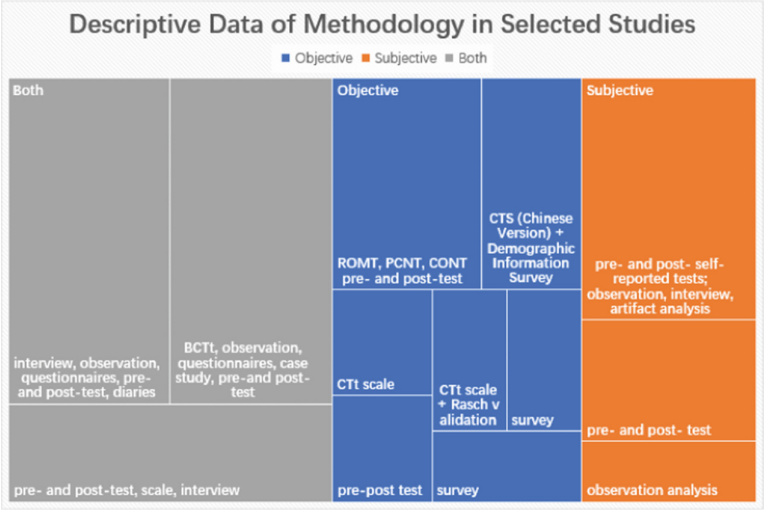

Fig. 11. Descriptive Data of Instruments

Roman-Gonzalez, 2022; Fraillon et al., 2019; Werner et al., 2012; Mühling et al., 2015). If instructors cannot access the CT assessment tools, the integration of CT skills development into the curriculum syllabus is a castle in the air. Secondly, many assessment tools are still in the piloting stage, especially those designed for the first time. Several papers mention that further research on the validity and reliability of the evaluation methods is yet to be conducted (Yusoff, Ashaari, Wook & Ali, 2020; Wong & Jiang, 2018; Jong, Geng, Chai & Lin, 2020; Pérez & Valladares, 2018). Thirdly, the research interest in CT assessment is not evenly distributed. As in the results section, the locality of the selected papers concentrates in Asia and Europe. Owning to the limited number of included articles, this systematic review might not be able to represent a more holistic landscape.

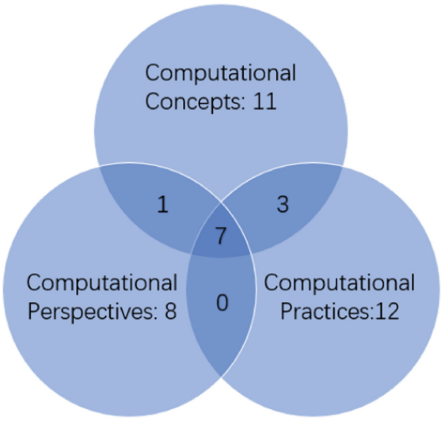

Fig. 12. Venn Diagram of CT Skills Aligned with Brennan and Resnick's (2012) 3-D CT Model Framework.

However, the absence of research from North America, Africa and Oceania deserves considerable attention. Studies in these areas may need to attach more importance to the issue of CT assessment. Fourthly, despite this review covering all educational stages, the studies that take place in primary school are far more than those in kindergarten or higher education. This coincides with the research concerns of some scholars, who criticize that a valid and reliable assessment of CT skills for children below 10 or adult students is yet to be developed (Zapata-Caceres, Martin-Barroso & Roman-Gonzalez, 2021; Oliveira, Correia & Bittencourt, 2021; Sun, Hu, Zhou & Yang, 2022; Fang, Shao, Hwang & Chang, 2022).

The major contributions of this review are twofold. On the one hand, the findings are conducive for the educators to better understand students' mastery and need for CT skills learning. The evaluation data help them to design CT curricula, textbook development, and teaching strategies, which are more suitable for the actual learning situations of their students. More importantly, the data-driven analytics corresponding with the flow theory enables real-time adjustment for pedagogical practices. For instance, Scratch, BAC, and Alice's 3D virtual world automatically renders learners' progress reports and learning development (Pérez & Valladares, 2018; Guggemos, Seufert & Roman-Gonzalez, 2022; Wong & Jiang, 2018; Perez-Marin, Hijon-Neira, Bacelo & Pizarro, 2020; Li, Xie, Vongkulluksn, Stein & Zhang, 2021). With well-matched learning materials and methods, even students in the early stage are potentially able to develop CT skills, which is of great significance to the fostering of 21st-century skills cultivation (Wong & Jiang, 2018).

On the other hand, the discovery of this systematic review can provide insights for further research both theoretically and empirically. This study finds that several assessment methods serve as a supplement to the 3-D CT model framework. For example, the thinking skill of diffusion can be included in the CTt (Guggemos, Seufert & Roman-Gonzalez, 2022). In addition, some scholars mention that in order to enable learners to be problem solvers in a digital world, the mere cultivation of CT practices and CT concepts is insufficient. They expand the CT perspectives to CT attitudes or CT dispositions

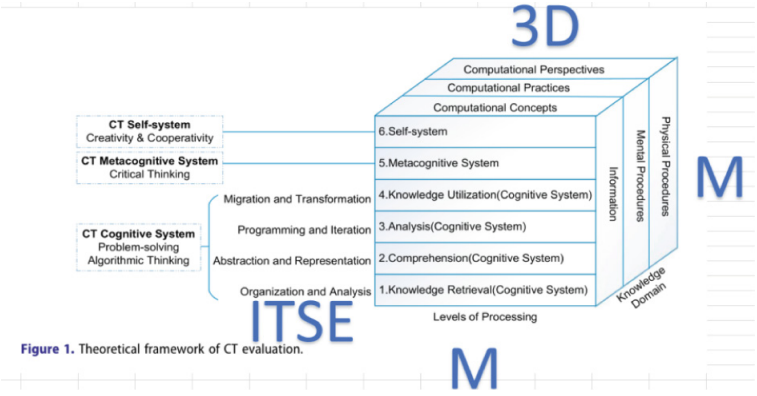

Fig. 13. Framework Proposed by Sun, Hu, Zhou, and Yang (2022)

and advocate the utilization of the Computational Attitude Survey (CAS), MSLQ-A, or OLVSES (Jong, Geng, Chai & Lin, 2020; Oliveira, Correia & Bittencourt, 2021; Sun, Hu, Zhou & Yang, 2022). Empirically speaking, a universal prospect among these selected articles is to develop a CT assessment system that involves multiple mutually-supplementary evaluation tools and covers all three aspects of the 3-D CT model. An inspiring CT assessment system is exemplified by the framework proposed by Sun, Hu, Zhou, and Yang (2022). It is a combination of Marzano's (2001) taxonomy of educational objectives, Brennan and Resnick's (2012) 3-D CT framework and ISTE's operational definitions of CT (Fig. 13).

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