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FROM DIGITAL GAMES TO COMPUTATIONAL THINKING: A META-ANALYTIC REVIEW IN MATHEMATICS EDUCATION

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Abstract
In the last ten years, there has been considerable growth in empirical studies examining the effects of digital games on mathematics learning and computational thinking (CT). However, a review of the existing literature indicates that the outcomes of digital game-enhanced math instruction on students' CT skills have yielded inconsistent results. This research intends to evaluate how effective digital game-supported mathematics education is in developing students' CT abilities, while taking into account various factors such as educational level, duration of the intervention, learning context, game developer, and type of game. A meta-analytic review was conducted, analyzing 15 pertinent studies published between 2011 and 2023, which produced 21 effect sizes and included a total of 8,911 students. Statistical analyses, including the Q Cochrane test, publication bias assessment, Z test, and sensitivity analyses, were performed using CMA software to scrutinize the data. The results indicated a statistically significant but modest positive effect ($g = 0.344$; $p < 0.05$) of digital game-supported math education on students' CT skills. Several factors, including the length of the intervention, the software developer, and the type of game, significantly impacted CT outcomes, whereas other factors, such as educational level and learning environment, did not show a significant influence. These findings suggest that digital game-supported mathematics instruction can be an effective technological approach to enhance students' computational thinking abilities.

Keywords: computational thinking, digital game, mathematics instruction, meta-analysis, systematic review

Introduction

The rapid advancements in technology and science in the 21st century require individuals, particularly students within educational settings, to adapt to new challenges, including various difficulties and problems. These challenges across sectors such as education, business, healthcare, and industry require programming skills, a fundamental aspect of computer science (Ehsan et al., 2018; Henderson et al., 2007; Lu & Fletcher, 2009).The necessity for educators to possess programming skills emphasizes the importance of computational thinking (CT), which has become a central topic in educational technology discussions in many countries (e.g., Barrón-Estrada et al., 2022; Fry et al., 2023; Sung et al., 2023). Molina-Ayuso et al. (2022) assert that CT is a comprehensive skill that aids students in addressing complex issues across various scientific fields, including mathematics, science, technology, engineering, and the arts. Therefore, promoting and enhancing this skill in educational environments is crucial.

CT encompasses a cognitive approach to problem-solving, incorporating effective, efficient, and comprehensive strategies such as algorithms, pattern recognition, abstraction, and decomposition, which are foundational concepts in computer science (e.g., Brackmann et al., 2017; Brennan & Resnick, 2012; Grover & Pea, 2018; Wing, 2006). Notably, CT is closely linked to mathematics, regarded as the foundational language of sciences, as mathematical reasoning often necessitates CT skills. Some studies have indicated a positive correlation between mathematics achievement and CT skills, implying that higher levels of CT skills are associated with better math performance, and vice versa (Abouelenein & Elmaadaway, 2023; Aminah et al., 2023; Kaup et al., 2023). This highlights the importance of CT skills for success in mathematics. However, other empirical research has shown that student performance in CT is not optimal, with many students demonstrating low CT proficiency (Aho, 2012; Fanchamps et al., 2021; Leonard et al., 2023). As a result, effective interventions in mathematics learning environments are necessary to enhance students' CT.

Incorporating educational technology, particularly digital games as supportive tools in mathematics instruction, represents an additional intervention to foster students' CT. Games typically present challenges that engage players. Alcaraz-Muñoz et al. (2020) highlight that students can gain many benefits from engaging in gameplay. Furthermore, gaming activities help students develop problem-solving abilities, critical and creative thinking, and logical reasoning to succeed in various games (Hunsaker, 2020; Yadav et al., 2017). Fokides (2018) defines digital educational games as applications or programs intended for both educational and entertainment purposes, utilizing digital technologies such as computers, smartphones, and gaming consoles. These games can aid in cultivating various competencies, including logic, creativity, problem-solving, and digital literacy (Jensen & Skott, 2022; Vanbecelaere et al., 2020). Additionally, these games can boost students' motivation to learn by providing an interactive, challenging, and enjoyable learning experience (Fadda et al., 2022; Yong et al., 2016). Digital educational games possess characteristics such as interactivity (allowing players to engage directly with the content and interface), adaptability (modifying the difficulty level and content according to players' abilities), and clear learning objectives (designed to achieve specific, measurable goals) (Byun & Joung, 2018; Moyer-Packenham et al., 2019). Moreover, these educational games are created using various software development platforms, such as Unity, Scratch, HTML5, code.org, and visual programming + 3D. The digital games developed can be accessed on computers, virtual tools, smartphones, and websites, making them widely available (Chou et al., 2021; Ribeiro et al., 2021). Thus, digital game-supported mathematics instruction is expected not only to enhance students' CT but also to stimulate their interest in learning.

To date, extensive research has examined the role of digital games in enhancing students' computational thinking (CT) within mathematics learning contexts. Some studies suggest that digital games positively impact students' CT performance (Agbo et al., 2021; Hooshyar et al., 2020, 2021; Huang et al., 2023; Jun et al., 2017; Soboleva et al., 2021). Conversely, other studies indicate insufficient evidence to confirm a significant positive effect of digital games on CT outcomes (Bakker et al., 2015; Rose et al., 2020; Wahyudin et al., 2021; Zaibon & Yunus, 2021). This mixed evidence reveals inconsistency in the impact of digital game use on CT optimization within math instruction. Furthermore, while some studies report a moderate positive effect (Agbo et al., 2021; Hooshyar et al., 2020, 2021; Jun et al., 2017; Wahyudin et al., 2021) or a strong positive impact on CT outcomes (Huang et al., 2023; Soboleva et al., 2021), others note a weaker effect (Bakker et al., 2015; Rose et al., 2020; Zaibon & Yunus, 2021) or even a negative effect (Asbell-Clarke et al., 2021; del Olmo-Muñoz et al., 2020; Liu et al., 2011; Ríos Félix et al., 2020; Rose et al., 2017). These findings illustrate the heterogeneous effects of digital game-based learning on CT, indicating variations in CT outcomes among students when digital games are used in mathematics education. Thus, a systematic review of empirical research on digital games in math learning and CT is crucial to form a clearer conclusion.

The varied influence of digital educational games on students' CT outcomes reflects the diversity of cognitive aspects in math learning. This diversity implies that numerous variables may influence the success of digital games in enhancing CT, pointing to potential moderating factors that indirectly affect the relationship between the independent and dependent variables (Ariani et al., 2024; Suparman et al., 2024). In this study, alongside examining the influence of digital games on CT, several moderating variables are anticipated to play a role in students' CT performance. According to Lipsey and Wilson (2001), these substantial factors can significantly impact both independent and dependent variables. Five moderating factors are examined in this study: educational level, intervention duration, game type, learning environment, and software developer. Educational level, for instance, relates directly to students' CT, while other factors like intervention duration, learning environment, developer, and game type are linked to digital game-supported learning. Research by Helsa et al. (2023) suggests that educational level and game type may affect CT outcomes, while Ye et al. (2022) showed that intervention duration and learning environment can impact CT skills. Therefore, these moderating factors likely contribute to varied CT achievements in digital game-based math education.

Previous systematic reviews have offered insights into CT and digital games (Akerfeldt et al., 2024; da Silva & Silveira, 2020; Giannakoulas & Xinogalos, 2023; Sukirman et al., 2021; Sun et al., 2023; Theodoropoulos & Lepouras, 2021; Triantafyllou et al., 2024; Varghase & Renumol, 2023; Videnovik et al., 2023). Certain reviews focused on gamification and CT through bibliometric analysis (Akerfeldt et al., 2024; Triantafyllou et al., 2024; Videnovik et al., 2023), educational games and CT through qualitative meta-synthesis (da Silva & Silveira, 2020; Giannakoulas & Xinogalos, 2023), and digital games and CT using both bibliometric and meta-synthesis approaches (Sukirman et al., 2021; Theodoropoulos & Lepouras, 2021; Varghase & Renumol, 2023). Additionally, Sun et al. (2021) reviewed educational games and CT through meta-analysis. The present study, however, applies a meta-analytic method to analyze recent empirical studies from the last decade on digital games in math learning and CT. The study thus aims to evaluate the effectiveness of digital game-supported math education on students' CT, considering moderating factors like game type, intervention duration, learning environment, educational level, and software developer. Investigating these factors is essential to understanding differences in CT outcomes in math education supported by digital games. This review aims to provide a clear, evidence-based conclusion on the effectiveness of digital games for fostering CT skills in mathematics learning.

Method

Research design

A systematic review was performed to conduct recent study. Moreover, this recent study involved a meta-analytic technique ─ a series of quantitative procedures employing the effect size (Fuad et al., 2023; Helsa et al., 2023), was applied to examine the effect of digital games to students' CT achievement in mathematics learning, and some moderating factors, such as intervention duration, learning environment, software developer, educational level and digital game type in differentiating students' CT in digital games-assisted mathematics learning. Each of systematic review phase was discussed in the next subsections.

Inclusion criteria

To narrow the scope of the identified issues, specific inclusion criteria were established. First, each document's title was required to include the keywords: "computational thinking," "mathematics," and "digital games." Second, documents had to be in English and consist of either conference papers or articles sourced from journals or conference proceedings. Third, they needed to be published between 2011 and 2023, addressing fields like social sciences, computer sciences, mathematics, arts and humanities, or multidisciplinary studies. Fourth, the studies focused on populations of Asian, American, European, or African students at elementary, middle school, or university levels. Fifth, the intervention featured digital games-assisted mathematics learning. Sixth, the comparator was traditional mathematics teaching methods. Seventh, computational thinking served as the outcome variable. Eighth, a quasi-experimental design was required for the research. Ninth, each document needed to report sufficient statistical data for calculating effect size. Documents that did not meet these criteria were excluded in the document selection process for the current study.

Literature search and document selection

The Scopus database was utilized to locate literature related to computational thinking and digital game-supported mathematics learning. Scopus is recognized for its extensive collection of credible and high-quality scholarly literature (Zhu & Liu, 2020). To streamline the document search, a combination of keywords—such as "computational thinking," "mathematics," and "digital games"—was employed. An initial search on January 31, 2024, at 11:59 PM identified 137 documents published between 1970 and 2023. A systematic selection process was then applied to these documents, following four key steps: (1) identification, (2) screening, (3) eligibility, and (4) inclusion (Susiyanti et al., 2022; Yunita et al., 2022; Zainil et al., 2024). Figure 1 provides a concise and detailed summary of this document selection process.

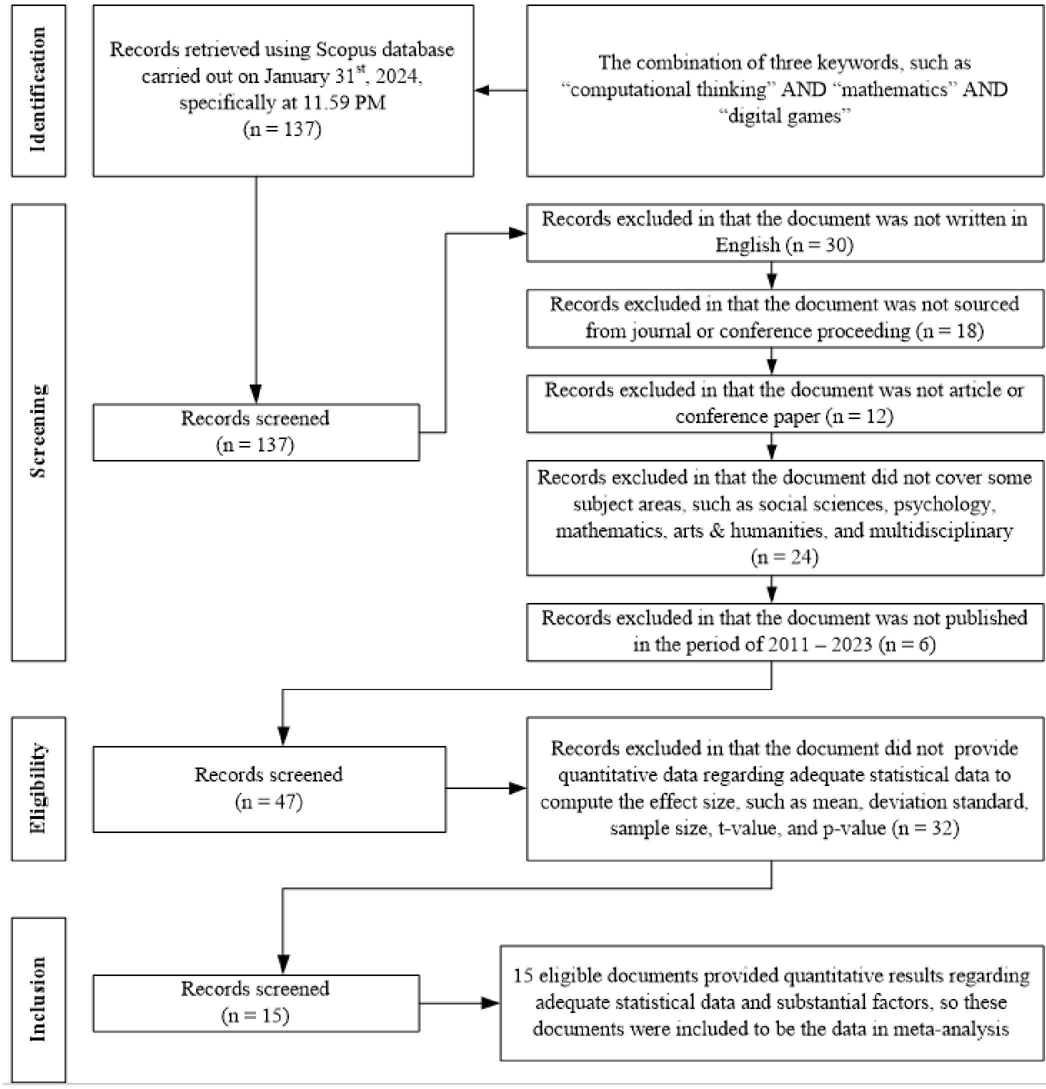

Figure 1. The systematic process of document selection

Data extraction

Fifteen qualifying documents were compiled for the meta-analysis and recorded in a coding sheet. This sheet included information such as code, author, quantitative findings, moderating variables, document type, name of the journal or proceedings, email, and DOI or URL. The 15 selected documents produced 21 effect size units, encompassing a total of 8,911 participants across various educational levels. To ensure the credibility and validity of the data utilized in this research, which is essential for producing quality reports (Cohen et al., 2018), two meta-analysis experts were consulted to validate and justify the information. After these experts recoded and verified the data on the coding sheet, coding consistency was assessed for both the meta-analysis and qualitative meta-synthesis sections. The Cohen's Kappa test was used to evaluate coding consistency among the two experts involved in each section (McHugh, 2012).

Table 1. The results of Cohen's Kappa test

Coding Item	Kappa Value	Agreement Level	Significance Value
Mean of Experiment Group	0.923	Almost Perfect	0.009
Dev. Std. of Experiment Group	0.912	Almost Perfect	0.009
Sample Size of Experiment Group	0.927	Almost Perfect	0.009
Mean of Control Group	0.957	Almost Perfect	0.008
Dev. Std. of Control Group	0.943	Almost Perfect	0.008
Sample Size of Control Group	0.952	Almost Perfect	0.008
T-value	0.962	Almost Perfect	0.007
Intervention Duration	0.822	Strong	0.018
Educational Level	0.845	Strong	0.017
Learning Environment	0.889	Strong	0.011
Software Developer	0.872	Strong	0.011
Digital Game Type	0.867	Strong	0.012

From Table 1, it can be stated that the agreement level for each of coding item was from moderate to almost perfect. Moreover, the significant value for every coding item was less than 0.05 in which this interprets that they for each part significantly agree on the extracted data (Suparman & Juandi, 2022a, 2022b). Consequently, this provides strong evidences that the data included to meta-analysis was credible and valid, and then the data is able to be analyzed.

Data analysis

In this meta-analysis, a random-effects model was employed to assess various outcomes, including estimated effect sizes, publication bias evaluation, sensitivity analysis, Z-test, and Q Cochran test. This model was selected for its ability to accommodate the varied characteristics found across the empirical studies, including differences in country, educational level, instruments, duration of intervention, learning environment, mathematical topics, and class size (Fuad et al., 2022; Juandi et al., 2023; Sulistiawati et al., 2023; Suyanto et al., 2023). Hedges' equation was utilized to compute effect sizes, which is particularly effective for quantitative empirical studies with relatively small sample sizes (Borenstein, 2019). According to Pigott (2012), Hedges' formula is represented as follows:

$$g = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}}} \times \left(1 - \frac{3}{4df - 1}\right)$$

Additionally, the Z test was conducted to determine the significance of the impact of digital games-assisted mathematics learning on students' CT achievement. The Q Cochran's test was also applied to explore five moderating factors influencing differences in students' CT performance within the context of digital games-assisted mathematics learning.

Findings and Discussion

This meta-analysis explained some parts, such as sensitivity analysis and publication bias, estimated effect size, and subgroup analysis. Each of this meta-analysis part was explained in the following subsections.

Sensitivity analysis and publication bias

To check for indications of publication bias, the distribution of effect size data was analyzed using a funnel plot (see Figure 2).

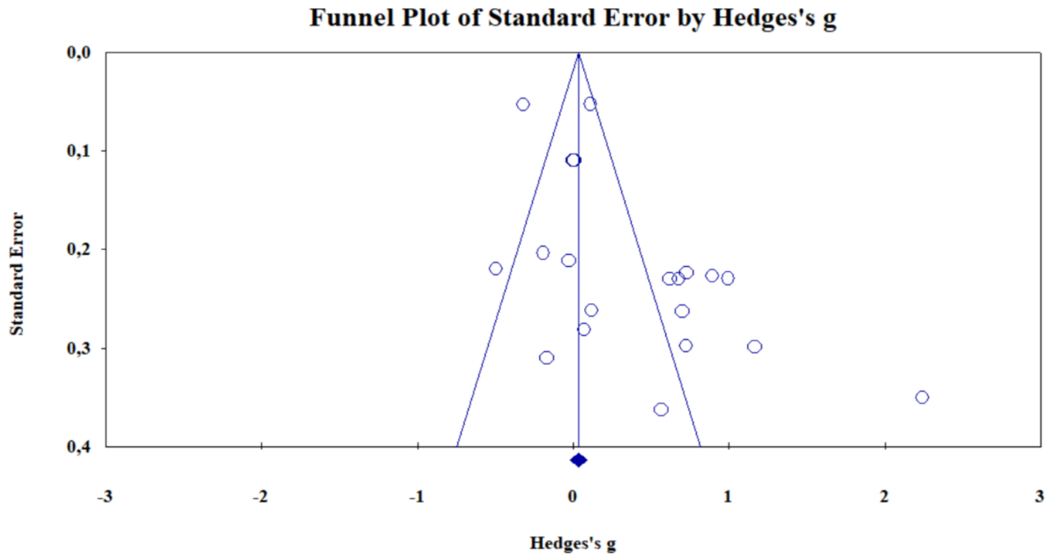

Figure 2. The distribution of effect size data in the funnel plot

From the observations in Figure 2, it is evident that the effect size data exhibits a symmetrical pattern in the funnel plot. To further validate this observation, a trim and fill test was conducted (see Table 2).

Table 2. The results of fill and trim test

	Studies Trimmed	Effect Size in g	Lower Limit	Upper Limit	Q-value
Observed Values		0.344	0.148	0.541	179.05
Adjusted Values	0	0.344	0.148	0.541	179.05

Table 2 shows that no effect size data points were necessary to remove from either end of the distribution, confirming the symmetrical distribution of effect size data in the funnel plot. This suggests that there is no evidence of publication bias in the effect size data collected (Tawaldi et al., 2023).

A sensitivity analysis was carried out to assess the robustness of the effect size data and identify any outliers among the minimum and maximum effect sizes (Bernard et al., 2014). The analysis found that the lowest effect size was 0.267, while the highest was 0.387. The estimated point for the 21 effect sizes was 0.344, which lies between 0.267 and 0.387, indicating no outliers are present. Thus, it can be concluded that there are no signs of sensitivity changes in the effect size data collected.

The effectiveness of digital games-assisted mathematics learning on students' CT achievement

15 eligible documents included in meta-analysis generated 15 units of effect size in g and involved 8,911 students. The unit of effect size was heterogeneous in the perspective of direction, significance, and strength (See Table 3).

Table 3. The results of calculations of effect size

Document	Effect Size in g Unit	P-value
Agbo et al. (2021)	0.723 [0.139; 1.307]	0.015
Olmo-Munoz et al. (2020)	-0.496 [-0.926; -0.066]	0.024
Hooshyar et al. (2021)	0.619 [0.168; 0.1.071]	0.007
Hooshyar et al. (2020)	0.675 [0.224; 0.1.126]	0.003
Rose et al. (2020a)	0.700 [0.185; 1.215]	0.008
Rose et al. (2020b)	0.117 [-0.396; 0.630]	0.655
Felix et al. (2020)	-0.026 [-0.441; 0.388]	0.900
Huang et al. (2023)	1.164 [0.578; 1.750]	0.000
Jun et al. (2017a)	0.994 [0.545; 1.444]	0.000
Jun et al. (2017b)	0.892 [0.447; 1.337]	0.000
Jun et al. (2017c)	0.728 [0.290; 1.167]	0.001
Bakker et al. (2015a)	0.000 [-0.214; 0.214]	1.000
Bakker et al. (2015b)	0.007 [-0.207; 0.221]	0.949
Bakker et al. (2015c)	0.000 [-0.214; 0.214]	1.000
Zaibon & Yunus (2021)	0.072 [-0.479; 0.624]	0.797
Clarke et al. (2020a)	0.111 [0.008; 0.214]	0.034
Clarke et al. (2020b)	-0.322 [-0.425; -0.218]	0.000
Rose et al. (2017)	-0.168 [-0.777; 0.440]	0.588
Liu et al. (2011)	-0.193 [-0.592; 0.206]	0.343
Wahyudin et al. (2021)	0.565 [-0.145; 1.276]	0.119
Soboleva et al. (2021)	2.240 [1.553; 2.927]	0.000
Estimated Effect Size	0.344 [0.148; 0.541]	0.001

Table 3 indicates that the estimated effect size for the 21 data units is 0.344, suggesting that digital game-assisted mathematics learning positively and moderately impacts students' critical thinking (CT) skills (Cohen et al., 2018). Additionally, the Z test produced a significance value below 0.05, indicating that the intervention had a substantial effect on students' CT achievement. Therefore, it can be asserted that digital game-assisted mathematics education effectively enhances students' CT skills.

This research supports the finding that an estimated effect size of 0.344 reflects a positive and moderate influence of digital games on students' CT performance. A meta-analysis by Sun et al. (2021) examining 22 empirical studies also showed a favorable moderate effect of educational games on the development of CT skills. Furthermore, Ginnakoulas and Xinogalos (2023) evaluated 61 empirical studies, confirming that educational programming games positively affect students' CT development. These outcomes reinforce the conclusion that interventions such as digital game-assisted mathematics instruction enhance students' CT abilities. The current study further emphasizes the significant impact of this instructional method on students' CT achievement, illustrating its effectiveness in mathematics education.

Critical thinking is closely associated with mathematics, regarded as the foundational language of the sciences, as mathematical thinking necessitates CT skills. Several studies have identified a positive correlation between mathematics achievement and CT skills, indicating that higher levels of CT skills correlate with better mathematics performance, and vice versa (Aminah et al., 2022, 2023; Angraini et al., 2023; Hanid et al., 2022; Kaup et al., 2023). This underlines the importance of developing CT skills to improve mathematics achievement.

Consequently, strategies to enhance CT in mathematics education should be implemented.

Learning environments in mathematics, such as constructive, cooperative, and collaborative learning, offer various advantages for fostering complex problem-solving skills (Chan et al., 2020; Rich et al., 2020; Rodríguez-Martínez et al., 2020). Given that complex problem-solving is a primary objective of CT development (Molina-Ayuso et al., 2022), these instructional methods are well-suited for promoting CT within mathematics activities. Furthermore, integrating digital games as a technological resource in mathematics education can enhance students' CT capabilities. The current study, along with relevant literature, demonstrates that digital game-assisted mathematics learning significantly benefits students' CT achievement.

Many instructional models employed in mathematics, including cooperative, constructive, and collaborative learning, share constructive elements. Literature describes constructive learning as an educational approach focused on helping students build their own knowledge (Liu & Zhang, 2023; Sung et al., 2023; Tan et al., 2022; Tsai et al., 2023). This perspective posits that students actively construct their understanding through creative and reflective thinking processes. Additionally, using educational technology, such as digital games, serves as a supplementary intervention to boost students' CT. Games inherently present challenges for participants. Alcaraz-Munoz et al. (2020) highlight various benefits students gain from engaging with games. Moreover, gameplay encourages problem-solving, critical and creative thinking, and logical reasoning to achieve success (Hunsaker, 2020; Yadav et al., 2017). Some studies assert that educational games actively and creatively motivate students to engage in the learning process by presenting challenges (Molnar et al., 2015; Shoukry et al., 2015; Vee Senap & Ibrahim, 2019). Consequently, digital game-assisted mathematics instruction not only enhances CT skills but also stimulates students' interest in learning. Therefore, it is logical to conclude that digital educational games can effectively optimize students' CT development in mathematics education.

Heterogenous effect in digital games-assisted mathematics learning

The Q Cochrane test was applied to test some moderating factors, such as educational level, intervention duration, learning environment, software developer, and digital game type predicted in differentiating students' CT in digital games-assisted mathematics learning (See Table 4).

Table 4. The results of Q Cochrane test

Substantial Factor	Groups	Effect Size in g Unit	P-value
Educational Level	Elementary School	0.433	0.212
	Middle School	0.013	
	College/University	0.239	
Intervention Duration	1 Week	0.538	0.012
	2 Weeks	0.437	
	3 Weeks	0.546	
	4 Weeks	0.997	
	8 Weeks	-0.203	
	10 Weeks	0.002	
	Constructionist Learning	0.599	0.112

Substantial Factor	Groups	Effect Size in g Unit	P-value
Learning Environment	Cooperative Learning	-0.005	
	Direct Learning	0.515	
	Game-Based Learning	-0.068	
	Programming Learning	0.408	
Software Developer	Code.org	0.218	0.000
	HTML5	0.165	
	Scratch	0.575	
	Unity	0.847	
	Visual Programming + 3D	-0.113	
Digital Game Type	Computer Games	0.427	0.021
	Simulation Games	-0.193	
	Virtual Games	0.596	
	Web-Based Games	-0.105	

According to Table 4, certain moderating factors—including the duration of the intervention, type of digital game, and the software developer—showed significant differences in students' critical thinking (CT) skills when engaged in digital game-assisted mathematics learning. However, there is insufficient evidence to claim that factors like educational level and learning environment significantly influenced students' CT skills in this context. Each of these key factors will be discussed in the following subsections.

Educational level

There is inadequate evidence to suggest that educational level significantly impacts students' CT skills in digital game-assisted mathematics instruction. Several relevant meta-analyses have shown that educational level does not differentiate CT achievement in various interventions, including unplugged activities and programming tasks (Chen et al., 2023; Xu et al., 2023). These findings reinforce the results of the current study, which indicates no significant differentiation based on educational level. Notably, the impact of digital games on the CT skills of elementary students was found to be greater than on those in other educational levels. This suggests that employing digital games in mathematics education is particularly effective for enhancing CT skills in elementary school students compared to other educational stages.

Intervention duration

The duration of the intervention had a significant effect on the development of students' CT skills in digital game-assisted mathematics learning. Several reviews provide strong evidence that intervention length plays a critical role in students' CT achievement (Cheng et al., 2023; Xu et al., 2023). These findings support the current study's conclusion that the duration of the intervention significantly influences the acquisition of CT in mathematics learning through digital games. Specifically, interventions lasting four weeks yielded a greater effect on CT acquisition than those lasting one to three weeks or eight to ten weeks. Thus, it can be inferred that implementing digital games in mathematics learning over a four-week period is more effective for enhancing students' CT than shorter or longer durations.

Learning environment

There is insufficient evidence to assert that the learning environment significantly affects the development of students' CT in digital game-assisted mathematics instruction. Other relevant meta-analyses also found that the learning environment does not significantly differentiate students' CT achievement in various CT interventions, including programming instruction and related activities (Hwang & Hwang, 2020; Sun et al., 2021). These studies support the notion that the learning environment does not play a significant role in influencing CT achievement. However, descriptively, constructive learning showed a more substantial impact on students' CT achievements compared to other learning environments. This suggests that integrating digital games within constructive learning environments may be more effective for enhancing students' CT skills than in other settings.

Software developer

The software developer used in creating digital games significantly influenced students' CT acquisition in mathematics learning. Specifically, the impact of digital game-assisted mathematics instruction developed using Unity was notably higher compared to that developed with other software platforms. Therefore, it can be concluded that digital games designed with Unity are more effective in enhancing students' CT than those created using alternative software.

Digital game type

This factor also significantly affected the acquisition of students' CT in digital game-assisted mathematics learning. Sun et al. (2021) found that different types of digital games markedly differentiated students' CT skill development. These findings bolster the current study's conclusion that the type of digital game used plays a significant role in influencing students' CT achievement. Particularly, the use of virtual games in mathematics instruction had a significantly greater impact on CT acquisition than other types of digital games. Hence, virtual games are more effective for enhancing students' CT in mathematics education.

Implications and suggestions for mathematics education

This study offers several implications for future research on CT in mathematics education. Digital game-assisted mathematics learning has a positive and moderate impact on students' CT acquisition. Moreover, using digital games has proven to be significantly effective in enhancing students' CT over the past decade. Therefore, integrating digital games into mathematics education can facilitate the development of students' CT skills. Furthermore, utilizing digital games over a four-week period is more effective than shorter (one to three weeks) or longer (eight to ten weeks) interventions for improving students' CT. Consequently, to maximize CT development, implementing digital games over four weeks is recommended as an optimal intervention duration. Additionally, the development of digital games using Unity is more effective than alternatives such as Scratch, HTML5, Code.org, and visual programming with 3D components. This suggests that Unity should be the preferred software for developing digital games aimed at enhancing students' CT in mathematics. Furthermore, utilizing virtual games is more beneficial for optimizing students' CT compared to computer games, simulation games, or web-based games. Therefore, mathematics instruction should focus on using virtual games to enhance students' CT achievement.

This meta-analytic review has certain limitations. Many prospective documents identified in various databases could not be accessed due to publisher restrictions, necessitating payment for access. Additionally, numerous documents lacked sufficient statistical information to compute effect size units. Therefore, for future research on CT in mathematics education, it is recommended that researchers directly reach out to authors of restricted documents to request free access.

Conclusion

In conclusion, this study found that the estimated effect size of 21 data units was 0.344, indicating that digital games in mathematics education have a positive and moderate impact on students' CT acquisition. Digital game-assisted mathematics instruction significantly enhances students' CT skills. Furthermore, moderating factors such as digital game type, software developer, and intervention duration significantly influenced students' CT development, while educational level and learning environment did not show a significant differentiating effect in this context.

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