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Enhancing mathematical reasoning through digital media: A meta-analysis

Fahruh Juhaevah *

Doctoral Program of Mathematics Education, Postgraduate of Universitas Negeri Makassar, Makassar, Indonesia.

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Abstract

This meta-analysis investigated the effect of digital media on mathematical reasoning across 18 studies involving primary, secondary, and higher education students. A random model revealed a significant overall effect size (ES = 2.53, 95% CI: [1.44, 3.62]), indicating that digital media interventions substantially enhance mathematical reasoning abilities. However, significant heterogeneity was observed among the studies ($Q = 1089.8704$, $df = 17$, $p < 0.0001$, $I^2 = 98.44\%$). Subgroup analyses showed that the effectiveness of digital media varied across mathematical content (numbers and geometry) ($Qb = 237.2527$, $df = 5$, $p < 0.0001$) and educational levels (primary and secondary) ($Qb = 73.0728$, $df = 2$, $p < 0.0001$), but not across sample sizes ($Qb = 0.0050$, $df = 1$, $p = 0.9435$). Potential publication bias was suggested, but Egger's test did not provide strong evidence for it. The findings support the use of digital media to enhance mathematical reasoning skills, highlighting the importance of considering content area and educational level when designing interventions.

Keywords: Digital Media; Educational Level; Mathematical Content; Mathematical Reasoning; Meta-Analysis

1. Introduction

Mathematical reasoning is a fundamental aspect of mathematics education [1], [2], essential for developing students' mathematical competence and problem-solving skills [3], [4]. It encompasses various cognitive processes, such as analyzing problems, implementing strategies, making connections, and reflecting on solutions. Mathematical reasoning enables students to think critically, justify their solutions, and generalize mathematical concepts, fostering a deeper understanding of mathematical principles [5]. By promoting creative thinking, deductive reasoning, and argumentation skills, mathematical reasoning enhances students' mathematical achievement and cognitive development [6]. Moreover, spatial reasoning, abductive reasoning, and covariational reasoning are integral components of mathematical reasoning that contribute to students' mathematical literacy and relational thinking [7]. The incorporation of digital media, such as virtual mathematics kits [8] and interactive tools [9], can further support students in developing their mathematical reasoning abilities. Overall, mathematical reasoning is a key skill that empowers students to engage effectively with mathematical concepts, solve complex problems, and apply mathematical knowledge in various contexts.

In recent years, the rapid advancement of digital technologies has transformed the educational landscape, offering new opportunities for enhancing teaching and learning processes [10]–[12]. Digital media, in particular, has shown promise in supporting the development of mathematical reasoning skills, which are critical for students' academic success and future careers [13], [14]. Numerous studies have investigated the effectiveness of digital media interventions in various mathematical content areas and across different educational levels [15]–[18].

Ideally, digital media interventions should be designed to effectively support students' mathematical reasoning abilities [19], [20], regardless of the specific content area or educational level. They should provide engaging, interactive, and

* Corresponding author: Fahruh Juhaevah

personalized learning experiences that foster deeper understanding and facilitate the application of mathematical concepts to real-world problems [21]. Moreover, digital media should be accessible to all students, irrespective of their background or prior knowledge, ensuring equitable learning opportunities [20].

However, the existing literature on the effectiveness of digital media in mathematical reasoning presents a fragmented and inconsistent picture. While some studies report large positive effects [22], [23], others show more modest or even negligible impacts [24], [25]. Furthermore, most studies focus on specific content areas or educational levels, making it difficult to generalize the findings across different contexts. There is a need for a comprehensive meta-analysis that synthesizes the available evidence, explores potential sources of heterogeneity, and provides a more nuanced understanding of the effectiveness of digital media in supporting mathematical reasoning.

This meta-analysis addresses these research gaps by quantitatively synthesizing the findings some studies that investigated the impact of digital media on mathematical reasoning across various content (number, statistics, logic, geometry, algebra, and multiple materials) and educational levels (primary, secondary, and higher education). This study lies in its comprehensive approach, which not only estimates the overall effect size but also explores potential moderating factors through subgroup analyses. Moreover, this meta-analysis employs advanced statistical techniques, such as random-effects modeling and publication bias assessment, to provide a more robust and reliable synthesis of the available evidence.

The main contributions of this meta-analysis are twofold. First, it provides a comprehensive and up-to-date synthesis of the effectiveness of digital media in supporting mathematical reasoning, which can inform educational policy and practice. Second, by identifying potential sources of heterogeneity and limitations in the existing literature, this study highlights areas for future research and methodological improvements. The purpose of this meta-analysis is to advance our understanding of how digital media can be effectively leveraged to enhance mathematical reasoning skills across various educational level, ultimately contributing to students' academic success and preparation for future challenges.

2. Methodology

2.1. Literature Search and Selection Criteria

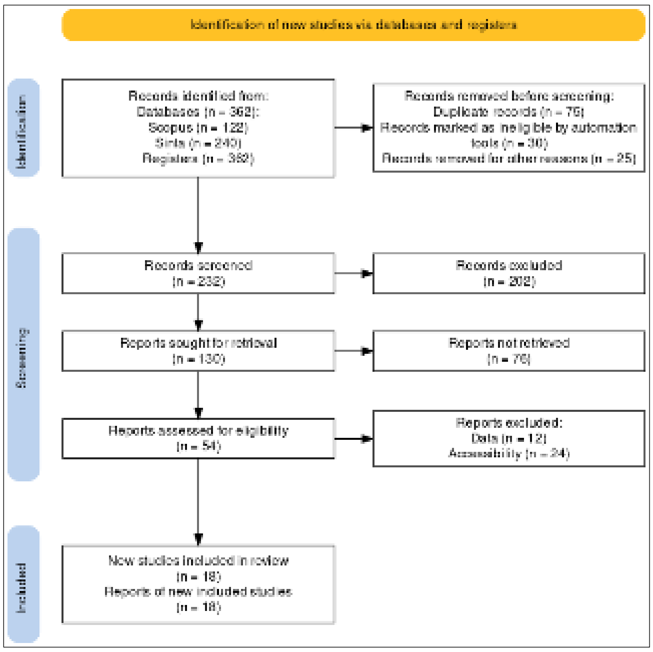

Figure 1 PRISMA Flowchart

A systematic literature search was conducted in two databases, Scopus and Sinta, to identify relevant studies published up to May 2024. The search strategy included combinations of keywords related to digital media, mathematical reasoning, and educational levels. The search yielded 122 records from Scopus and 240 records from Sinta (Science and Technology Index). After removing duplicates, 18 records were screened based on predefined inclusion and exclusion criteria. Studies were included if they (a) investigated the effect of digital media interventions on mathematical reasoning, (b) reported sufficient data to calculate effect sizes, (c) published start from 2018, and (d) were published in English. Studies that did not meet these criteria were excluded. The following presents the stages of the PRISMA model that were carried out.

Based on the analysis using the PRISMA flowchart, 18 relevant studies were identified for inclusion in this meta-analysis. The results of the analysis are presented in the following table.

Table 1 Analysis Reviewed Articles

Researchers	Content	Level	N	ES	SE
[15]	Number	Primary	< 33	1.001	0.956
[16]	Number	Higher	< 33	0.78	2.28
[17]	Number	Secondary	< 33	1.93	1.65
[18]	Statistics	Secondary	> 33	2.11	0.73
[22] (a)	Logic	Primary	> 33	3.25	0.92
[22] (b)	Logic	Primary	> 33	4.2	0.69
[24] (a)	Geometry	Secondary	< 33	0.48	0.76
[24] (b)	Geometry	Secondary	< 33	0.48	0.78
[24] (c)	Geometry	Secondary	< 33	0.13	0.66
[25]	Geometry	Secondary	> 33	0.519	0.038
[26]	Multiple material	Higher	> 33	1.29	1.67
[27]	Number	Primary	> 33	0.64	4.42
[23]	Algebra	Secondary	< 33	6.92	0.93
[23]	Algebra	Secondary	< 33	8.54	1.13
[28]	Geometry	Secondary	> 33	3.72	0.51
[28]	Geometry	Secondary	> 33	3.03	0.43
[29]	Geometry	Secondary	< 33	1.16	0.294
[30]	Number	Secondary	< 33	3.68	0.59

2.2. Data Extraction and Analysis

Extracted data from the included studies, including sample sizes, means, standard deviations, and correlation coefficients. Disagreements were resolved through discussion and consensus. The Comprehensive Meta-Analysis (CMA) software was used to calculate effect sizes (Hedges' g) and conduct statistical analyses. Here are the presented criteria for classifying effect size based on [31].

Table 2 Effect Size Classification

Effect Size (Hedge's g)	Classification
0.00 - 0.20	Small
0.21 - 0.50	Small to Medium
0.51 - 0.80	Medium
0.81 - 1.20	Medium to Large
1.21 - 2.00	Large
> 2.00	Very Large

A random-effects model was employed to account for heterogeneity among studies. Subgroup analyses were performed to examine the impact of digital media across different mathematical content areas, educational levels, and sample sizes. Heterogeneity was assessed using the Q-statistic and I^2 index. Publication bias was evaluated using a funnel plot and Egger's regression test.

3. Results and discussion

3.1. Overall Effect Size

To perform the Comprehensive Meta-Analysis (CMA) for this meta-analysis, we need to consider the overall effect size, heterogeneity assessment, and the appropriate meta-analysis model. The following presents the overall effect size.

Table 3 Coefficients

	Estimate	**Standard Error**	**z**	**p**
intercept	2.532	0.557	4.544	< 0.001
Note. Wald test.				

The forest plot reveals considerable heterogeneity among the studies, as evidenced by the varying effect sizes and non-overlapping confidence intervals. To quantify the heterogeneity, we can calculate the Q-statistic and I^2 index: Q-statistic: Q = 1089.8704, df = 17, $p < 0.0001$ The Q-statistic is significant ($p < 0.0001$), indicating the presence of substantial heterogeneity among the studies. I^2 index: I^2 = 98.44% The I^2 index suggests that 98.44% of the total variation across studies is due to true heterogeneity rather than chance. This high value of I^2 confirms the presence of substantial heterogeneity.

Table 4 Residual Heterogeneity Estimates

	Estimate
τ^2	4.494
τ	2.120
I^2 (%)	95.180
H^2	20.747

Given the presence of significant heterogeneity, the random-effects model is more appropriate than the fixed-effect model for this meta-analysis. The random-effects model accounts for both within-study and between-study variability, providing a more conservative estimate of the overall effect size and wider confidence intervals.The forest plot visually represents the individual study effect sizes and their confidence intervals, along with the overall effect size estimate.

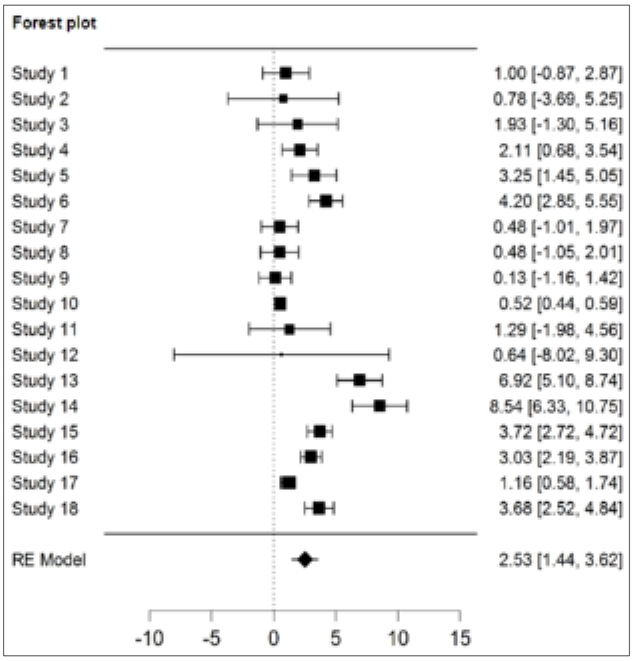

Figure 2 Forest Plot

The random-effects model used in this meta-analysis yielded an overall effect size estimate of 2.53, with a 95% confidence interval of [1.44, 3.62]. The CMA for this meta-analysis reveals a very large positive overall effect size of digital media on mathematical reasoning abilities (ES = 2.53, 95% CI: [1.44, 3.62]). By leveraging digital tools and resources, educators can create interactive and engaging learning experiences that promote critical thinking, problem-solving skills, and mathematical reasoning among students. Research studies have shown the positive impact of digital media on mathematical reasoning abilities, providing immediate feedback and enhancing students' overall understanding of mathematical concepts [22], [23]. Furthermore, the integration of dynamic geometry software [32], educational games [33], and digital learning environments can facilitate the development of mathematical reasoning skills by offering interactive functions, multimedia content, and metacognitive feedback to students [34].

Digital media not only enhance students' engagement and motivation but also support their reasoning processes, including formulating questions, testing generalizations, and justifying mathematical conjectures [35]–[37]. Incorporating digital media in mathematics education can also improve students' problem-solving abilities, decision-making skills, and reflective reasoning processes. By utilizing technology-based learning media like Geogebra, digital games, and virtual mathematics kits, educators can create a conducive learning environment that encourages students to think critically, apply mathematical concepts, and enhance their mathematical reasoning proficiency [8], [28], [38]. Overall, the strategic use of digital media technology in mathematics education can significantly contribute to the enhancement of students' mathematical reasoning abilities, providing them with the necessary tools and resources to succeed in their mathematical learning journey.

However, there is substantial heterogeneity among the studies ($Q = 1089.8704$, $df = 17$, $p < 0.0001$, $I^2 = 98.44\%$), which supports the use of the random-effects model. The presence of heterogeneity suggests that the effectiveness of digital media may vary across different contexts, and further exploration of potential moderators is warranted to explain this variability. For this reason, subgroup analysis is required.

3.2. Subgroup Analyses

Subgroup analyses were conducted to explore potential sources of heterogeneity (Table 3). The effectiveness of digital media varied significantly across different mathematical content areas ($Qb = 237.2527$, $df = 5$, $p < 0.0001$) and educational levels ($Qb = 73.0728$, $df = 2$, $p < 0.0001$), but not across sample sizes ($Qb = 0.0050$, $df = 1$, $p = 0.9435$).

Table 3 Subgroup Analysis

Subgroup	Qb	df	p-value
Content	237.2527	5	< 0.0001
Educational Level	73.0728	2	< 0.0001
Sample Size	0.0050	1	0.9435

To analyze the subgroup effects based on the provided categories (content, educational level, and sample size), we will use the Q-statistic, which is partitioned into Q-between (Qb) and Q-within (Qw) for each subgroup analysis.

3.2.1. Mathematical Content Subgroup Analysis

Table 4 Content Subgroup Analysis

Category	Q	df	p-value
Content	237.2527	5	< 0.0001
Number	93.5331	4	< 0.0001
Statistics	0	0	1
Logic	1.4104	1	0.2351
Geometry	173.3929	5	< 0.0001
Multiple material	0	0	1
Algebra	1.7860	1	0.1814

The significant Qb (237.2527, df = 5, p < 0.0001) indicates that the effect sizes differ across the subgroups of content. The significant Qw values for Number and Geometry suggest heterogeneity within these subgroups. Overall, the utilization of digital media has a significant impact, particularly in terms of the differences in subject matter.

The use of digital media in geometry learning can enhance the understanding of complex geometric concepts [39]. Furthermore, utilizing dynamic geometry programs and interactive virtual representations in digital resources has been found to boost student achievement in solving geometric problems, emphasizing the importance of visual representations in geometry learning [40] . Moreover, the need for interactive multimedia learning based on guided inquiry in geometry material has been highlighted to enhance students' problem-solving abilities in geometry, emphasizing the necessity for creative and effective educational innovations in digital media for mathematics [41]. Lastly, the use of virtual and augmented reality technologies in teaching geometry has been recognized as a promising approach to stimulate visualization and create an engaging learning environment for students, especially in the context of training future mathematics teachers [42].

Digital resources offer interactive features, multimedia elements, and game-based methods that engage students, improve understanding, and increase interest in numerical concepts. Additionally, the development of digital multimedia materials has shown positive effects on enhancing their number sense and cognitive competence [43]. By integrating digital media into educational practices, educators can create a more dynamic and effective learning environment that fosters numeracy literacy, boosts student engagement, and ultimately enhances mathematical proficiency for students of all ages [44].

3.2.2. Educational Level Subgroup Analysis

The significant Qb (73.0728, df = 2, p < 0.0001) indicates that the effect sizes differ across the subgroups of level. The significant Qw values for Primary and Secondary suggest heterogeneity within these subgroups. The use of digital media in mathematics education has a significant impact, especially across different educational levels. For each level, digital media is suitable for primary and secondary education but not for higher education. The use of digital media at the primary and secondary levels can foster motivation among students [45]–[47] and students' interest [29], [48]. On the other hand, several studies show that students with high motivation to learn mathematics have better reasoning skills [49], [50]. Additionally, students prefer concrete visual objects compared to abstract learning media [8], [14], [51].

Table 5 Educational Level Subgroup Analysis

Category	Q	df	p-value
Level	73.0728	2	< 0.0001
Primary	54.7435	3	< 0.0001
Secondary	439.7237	12	< 0.0001
Higher	0.2428	1	0.6221

3.2.3. Sample Size Subgroup Analysis

Table 6 Sample Size Subgroup Analyses

Category	Q	df	p-value
N	0.0050	1	0.9435
< 33	301.2423	9	< 0.0001
> 33	788.6230	7	< 0.0001

The non-significant Qb (0.0050, df = 1, p = 0.9435) indicates that the effect sizes do not differ significantly between the subgroups of N (< 33 and > 33). However, the significant Qw values for both subgroups suggest heterogeneity within each subgroup. The effectiveness of using digital media in enhancing students' reasoning abilities is not influenced by the number of students. Digital media can accommodate all students simultaneously [34], [47], whether in small or large numbers, as well as student diversity. Therefore, the use of digital media can create inclusive learning [52].

3.3. Publication Bias

Analyzing publication bias is essential to ensure research findings are accurate and comprehensive, including both significant and non-significant results. It boosts the credibility and reliability of scientific research by promoting transparency. Addressing publication bias provides a balanced evidence base for better decision-making, identifies research gaps, and ensures robust meta-analyses, leading to a more thorough understanding of the topic. The funnel plot suggests potential publication bias, with smaller studies reporting larger effect sizes.

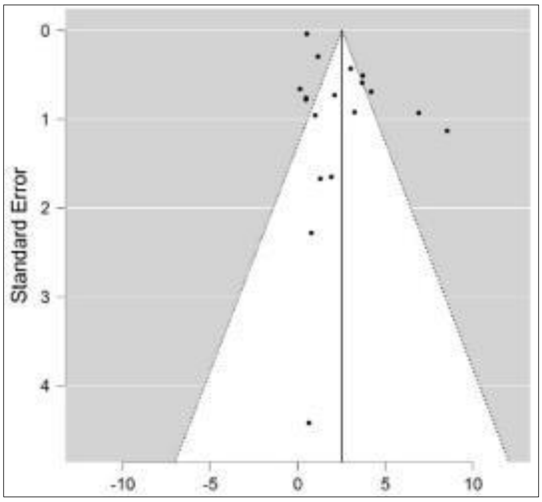

Figure 3 Funnel Plot

The preliminary analysis of Figure 2 indicates an asymmetry, necessitating further testing using Egger's test as presented in the following table.

Table 7 Egger's Test

	z	**p**
sei	0.023	0. 982

The p-value of 0.982 indicates that there is no statistically significant evidence of funnel plot asymmetry. This suggests that publication bias is unlikely to be a concern in this analysis. Egger's test for funnel plot asymmetry does not show significant asymmetry ($p > 0.05$), meaning the effect sizes are symmetrically distributed. A symmetrical funnel plot provides confidence that the meta-analysis results are robust, unbiased, and reliable. It suggests that the conclusions drawn from the meta-analysis are likely to reflect the true effect size and can be trusted for making informed decisions and policy recommendations based on the synthesized evidence.

4. Conclusion

This meta-analysis provides strong evidence for the effectiveness of digital media interventions in enhancing mathematical reasoning skills across various educational settings. The very large overall effect size indicates that digital media can be a powerful tool for improving students' ability to reason mathematically. However, the significant heterogeneity among studies highlights the importance of considering the specific context, content area, and educational level when designing and implementing digital media interventions.

The findings have important implications for educational policy and practice. Educators and policymakers should consider incorporating digital media interventions into mathematics curricula, while researchers should continue to investigate the factors that influence their effectiveness and explore innovative approaches to maximize their impact like learning model, strategies, duration to use digital media, and learning approach.

Compliance with ethical standards

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Disclosure of conflict of interest

The author declares no conflict of interest with any parties involved in this research. This study was conducted independently and objectively without any external influence that could affect the research outcomes.

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