# When Math Meets Play: A Meta-Analysis of Digital Game-Based Learning Effectiveness

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**Abstract.** Digital game-based learning (DGBL) is an increasingly popular approach in K-12 education. While previous research has demonstrated the positive impact of DGBL on student learning outcomes, research specifically examining how different mathematics content areas affect DGBL effectiveness is scarce. This research employs a meta-analysis to evaluate the overall effectiveness of digital game-based learning on the mathematics learning outcomes of K-12 students, based on effect sizes from 15 studies published between 2018 and 2025. The analysis also investigates how the type of mathematics content moderates the effects of DGBL. Findings show that the effectiveness of DGBL depends on the content area, with algebra and ratio demonstrating greater gains compared to geometry, fractions, and arithmetic. These findings can help educators design more effective DGBL experiences and choose appropriate content areas for this approach.

**Keyword:** digital game-based learning; elementary school; mathematical content; meta-analysis

## INTRODUCTION

Digital Game-Based Learning (DGBL) has emerged as a promising and increasingly adopted approach in education, particularly at the K-12 level (Kindergarten through 12th grade) (C. C. Chen & Huang, 2020; Ilić et al., 2024). The integration of game elements into the learning process offers an engaging and interactive way to enhance student motivation, involvement, and, ultimately, learning outcomes (Nguyen-Viet & Nguyen-Viet, 2023). DGBL harnesses the inherent appeal of digital games to create engaging and relevant learning environments for today's students (Bertram, 2020). This makes DGBL a potentially valuable strategy for improving learning across educational levels.

Various studies have highlighted the potential of Digital Game-Based Learning (DGBL) in enhancing various aspects of learning (Bertram, 2020; H. L. Chen & Wu, 2023; Gui et al., 2023; Tahir & Wang, 2024). These studies generally indicate a positive impact of DGBL on knowledge acquisition, the development of cognitive skills, and the improvement of students' attitudes towards specific subjects (Chin & Chen, 2023; Manzano-León et al., 2024; Tadiboyina et al., 2023). DGBL offers flexibility in delivering material (Pontes et al., 2020), allowing students to learn at their own pace and receive instant feedback (Kahyaoğlu Erdoğmuş & Kurt, 2023), which can help reinforce concept understanding. Therefore, many researchers have explored the effectiveness of DGBL in various fields.

While evidence supporting the effectiveness of Digital Game-Based Learning (DGBL) continues to mount, a deeper understanding of the factors influencing its successful implementation is still needed (Imlig-Iten & Petko, 2018). However, the interaction between different types of curriculum content and DGBL effectiveness needs further investigation. It's likely that not all content is equally suitable for digital game-based delivery.

This research aims to address this knowledge gap by conducting a meta-analysis of studies published between 2018 and 2025, investigating the effectiveness of Digital Game-Based Learning (DGBL) on learning outcomes for K-12 students. Specifically, this study will explore the role of curriculum content type as a moderator variable in the relationship between DGBL and learning outcomes. By analyzing effect sizes from different studies, this research aims to provide a more detailed understanding of the conditions that optimize DGBL effectiveness and identify the content areas most appropriate for this approach. The findings of this research are expected to provide evidence-based guidance for educators and educational game developers in designing and implementing DGBL experiences that significantly improve learning outcomes for K-12 students.

## METHOD

To identify the studies that would be used in this meta-analysis, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed (Alotaibi, 2024; Moher et al., 2009). PRISMA offers a standardized methodology, widely accepted by experts, that includes a guideline checklist.

### Literature Search

The articles analyzed were published in the Scopus database and focused on digital game-based learning in mathematics education for K-12 students. Articles were searched for in the Scopus database. The search terms used encompassed synonyms for digital game-based learning, mathematics learning, and learning outcomes. These terms were used in both free-text and subject heading searches to ensure that all relevant studies were found. Furthermore, the search was limited to articles published between 2018 and 2025, with English as the language of publication, and targeting kindergarten, elementary, and secondary (K-12) students.

Figure 1 shows the PRISMA flow diagram (Moher et al., 2009), illustrating the results of the literature search and article selection process. The diagram details the number of articles identified, included, and excluded at each stage of the review. The PRISMA flow diagram illustrates the study selection process for a systematic review. Initially, study identification was conducted using the Scopus database, yielding 929 records, and from registers, no records were found. Following the removal of 173 duplicate records, 756 records were screened based on title and abstract, resulting in the exclusion of 578 records due to irrelevance. Subsequently, 178 reports were assessed for eligibility, and 163 reports were excluded for various reasons, including inaccessible reports, publications outside the 2018-2025 timeframe, non-English language works, unsuitable topics, or non-final publication stages. Ultimately, only 15 studies met the eligibility criteria and were included in the systematic review. No additional study reports were included. The 15 articles include Pan & Ke (2023); Arztmann et al.,(2023); Demirel & Karakus Yilmaz (2019); Kim et al., (2017); Gresalfi et al.,(2018); Mercimek et al.,(2020); H. K. Lee & Choi (2020); Liu et al.,(2021); J. E. Lee et al., (2022); C. H. Chen et al.,(2023); K. F. Chen et al., (2024); K. H. Yang et al., (2025); Wu et al., (2025); Hilz et al., (2023); Ke et al., (2019); Ke & M. Clark (2020).

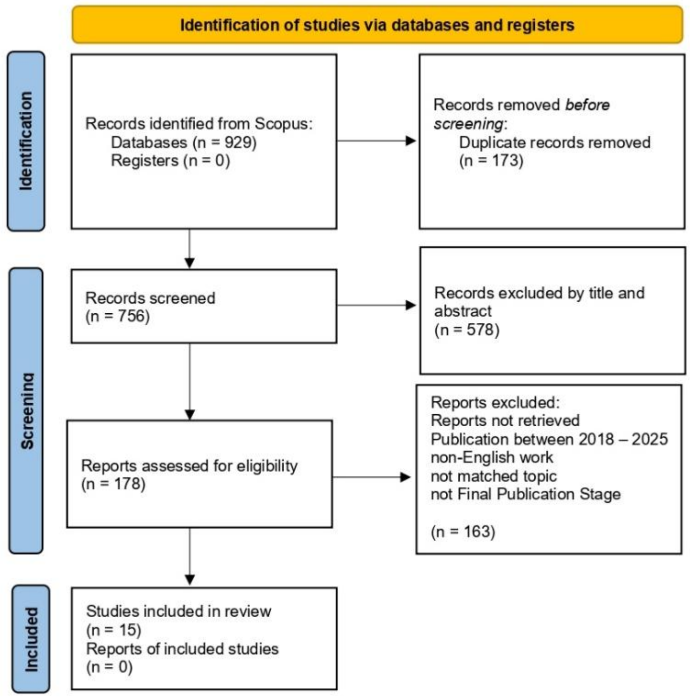


**FIGURE 1.** PRISMA diagram

## Coding of Study Characteristics and Moderator Variables

First, we coded basic information from the research, specifically general study information (e.g., authors, year of publication), educational context features (e.g., academic domain), and methodological characteristics (e.g., type of control group). Next, we coded information needed to calculate effect sizes, including learning outcome variables and statistical data such as the number of participants, means, and standard deviations. Outcome variables were coded as learning outcomes (e.g., learning achievement). Material type variables included detailed information on the type of mathematics material (e.g., arithmetic, geometry, ratios, fractions) to aid in interpreting potential effects in moderator analyses. Research characteristics (e.g., journal type) were included to assess the effect of research quality on the outcomes. Each article provided the following information:

1. Publication details (title, author, year)
2. Type of material (e.g., geometry, arithmetic, etc.)
3. Learning outcomes (cognitive, skill-based, affective)
4. Data for calculating effect sizes (means, standard deviations, sample sizes, t-values, p-values, etc.)

## Criteria for Inclusion

The articles selected for analysis must adhere to the following inclusion criteria:

1. Focus on Digital Game-Based Learning (DGBL) Interventions: The study must investigate the effectiveness of digital game-based learning interventions on the mathematics academic performance of K-12 students, as measured by tests. Articles that do not address DGBL interventions in K-12 or do not include student mathematics academic achievement are excluded.
2. Peer-Reviewed Journal Publication and Date Range: The study must be published in a peer-reviewed journal from 2018 to 2025 and be available in English. Articles concerning secondary data analysis, literature reviews, conference papers, and book chapters are excluded from the selection process.

3. Experimental Design with Control and Experimental Groups: The study must employ an experimental design, including both a control group and an experimental group.
4. Independent Control Group: Studies must utilize an independent control group. The comparison condition should not incorporate any form of self-regulation strategy, but may include traditional teacher-led classroom instruction, or instruction in an online or blended learning environment.
5. Diverse Learner Sample: The study must include all types of learners in the sample. Samples can range from kindergarten to secondary level, and from formal education systems to all types of informal education.
6. Quantitative Information for Effect Size Calculation: The study must provide the quantitative information necessary for the calculation or estimation of effect sizes.

## Calculation of The Effect Size

This meta-analysis was conducted using R-Studio software (Tamphu et al., 2024). Furthermore, Hedges' g was used to calculate the effect size (Brydges, 2019). Hedges' g was chosen over Cohen's d because differences in sample sizes across studies can affect effect size estimations. Hedges' g provides a more reliable estimation than Cohen's d for studies with smaller sample sizes (less than 20) (Cooper et al., 2009). Fifteen studies used a posttest-only control group design, where students were randomly assigned to experimental and control groups and assessed only after the intervention. According to Thalheimer & Cook's (2002) guidelines for interpreting effect sizes, the effect size is negligible if $-0.15 < g < 0.15$; small if $0.15 \leq g < 0.40$; medium if $0.40 \leq g < 0.75$; large if $0.75 \leq g < 1.10$; very large if $1.10 \leq g < 1.45$; and extremely large if $g \geq 1.45$. In addition, to test whether there is heterogeneity in the variation of effect sizes within the reviewed studies, Q and $I^2$ were evaluated.

## Publication Bias

Publication bias is assessed using funnel plots, Egger's regression intercept test, and the trim-and-fill method (Egger et al., 1997). Egger's regression intercept test uses a significant t-test to indicate asymmetry. When asymmetry is detected, the trim-and-fill method estimates the number of studies that should be removed, added, or trimmed from one side of the funnel plot to achieve symmetry in the remaining effect sizes.

# RESULT

## Effectiveness of Digital Game-Based Learning in K-12 Mathematics Education

The calculations performed using R-Studio yielded several findings relevant to the objectives. The results can be seen in Table 1.

**TABLE 1.** General Study Information

| Aspect | Value |
|---|---|
| Number of studies (k) | 15 |
| Number of observations (o) | 1125 |
| Observation of Experiment (o.e) | 565 |
| Control observation (o.c) | 560 |

This meta-analysis combines 15 studies with a total of 1,125 participants (Table 1). The experimental group comprised 565 participants, while the control group comprised 560, indicating a near balance between the groups. This relatively large sample size increases the reliability of the meta-analysis.

**TABLE 2.** Results of the General Effect Model vs. Random Effect Model

| Model | SMD (Hedges' g) | 95% CI | z | p-value |
|---|---|---|---|---|
| Common effect model | 0.9150 | [0.7870; 1.0430] | 14.01 | < 0.0001 |
| Random effects model | 0.8374 | [0.5543; 1.1204] | 5.80 | < 0.0001 |

Table 2 presents the results of the effect size analysis (standardized mean difference or Hedges' g) from two models: the fixed-effect model (common effect model) and the random-effects model. For the fixed-effect model, the effect size obtained was 0.9150, with a 95% confidence interval ranging from [0.7870; 1.0430]. The z-test value was 14.01 with a p-value less than 0.0001, indicating that the effect size is statistically significant. Meanwhile, for the random-effects model, the effect size obtained was 0.8374, with a 95% confidence interval ranging from [0.5543; 1.1204]. The z-test value was 5.80 with a p-value less than 0.0001, also indicating that the effect size in the random-effects model is statistically significant. Overall, the analysis results demonstrate a positive and significant effect size in both the fixed-effect and random-effects models. According to Cohen's criteria (≥ 0.8), the treatment effect is large. This indicates that there is a substantial difference between the experimental and control groups in the analyzed studies. This suggests that DGBL is effective in improving mathematics learning outcomes for K-12 students.

**TABLE 3.** Heterogeneity

| Parameter | Value | 95% CI |
|---|---|---|
| $\tau^2$ (tau²) | 0.2370 | [0.0922; 0.6728] |
| $\tau$ (tau) | 0.4868 | [0.3036; 0.8203] |
| $I^2$ | 78.9% | [65.9%; 87.0%] |
| H | 2.18 | [1.71; 2.77] |

Based on Table 3, it can be seen that there is substantial heterogeneity among the analyzed studies. This is shown by the random-effects variance component estimate ($\tau^2$ = 0.2370, 95% CI [0.0922; 0.6728]) and the heterogeneity index ($I^2$ = 78.9%, 95% CI [65.9%; 87.0%]). The heterogeneity index value (H) of 2.18 with an interval [1.71; 2.77] also indicates significant variability among the studies, which cannot be explained solely by sampling differences. This means that other factors that may affect the effectiveness of DGBL on K-12 student learning outcomes need to be considered.

**TABLE 4.** Test The Differences Between Studies

| Q | df | p-value |
|---|---|---|
| 66.40 | 14 | < 0.0001 |

The significant Q test ($p < 0.0001$) showed in Table 4 indicates significant differences in effect sizes among the studies, suggesting substantial heterogeneity. Given this heterogeneity, the use of a random-effects model is more appropriate because the assumption that the effect size is the same across all studies (homogeneity) is not met. The random-effects model allows for varying effect sizes between studies, thus providing a more accurate and representative estimate of the overall pooled effect.

## Publication Bias

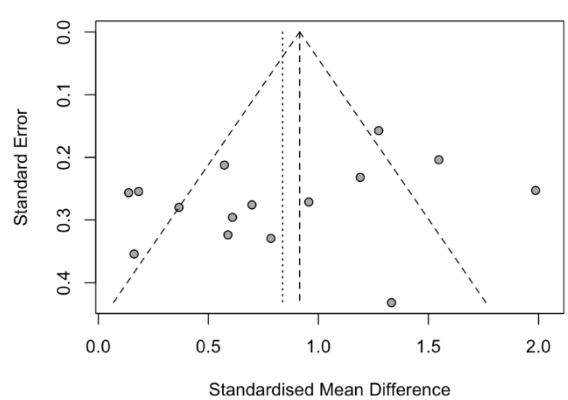


**FIGURE 2.** Funnel Plot

Publication bias was observed based on the funnel plot generated from the analysis. The results are illustrated in Figure 2, which shows a symmetrical funnel plot, indicating a low probability of publication bias.

## Moderator Analysis

Moderator analysis was conducted to determine whether the type of learning content influences the effectiveness of digital game-based learning in improving mathematics learning outcomes for K-12 students. The results of the analysis can be seen in Table 5.

**TABLE 5.** Subgroup Difference Test

| Model | Q | df | p-value |
|---|---|---|---|
| Random effects | 13.73 | 4 | 0.0082 |

The random-effects ANOVA reveals a significant difference between content areas ($Q = 13.73$, $df = 4$, $p = 0.0082$), indicating that the type of mathematics content moderates the effectiveness of the intervention. Therefore, the intervention's effect varies depending on the math content.

**TABLE 6.** Subgroup Analysis

| Content | k | SMD | 95% CI | $\tau^2$ | $\tau$ |
|---|---|---|---|---|---|
| Ratio | 3 | 1.0188 | [0.5935; 1.4441] | 0.0493 | 0.2221 |
| Geometry | 4 | 0.4333 | [0.1473; 0.7193] | 0 | 0 |
| Algebra | 2 | 1.6029 | [0.9065; 2.2994] | 0.2097 | 0.4579 |
| Arithmetic | 4 | 0.8478 | [0.2582; 1.4375] | 0.2983 | 0.5462 |
| Fractional | 2 | 0.4644 | [0.1074; 0.8214] | 0 | 0 |

Table 6 presents the analysis results of the effect size (standardized mean difference or SMD) for various types of learning content: ratio, geometry, algebra, arithmetic, and fractions. For ratio content, the effect size obtained was 1.0188 with a 95% confidence interval [0.5935; 1.4441]. The estimated variance of the random component ($\tau^2$) was 0.0493, with its square root ($\tau$) being 0.2221. This indicates relatively small heterogeneity among the studies on ratio content. For geometry content, the effect size was 0.4333 with an interval [0.1473; 0.7193]. The estimated variance of the random component ($\tau^2$) and its square root ($\tau$) were 0, indicating no substantial heterogeneity among the studies on geometry content.

For algebra content, the effect size obtained was 1.6029 with an interval [0.9065; 2.2994]. The estimated variance of the random component ($\tau^2$) was 0.2097, with its square root ($\tau$) being 0.4579. This indicates considerable heterogeneity among the studies on algebra content. For arithmetic content, the effect size was 0.8478 with an interval [0.2582; 1.4375]. The estimated variance of the random component ($\tau^2$) was 0.2983, with its square root ($\tau$) being 0.5462. This indicates considerable heterogeneity among the studies on arithmetic content. Finally, for fractions content, the effect size obtained was 0.4644 with an interval [0.1074; 0.8214]. The estimated variance of the random component ($\tau^2$) and its square root ($\tau$) were 0, indicating no substantial heterogeneity among the studies on fractions content. Overall, there is variation in effect sizes and levels of heterogeneity among the various types of learning content analyzed. Algebra and ratio content demonstrated the largest effect sizes compared to the other areas.

# DISCUSSION

This meta-analysis shows that DGBL has a positive and significant effect on mathematics learning outcomes for K-12 students. The combined effect size, obtained using both fixed-effect and random-effect models, falls into the large category. This finding aligns with prior research indicating the positive impact of DGBL on knowledge acquisition and skills development (Mtebe & Christina, 2024). In addition to increasing student motivation and engagement, digital learning games can effectively improve learning outcomes and efficiency (Y. Yang et al., 2024). The interactive nature of these games, with their diverse visuals and technology-based features, can improve student understanding of the material (Alipova et al., 2024). Abstract mathematical concepts can be easier to understand when presented in concrete ways, such as through digital games (Al-Barakat et al., 2025). In essence, the results of this analysis reinforce existing findings, confirming the positive influence of DGBL on student learning outcomes across various grade levels.

Further analysis reveals that the type of mathematics learning content significantly moderates the effectiveness of DGBL. Specifically, the effectiveness of digital game-based learning in improving learning outcomes is dependent on the type of material being presented. Because each type of content has different characteristics and structures, tailored strategies are needed for each (Gresalfi et al., 2018). The findings also indicate that DGBL is more effective for teaching concepts in algebra and ratio. Algebra is considered a challenging subject due to its abstract nature, which uses symbols or letters (variables) to represent unknown numbers or values (Hulse et al., 2019). Its highly abstract nature benefits from tools that can depict the concepts in a concrete way (Vanacore et al., 2023). Algebra is considered a complex subject that can potentially cause cognitive overload, thus requiring strategies to reduce cognitive load during teaching (Gupta & Zheng, 2020). In addition to algebra, ratio concepts also present complexity and abstractness.

Ratio concepts rely on symbolic representation and understanding relationships, making them abstract and challenging for many K-12 students (Pan & Ke, 2023). Games can display graphs, animations, or object manipulations, which help students associate mathematical symbols with concrete representations (Vanacore et al., 2023). Therefore, the effectiveness of DGBL is not uniform across all mathematical domains, but rather depends on the extent to which game-based elements can address the specific cognitive challenges associated with each content area, making it particularly advantageous for subjects like algebra and ratio that require a strong grasp of abstract concepts.

## CONCLUSION

This meta-analysis demonstrates that digital game-based learning (DGBL) has a positive and significant effectiveness in improving mathematics learning outcomes for students in elementary and middle school (K-12). The combined effect size obtained falls into the large category, indicating a substantial impact of using DGBL in mathematics learning. Further analysis reveals that the type of mathematics learning content significantly moderates the effectiveness of DGBL. DGBL proves more effective for teaching algebra and ratio material compared to geometry, fractions, and arithmetic material. Algebra and ratio material, which tends to be more abstract and complex, appears to be conveyed more effectively through digital game formats, which can help students visualize and understand these concepts.

These findings offer evidence-based guidance for educators and game developers to design and implement DGBL experiences that significantly improve mathematics learning outcomes for K-12 students. By focusing on the math content best suited for DGBL, teachers and developers can create more effective and engaging learning activities, potentially improving student understanding and achievement in mathematics.

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