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Impact of Digital Game-Based Learning on STEM education in Primary Schools: A meta-analysis of learning approaches

Impacto del Aprendizaje Basado en Juegos Digitales en la educación STEM en las escuelas primarias: Un meta-análisis de enfoques de aprendizaje

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ABSTRACT

Enhancing learning outcomes in Science, Technology, Engineering, and Mathematics (STEM) subjects for primary school students remains a challenge. This meta-analysis, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), explores Digital Game-Based Learning (DGBL) interventions as a potential solution. Eighteen empirical studies published from 2010 to 2020 were analyzed to identify effective DGBL approaches. Key factors examined include subject disciplines, control treatment, game type, platforms, and intervention duration. Findings reveal significant positive effects of DGBL interventions on learning outcomes, particularly in mathematics, language, and science. The study underscores the importance of optimizing gameplay design and platform choices for DGBL effectiveness and highlights the potential benefits of incorporating DGBL into primary STEM education. Future research should further investigate contributing factors like game genres, technologies, implementation strategies, and specific game components to promote optimal learning processes in diverse educational settings.

KEYWORDS Digital Game-Based Learning; gamification; learning achievement; meta-analysis; primary education; STEM education.

RESUMEN

Mejorar los resultados de aprendizaje en las materias de Ciencias, Tecnología, Ingeniería y Matemáticas (STEM) para los estudiantes de primaria sigue siendo un desafío. Esta meta-análisis, guiada por las Directrices de Elementos Preferentes para las Revisiones Sistemáticas y Meta-Análisis (PRISMA), explora las intervenciones de Aprendizaje Basado en Juegos Digitales

(ABJD) como una posible solución. Se analizaron dieciocho estudios empíricos publicados entre 2010 y 2020 para identificar enfoques efectivos de ABJD. Se examinaron factores clave, como las disciplinas de las materias, el tratamiento de control, el tipo de juego, las plataformas y la duración de la intervención. Los hallazgos revelan efectos positivos significativos de las intervenciones de ABJD en los resultados de aprendizaje, particularmente en matemáticas, lenguaje y ciencias. El estudio subraya la importancia de optimizar el diseño del juego y las opciones de plataforma para la efectividad del ABJD y destaca los posibles beneficios de incorporar el ABJD en la educación STEM de primaria. Las investigaciones futuras deberían investigar más a fondo los factores contribuyentes, como géneros de juegos, tecnologías, estrategias de implementación y componentes específicos del juego para promover procesos de aprendizaje óptimos en diversos entornos educativos.

PALABRAS CLAVE Aprendizaje Basado en Juegos Digitales; gamificación; rendimiento de aprendizaje; meta-análisis; educación primaria; educación STEM.

1. INTRODUCTION

1.1. The Role of DGBL in STEM Education

In the digital age, the integration of technology in education has become more widespread (Bai et al., 2020). STEM education is crucial for equipping students with essential skills for the future workplace (Arztmann et al., 2023). DGBL offers an interactive and engaging way to explore STEM concepts (Gui et al., 2023; Onyekwere & Hoque, 2023), addressing the growing demand for skilled professionals in this sector (Borenstein et al., 2021; Gao et al., 2020; Li et al., 2019). Developing STEM education is vital for unlocking students' career prospects (Oguguo et al., 2023; Wang et al., 2022).

Although the interdisciplinary nature of STEM subjects poses challenges to their comprehension (Corredor et al., 2014; Homer et al., 2020; Sedig, 2008; Yu et al., 2024), DGBL helps mitigate these issues by blending interactive elements with engaging gameplay (Connolly et al., 2012; Guan et al., 2024; Squire, 2006). Various game types, including simulation, role-playing, strategy, and puzzle games, cater to diverse learning preferences and styles (Kiili, 2005; Wouters et al., 2013).

DGBL serve as powerful tools that promote cognitive, social, and emotional growth (Guan et al., 2024; Habgood & Ainsworth, 2011; Papastergiou, 2009) by merging fun and learning to motivate learners (Garris et al., 2002; Gee, 2003; Guan et al., 2024). Their effectiveness in addressing challenges associated with STEM learning is evident as they enable understanding of complex concepts and develop problem-solving skills (Plass et al., 2015; Yu et al., 2024; Chu & Chang, 2014). DGBL encourages students to envision real-life problems, fostering cognitive preparedness and promoting intellectual engagement (Hwang et al., 2016; Prakasha et al., 2024). Endorsed by the National Science Foundation (Borgman et al., 2008; Wang et al., 2022), DGBLs are recognized as an innovative approach for learning in various STEM fields.

1.2. Evaluating the Impact of DGBL on STEM Education in Primary Schools

There is an ongoing debate regarding the definition and effectiveness of DGBL in primary education, particularly concerning their impact on STEM learning outcomes. While some scholars view DGBL as a type of play that generates unconscious learning (Shaffer, 2006; Haidar, 2024), others argue that it involves integrating gaming elements, such as points, rewards, or competition, into the teaching process (Al-Azawi et al., 2016; Chiappe et al., 2020). This study considers the latter perspective, recognizing gamification as one of the game genres (Chang & Hwang, 2019).

Studies on DGBL have yielded mixed results, with some indicating positive effects on satisfaction, attitudes (Sung & Hwang, 2013), knowledge tests (Erhel & Jamet, 2013), and skills (Qian & Clark, 2016). However, other studies question their effectiveness in theoretical framing (Wu et al., 2012), learning strategy integration (Charsky & Ressle, 2011), and learning objective setting (Sung & Hwang, 2013). Researchers emphasize that appropriate and theoretically sound learning mechanisms are essential for the effectiveness of DGBL in primary STEM education (Chang & Hwang, 2019; Kickmeier-Rust et al., 2008). To confidently incorporate DGBL into their instruction, educators require evidence-based strategies and exemplary cases. By examining these versatile and advantageous methods, teachers can harness the potential of DGBL to enhance STEM learning outcomes and contribute to the ongoing discourse on their effectiveness in primary education.

1.3. The Need for Assessing DGBL in Primary STEM Education

Despite extensive research on the effectiveness of DGBL technology in STEM education at various levels, there is a scarcity of literature specifically examining the impact of DGBL on promoting STEM learning outcomes in primary education (Huang et al., 2019). Existing studies have produced inconsistent results, with some suggesting negative effects on children's concentration and learning rate in STEM subjects (Videnovik et al., 2023), while others indicate positive influences on children's learning pace (Hung et al., 2014).

Although some studies propose that DGBL can enhance mathematical knowledge, reduce anxiety, and boost motivation among children (Hayati & Behnamnia, 2023; Hung et al., 2014), it is essential to acknowledge the lack of substantial evidence regarding their impact on students' academic progress (Arztmann et al., 2023; Giannakos, 2013; Khan et al., 2017). The findings on the influence of DGBL on early learners' STEM learning outcomes remain inconclusive. Consequently, educators face challenges in deciding whether to integrate DGBL into the preschool curriculum.

In this study, the authors focus on assessing the impact of DGBL on primary school students' learning outcomes in STEM subjects. The learning outcomes considered in the research include content knowledge, problem-solving skills, critical thinking, and motivation to learn. By examining the influence of DGBL on these outcomes, the authors aim to contribute to the ongoing discourse on the potential benefits and challenges of incorporating DGBL in primary STEM education. Assessing the effects of DGBL on the acquisition and dissemination of STEM knowledge in primary schools is crucial to provide guidance for educators seeking to optimize learning outcomes. A comprehensive understanding of the impact of DGBL on young learners will contribute to informed decision-making and the development of effective instructional strategies in primary STEM education.

1.4. Comparison between Previous DGBL Reviews and the Current Study

Previous research on the effectiveness of DGBL in STEM education has yielded mixed findings and focused primarily on specific aspects of game-based learning or individual games (Arztmann et al., 2023; Giannakos, 2013; Khan et al., 2017). These studies have offered valuable insights into the potential benefits and challenges associated with DGBL use. However, there remains a need for a comprehensive review that evaluates the broader impact of DGBL on primary school students' academic achievement in STEM education.

The present study aims to address this gap by providing an extensive meta-analysis of 18 academic studies, examining various moderator variables and their potential influence on learning outcomes. The study's focus extends beyond specific games or learning outcomes, offering a more holistic view of DGBL's impact in STEM education.

In comparison to previous reviews, this study considers a wider range of factors, including subject disciplines, control treatment, game type, platforms, and intervention duration, to provide a more comprehensive understanding of the complex interplay between these elements and their contributions to the overall impact of DGBL (Chang & Hwang, 2019; Hung et al., 2014; Qian & Clark, 2016). By expanding the scope of investigation, the current study seeks to offer educators and policymakers a more nuanced understanding of the potential benefits, challenges, and optimal conditions for the successful integration of DGBL in primary STEM education (Behnamnia et al., 2023; Romero & Barma, 2015; Zheng et al., 2024).

2. LITERATURE REVIEW

This section presents a comprehensive analysis of the existing literature on the impact of DGBL on STEM education for primary school students. The synthesis of findings from various studies endeavors to identify patterns, gaps, and trends in the field. This serves to contextualize the current study, which provides a comprehensive analysis of all subject fields in STEM, addressing gaps in existing research and contributing to a more holistic understanding of the role digital educational games play in shaping learning outcomes.

Several studies have investigated the potential benefits of DGBL for enhancing learning outcomes in STEM subjects. Tokac et al. (2019) explored the effects of game-based learning on primary school students' mathematics achievement and found positive influences on learning pace. Similarly, Gao et al. (2020) conducted a meta-analysis and concluded that educational computer games could improve students' learning performance in science and mathematics (Gao et al., 2020).

Research on DGBL has also considered their impact on students' motivation and engagement. For instance, Wu et al. (2012) reappraised game-based learning based on educational theory, emphasizing its potential for fostering learners' motivation and learning outcomes (Wu et al., 2012). Additionally, Qian & Clark (2016) examined the relationship between game-based learning and the development of 21st-century skills, highlighting the positive effects of digital games on students' collaboration, communication, and problem-solving abilities (Qian & Clark, 2016).

Despite these promising findings, some studies have reported mixed results or raised concerns about the effectiveness of DGBL in promoting academic achievement. Niemeyer (2006) suggested negative effects on children's concentration and learning rate in STEM subjects (Neimeyer, 2006), while others indicated that the impact of digital games on students' academic progress remains inconclusive (Arztmann et al., 2023; Giannakos, 2013; Khan et al., 2017).

Furthermore, several studies have focused on the importance of considering various game elements and contextual factors when evaluating the effectiveness of DGBL. For example, Chang & Hwang (2019) examined the effects of different game genres on learning performance (Chang & Hwang, 2019), while Gui et al. (2023) and Solanes et al. (2023) explored the potential of metaverse ecosystems and augmented reality in STEM education (Gui et al., 2023; Solanes et al., 2023).

In conclusion, the literature review demonstrates the complexity and heterogeneity of findings on the impact of DGBL on primary school students' STEM learning outcomes. While some studies suggest positive influences, others report mixed results or raise concerns about their effectiveness. The present study aims to address these inconsistencies by conducting a comprehensive meta-analysis of 18 academic studies, examining various moderator variables, and offering a more holistic view of the role of DGBL in primary STEM education.

3. META-ANALYSIS PURPOSE

This study aims to address the limitations and discrepancies found in previous research on Digital Game-Based Learning (DGBL) in primary STEM education. The research focuses on assessing the efficacy of utilizing DGBL in enhancing learning outcomes across STEM subjects. By examining key variables, such as subject disciplines, control treatment, game type, platforms, and intervention duration, the study aims to identify essential principles of effective DGBL design that contribute to learning progress. The following research questions guide this investigation:

1. Is DGBL more effective in improving learning outcomes compared to traditional teaching methods in primary STEM education?
2. Do students' learning outcomes differ based on the STEM subject discipline (Science or Mathematics) when using DGBL?
3. How does gameplay design (game type or game platform) impact learning outcomes in primary STEM education when employing DGBL?
4. What is the relationship between intervention duration and students' academic achievement in DGBL interventions?
5. Do control treatments (traditional teaching methods vs. multimedia or non-game-based interventions) influence the effectiveness of DGBL interventions in primary STEM education?

By addressing these research questions, this study intends to contribute to the existing body of knowledge on the use of DGBL in primary STEM education. It will help identify the most effective approaches and design principles for implementing DGBL in the classroom, thereby improving learning outcomes and informing educational policy and practice.

4. METHOD

Meta-analysis is a widely employed methodology for conducting quantitative and exhaustive analyses of prior research outcomes on a given topic (Glass et al., 1981). This statistical analysis approach enables systematic studies to address research questions more accurately by adhering to stringent screening criteria (Noble Jr, 2006). As a result, the meta-analysis method facilitates a more reliable examination of independent studies within a systematic review, ensuring greater precision and validity of research results. By reconciling discrepancies arising from conflicting experimental experiences, meta-analysis generates more meaningful and robust outcomes (Paré et al., 2015). Consequently, this study adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method to maintain rigor and transparency in the research process (Moher et al., 2010; Moher et al., 2015).

4.1. Sources and strategy of data collection

In order to gather relevant information for this study, a thorough search was conducted across various online sources, such as journal collections and websites like Web of Science, ERIC, JSTOR, ESCBO, Science Direct, IEEE Xplore, Springer, Scopus, and Wiley. To further expand the search scope, the Google Scholar search engine was also utilized to cover more studies. The eligibility criteria for selecting studies included publications from 2010 to 2020, written in English.

4.1.1 Rationale for Journal Selection and Time Range

The selected journal was chosen for its relevance to the research topic, as it caters to an audience of researchers and practitioners in the fields of education and technology. The time range was chosen to capture recent advancements in digital game-based learning while ensuring the inclusion of studies that have informed current practices.

To facilitate an organized search process, three sets of keywords were defined, combined using Boolean operators (AND, OR). The first set of keywords aimed to establish the scope of DGBL, incorporating terms like “game,” “educational game,” “digital game,” and phrases such as “computer games,” “gamification,” “video games,” “simulation games,” “game-based learning,” “serious digital games,” and “teaching with games.”

The second set of keywords targeted STEM-related concepts, including “learning,” “education,” “science,” “technology,” “engineering,” “mathematics,” and “teaching.”

Finally, the third set of keywords focused on primary school education levels and was combined with the first and second sets of keywords. This set comprised terms such as “primary education,” “primary level,” and “primary school teaching.”

The keyword search was executed across various fields, including article titles, abstracts, and full-text content, to ensure a comprehensive and thorough coverage of relevant studies. This multi-faceted approach allowed for the identification of pertinent research articles that explored the impact of DGBL on teaching and learning outcomes in STEM subjects within the primary school setting. By examining and synthesizing these studies, a deeper understanding of the potential benefits and challenges of incorporating DGBL into the curriculum can be achieved, ultimately informing educators’ decisions on effective teaching strategies.

4.2. Literature Search and Eligibility Criteria

The literature search and eligibility criteria for this study concentrated on evaluating the effectiveness of DGBL interventions in primary STEM education in contrast to traditional teaching methods. Comparing these approaches was crucial for comprehending the impact of DGBL within the larger educational landscape. To facilitate this comparison, the search strategy and selection criteria intentionally incorporated conventional teaching methods as a reference point in the meta-analysis. The search strategy incorporated the following key elements:

- *Utilizing search terms related to traditional teaching approaches:* Keywords and phrases such as "conventional teaching," "traditional instruction," "non-digital learning," and "traditional teaching methods" were included to identify studies comparing DGBL interventions with conventional teaching practices.
- *Developing selection criteria for comparative studies:* To be considered for the meta-analysis, studies were required to compare the effectiveness of DGBL interventions with traditional teaching approaches. This entailed selecting studies featuring both an intervention group employing DGBL and a control group utilizing conventional methods.

By implementing a thorough search strategy and establishing clear selection criteria, the meta-analysis effectively captured relevant studies comparing DGBL interventions with traditional teaching approaches in primary STEM education. This approach enabled the analysis of DGBL's impact on learning outcomes and their potential benefits over conventional methods.

4.3. Including and excluding criteria

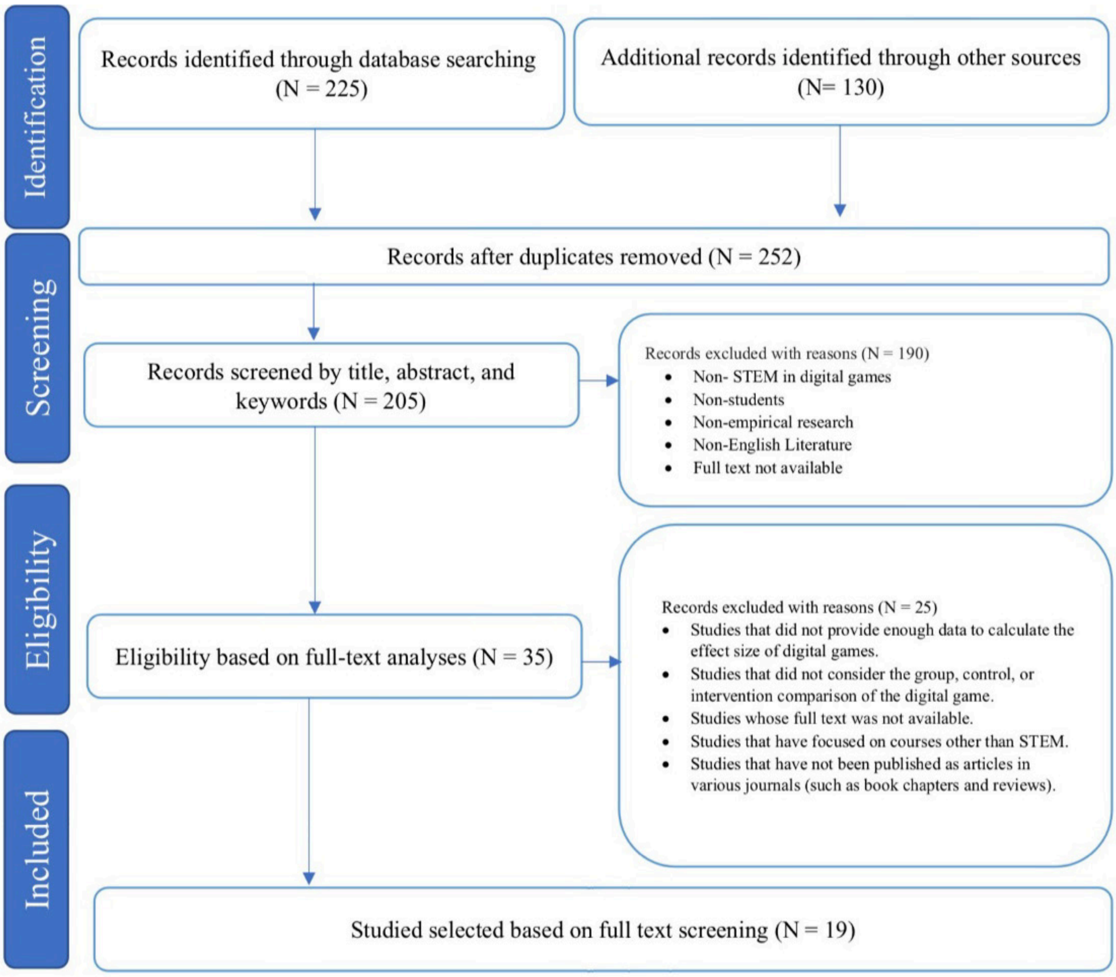
The entry and exit criteria are mentioned in Table 1 in order to find the questions of this research. Following the considering criteria, the research literature that satisfied the meta-analysis requirements of this study was included, while those that did not were omitted (see Table 1).

TABLE 1. Inclusion and Exclusion criteria in the meta-analysis used in this research

	INCLUSION CRITERIA IN THE META-ANALYSIS USED IN THIS RESEARCH (IC)
IC 1	Studies focusing on primary school level education.
IC 2	Studies written in English.
IC 3	Studies examining the impact of DGBL through group intervention and control/nonintervention group comparisons.
IC 4	Studies providing sufficient data to calculate the impact size of DGBL.
IC 5	Studies concentrating on STEM courses.
	EXCLUSION CRITERIA IN THE META-ANALYSIS USED IN THIS RESEARCH (EC)
EC 1	Studies lacking adequate data for calculating the effect size of DGBL.
EC 2	Studies without group comparisons, control groups, or digital game interventions.
EC 3	Studies with unavailable full-text versions.
EC 4	Studies focusing on non-STEM courses.
EC 5	Non-peer-reviewed studies or those published outside of academic journals (e.g., book chapters and reviews).

The data collection process in Figure 1 shows how the search, screening, and selection of qualified articles were done in this article. In the next step, 35 articles were examined for further review, and finally, 18 articles met the criteria for entering this meta-analysis (see Fig.1).

FIGURE 1. PRISMA flowchart for data collection



4.4. Meta-Analysis Approach

This study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method as the primary approach for conducting the meta-analysis. PRISMA is a widely recognized and accepted framework for performing and reporting systematic reviews and meta-analyses, emphasizing transparency, completeness, and rigor throughout the research process (Moher et al., 2010; Moher et al., 2015).

The PRISMA method was chosen for its systematic and comprehensive nature, making it particularly suitable for the research objectives of evaluating the effectiveness of DGBL interventions in primary STEM education. The approach enables a methodical and unbiased identification, selection, and evaluation of relevant studies, ensuring the reliability and generalizability of the findings.

The PRISMA method comprises several essential steps:

1. Define the research question and establish eligibility criteria for study inclusion and exclusion.
2. Conduct a comprehensive literature search using multiple databases and online sources.
3. Screen and select studies based on the predetermined eligibility criteria.
4. Extract relevant data from the selected studies and assess their quality.
5. Analyze the extracted data using appropriate statistical methods and techniques.
6. Interpret the results and draw conclusions based on the synthesized evidence.

By systematically following these steps, the PRISMA method allows for the assessment of the impact of DGBL interventions in primary STEM education, identification of potential gaps in the existing literature, and provision of insights into areas that require further investigation. In conclusion, the adoption of the PRISMA method ensures a thorough, transparent, and comprehensive approach to evaluating the effectiveness of DGBL interventions in primary STEM education.

4.5. Indicators of Moderation

Moderation indicators refer to specific characteristics in each study and their relationship with study results. These indicators cause variance in the effect size due to the variation in the outcomes of the studies. Common moderation indicators used in this study included subject disciplines, control treatment, game type, platforms, and intervention duration. These variables have also been employed in previous studies to determine the difference in effect size heterogeneity (Chen et al., 2018; Thompson & von Gillern, 2020; Zeng et al., 2020). To address the research questions, the following moderation indicators were coded (see Table 2).

TABLE 2. Moderator data in studies

Paper id	Sample size	Subject	Control treatment	Game type	Gaming platform	Intervention duration	Authors (year)
P 1	136	Science	Traditional	Tutorial Games	Computer	≥3 months	(Anderson & Barnett , 2011)
P 2	49	Science	Multimedia	Tutorial Games	Mobile	1 week–1 month	(Chen, 2020)
P 3	51	Science	Multimedia	Board Games	Mobile	<1 week	(Chen et al., 2016)
P 4	115	Science	Traditional	Immersive Games	Computer	1 month–3 months	(Chen et al., 2020)
P 5	53	Science	Multimedia	Immersive Games	Computer	<1 week	(Chu & Chang, 2014)
P 6	103	Mathematics	Traditional	Tutorial Games	Mobile	1 month–3 months	(van der Ven et al., 2017)
P 7	232	Science	Traditional	Immersive Games	Computer	1 month–3 months	(Hodges et al., 2020)
P 8	46	Mathematics	Traditional	Tutorial Games	Mobile	<1 week	(Hung et al., 2014)

Paper id	Sample size	Subject	Control treatment	Game type	Gaming platform	Intervention duration	Authors (year)
P 9	50	Science	Multimedia	Board Games	Computer	<1 week	(Hwang et al., 2012)
P 10	60	Science	Multimedia	Immersive Games	Computer	<1 week	(Hwang et al., 2013)
P 11	57	Science	Multimedia	Board Games	Mobile	<1 week	(Hwang et al., 2016)
P 12	61	Mathematics	Traditional	Immersive Games	Computer	1 month–3 months	(Ke, 2019)
P 13	132	Mathematics	Multimedia	Immersive Games	Computer	<1 week	(Kim & Ke, 2017)
P 14	62	Mathematics	Multimedia	Board Games	Computer	<1 week	(Lin et al., 2013)
P 15	185	Science	Multimedia	Immersive Games	Computer	<1 week	(Stege et al., 2012)
P 16	102	Science	Multimedia/ Traditional	Tutorial Games	Mobile	Not specified	(Su & Cheng, 2013)
P 17	36	Science	Traditional	Tutorial Games	Mobile	1 month–3 months	(Yallihep & Kutlu, 2020)
P 18	65	Mathematics	Traditional	Tutorial Games	Mobile	<1 week	(Zhang et al., 2020)

- Discipline of subject: Research investigating one of the STEM subjects was considered in line with the definition of the subject (Wahono et al., 2020). Based on the classification adopted in this study, the coding was categorized according to STEM disciplines, including science, mathematics, and technology or engineering. The analysis of the impact of DGBL on learning rate was conducted based on this coding.
- Control treatment: This study focused on whether DGBL are effective in promoting learning. In this context, the analysis based on control treatment was employed, which determines the extent of learning promotion through DGBL in comparison to non-digital game teaching methods. Control treatment has been regarded as a moderation index in past studies (Garzón & Acevedo, 2019; Merchant et al., 2014; Wouters et al., 2013). Two categories of coding, "traditional" and "multimedia," were utilized in the meta-analysis to analyze the moderation index in control treatment. Traditional education in classroom settings included the presence of teachers, textbooks with assignments, and real-world experimental experiments, while DGBL involving animation or lessons played on computers or other digital devices were coded as "multimedia."
- Game type: Games are typically divided into two categories: role-playing games (Li & Tsai, 2013) and non-role-playing games. DGBL encompasses eight categories: immersive games, educational games, training games, simulation games, adventure games, music games, board games, and alternative reality games (Hung et al., 2018). The framework for analyzing DGBL used in the studies is based on Hong et al.'s (2009) classification framework. The games identified in the reviewed studies consist of immersive games, tutorial games, and board games (Hong et al., 2009).

- Platforms: Common platforms include computers, mobile phones, touch tablets, gaming consoles (e.g., PlayStation or Xbox), and unidentified gadgets. Hardware types can influence how players learn in the game (Thompson & von Gillern, 2020). The most popular gaming platforms were selected based on reviews in the articles, which included PCs, mobile devices, and touch tablets.
- Intervention duration: The duration of an educational intervention, such as the use of DGBL, can influence the extent to which learning outcomes are achieved.
  - Shorter interventions, lasting less than one week, may lead to more immediate and targeted outcomes, such as the acquisition of specific content knowledge or the development of a particular skill. These interventions can be effective in reinforcing key concepts and engaging students in focused learning experiences.
  - Longer interventions, lasting more than three months, may provide more opportunities for learners to develop a deeper understanding of complex concepts and demonstrate higher-order thinking skills. These interventions can support the development of problem-solving strategies, critical thinking, and sustained motivation to learn. Intervention duration was coded based on the durations specified in the selected studies, following previous research (Bai et al., 2020; Chen et al., 2018). This coding comprised (a) <1 week, (b) 1 week to 1 month, (c) >1 month to 3 months, (d) >3 months, and (e) not specified.

4.6. Analysis of collected data

The study's focal point was the influence of DGBL on the acquisition of knowledge among primary school students. The study utilized Comprehensive Meta-analysis 3.0 software to compute impact size and ascertain moderating variables. The study's objective was to assess the efficacy of DGBL in contrast to non-digital educational games instruction, concentrating on determining the extent of the impact. The standardized mean difference was utilized to quantify the impact size. To evaluate study homogeneity, the Q statistic and I^2 value were utilized. The study's results indicated substantial heterogeneity, as suggested by a statistically significant Q statistic, which refuted the null hypothesis of homogeneity (Lipsey & Wilson, 2001). Borenstein et al. (2010) discovered that the random-effects model had a superior fit and suggested examining moderator variables (Borenstein et al., 2010). Hedges' (1982) method was utilized to determine ES(d) (Hodges et al., 2020).

$$\text{ES} = \frac{ME - MC}{\sqrt{\frac{(NE - 1)S_E^2 + (NC - 1)S_C^2}{(NE + NC - 2)}}}$$

The equation uses different variables to represent different aspects. ES represents the efficiency score of a specific entity, *ME* represents the mean efficiency score of all entities in the system, *MC* represents the marginal cost of production, *NE* represents the number of inputs used by the entity, S^2E represents the variance of inefficiencies in input, *NC* represents the number of outputs generated by the entity, and S^2C represents the variance of inefficiencies in output. This equation calculates the efficiency score of a particular entity by considering the mean efficiency of all entities, the marginal cost of production, the number of inputs and outputs, and the variances of inefficiencies in input and output. It is a useful tool for analyzing organizational efficiency in specific industries or contexts. In this study, *ME* and *MC* represent the estimated means of the experimental and control groups, respectively. *NE* and *NC* represent the sample sizes of these groups, and *S2E* and *S2C* represent their respective standard deviations.

4.7. Analysis of bias and variability in publications

Meta-analyses can be influenced by various biases, such as publication bias, where only positive outcomes are reported (Borenstein et al., 2010; Egger et al., 1997). To assess potential publication bias, this study employed the fail-safe value approach instead of the funnel plot technique. The fail-safe value method estimates the number of unpublished studies with null results needed to negate the observed effect, providing a quantitative measure of the robustness of meta-analytic findings (Rosenthal, 1979). The Begg and Mazumdar rank correlation test found no significant bias ($Z = 1.457 < 1.96$, $p = 0.145 > 0.05$), suggesting the absence of publication bias (Begg & Mazumdar, 1994). The traditional fail-safe N test was also employed, yielding a fail-safe value of 3001. This indicates that a substantial number of unpublished studies would be required to render the effect sizes insignificant, further supporting the absence of publication bias. Heterogeneity was evaluated using I^2 values. The I^2 test complements the Q-test, with values of 0%–25% indicating low, 25%–75% indicating moderate, and 75%–100% indicating substantial heterogeneity (Higgins et al., 2003). Significant heterogeneity was found ($p < 0.001$), necessitating the use of a random-effects model to account for variations in effect sizes across studies (Wang et al., 2020).

In this study, the fail-safe value was calculated as 83. This result suggests that 83 unpublished studies with null results would be needed to negate the positive outcomes reported in the meta-analysis, indicating a robust observed effect. Table 3 presents individual effect sizes, standard errors, variances, lower and upper limits, z-values, p-values, and overall effect sizes for each of the 18 studies included in the meta-analysis. All studies showed a large effect size, with p-values less than 0.05, except for studies P7 and P14. Despite these two studies having large effect sizes, their results are not statistically significant. Incorporating the fail-safe value in the analysis aimed to provide a transparent evaluation of potential publication bias, highlighting the robustness of the findings and contributing to the growing body of research on DGBL in primary STEM education (See Table 3 for more details).

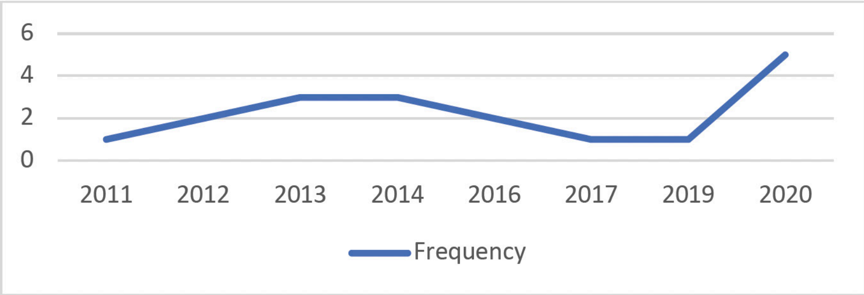
5. RESULTS

The 18 studies (P1-P18) examined DGBL in various primary STEM education contexts, focusing on subjects such as Science (11 studies) and Mathematics (7 studies). Control treatments included traditional teaching methods (9 studies) and multimedia/non-game-based interventions (remaining studies). Tutorial games were most commonly employed (9 studies), followed by immersive games (6 studies) and board games (3 studies). Platforms included computers (11 studies) and mobile devices (7 studies). Intervention durations ranged from short-term (<1 week; 8 studies) to medium-term (1-3 months; 4 studies) and long-term (>3 months; 3 studies). These studies offer insights into DGBL's efficacy in improving learning outcomes and its potential advantages over traditional teaching methods in primary STEM education.

5.1. Distribution of Studies Over Time

The reviewed studies demonstrated a gradual increase in DGBL research for primary STEM education, with a notable peak in 2020. Publication years ranged from 2011 to 2020, with the highest concentrations of studies in 2014 (3 studies) and 2020 (5 studies), indicating a growing interest and research field in this area (see Fig. 2).

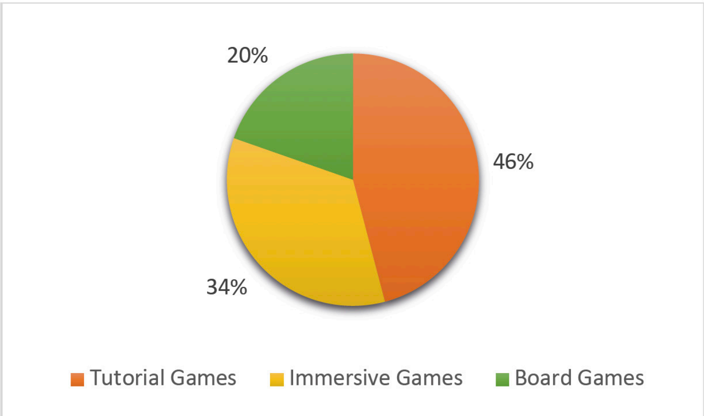
FIGURE 2. Number of published papers per year



5.2. Analysis of Game Types in DGBL Interventions

The studies reviewed predominantly employed tutorial games (44.4%; 8 studies) for DGBL interventions, likely due to their ability to provide guided instruction and enhance problem-solving skills in STEM subjects. Immersive games (33.3%; 6 studies) and board games (22.2%; 4 studies) were also utilized, reflecting diverse approaches to integrating DGBL in primary education (see Fig. 3).

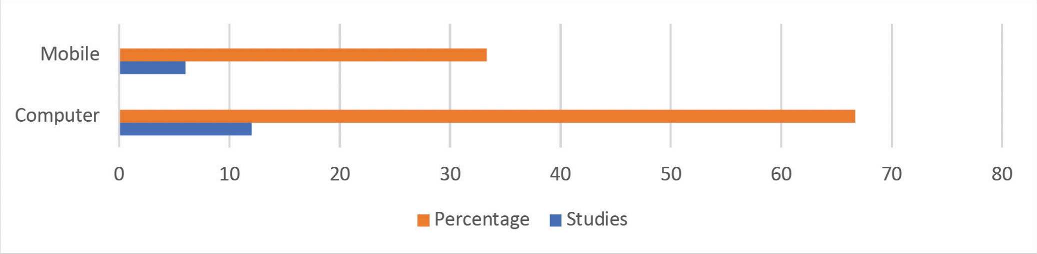
FIGURE 3. Pie Chart: Game Types



5.3. Analysis of Gaming Platforms in DGBL Interventions

The reviewed studies predominantly utilized computers (66.7%; 12 studies) as the gaming platform for DGBL interventions due to their versatility and functionality. However, mobile devices (33.3%; 6 studies) also demonstrated significant presence, reflecting a growing interest in leveraging portable and accessible technology for enhancing STEM learning among primary school students.

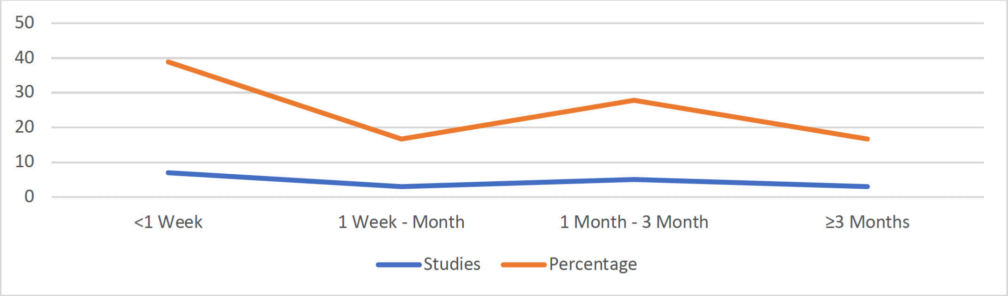
FIGURE 4. Gaming Platforms



5.4. Analysis of Intervention Duration in DGBL Studies

The studies primarily implemented short-term DGBL interventions (38.9%; 7 studies) due to factors like resource limitations and curriculum integration challenges. However, longer interventions (16.7%; 3 studies) were also present, acknowledging potential benefits of sustained DGBL engagement for enhancing primary school students' learning outcomes in STEM subjects. Intervention durations varied from less than one week to over three months (see Fig. 5).

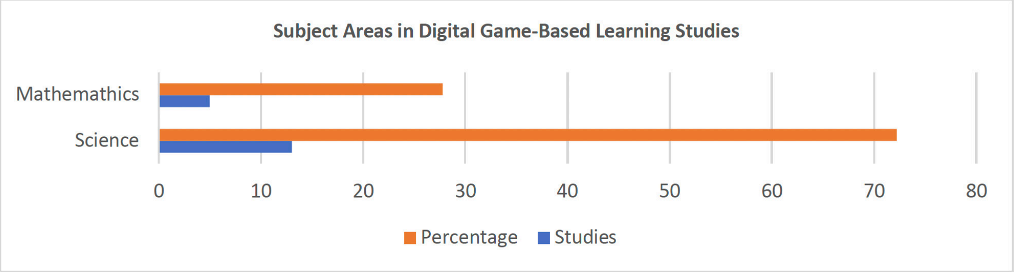
FIGURE 5. Intervention Duration



5.5. Analysis of Subject Areas in DGBL Studies

Most studies focused on using DGBL for Science subjects (72.2%; 13 studies), with fewer focusing on Mathematics (27.8%; 5 studies). This distribution highlights the preference for DGBL in Science education, likely due to its potential for integrating real-world phenomena through engaging game elements. Mathematics-focused interventions reflect DGBL's recognized value in promoting problem-solving skills and conceptual understanding in this key STEM subject (see Fig. 6).

FIGURE 6. Subject Areas in DGBL Studies



5.6. Findings of the study

This section discusses the findings of the study, addressing the following research questions:

5.6.1. The Impact of DGBL on STEM Learning in Primary Education

A meta-analysis of 18 studies (1595 participants) assessed DGBL's overall impact on students' learning outcomes, using Cohen's effect size criteria (Cohen, 2013). The weighted average of standardized differences in means across studies was 0.834 (standard error: 0.123), indicating a large effect size per Cohen's criteria. This suggests a significant positive impact of DGBL on primary school students' learning outcomes in STEM subjects. Table 3 summarizes the overall effect size and highlights DGBL's influence on learning outcomes in Mathematics, Science, and Language, supporting its integration in STEM education for enhancing primary school students' learning outcomes (see Table 3 for details).

TABLE 3. Random-effect model forest plot displaying all included effect sizes in the forest plot

Paper id	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-value	P-value	Effect size (cohen's d)	Authors (Year)
P 1	0.891	0.180	0.032	0.539	1.244	4.953	0.000	Large	(Anderson et al., 2011)
P 2	0.454	0.289	0.084	0.113	1.021	1.569	0.117	Medium	(Chen, 2020)
P 3	3.380	0.437	0.191	2.524	4.236	7.740	0.000	Large	(Chen et al., 2016)
P 4	0.554	0.190	0.036	0.182	0.927	2.916	0.004	Medium	(Chen et al., 2020)
P 5	0.854	0.287	0.082	0.291	1.416	2.975	0.003	Large	(Chu et al., 2014)
P 6	0.650	0.202	0.041	0.253	1.046	3.212	0.001	Medium	(van der Ven et al., 2017)
P 7	0.068	0.132	0.017	0.190	0.327	0.518	0.605	Small	(Hodges et al., 2020)
P 8	0.704	0.304	0.092	0.109	1.300	2.317	0.020	Medium	(Hung et al., 2014)
P 9	2.428	0.376	0.141	1.692	3.164	6.464	0.000	Large	(Hwang et al., 2012)
P 10	0.593	0.264	0.070	0.076	1.110	2.247	0.025	Medium	(Hwang et al., 2013)
P 11	0.517	0.270	0.073	0.011	1.046	1.919	0.055	Medium	(Hwang et al., 2016)
P 12	0.988	0.287	0.082	0.425	1.550	3.441	0.001	Large	(Ke, 2019)
P 13	1.161	0.188	0.035	0.792	1.529	6.168	0.000	Large	(Kim et al., 2017)
P 14	0.455	0.257	0.066	0.049	0.960	1.769	0.077	Medium	(Lin et al., 2013)
P 15	0.292	0.148	0.022	0.002	0.582	1.975	0.048	Small	(Stege et al., 2012)
P 16	0.758	0.261	0.068	0.246	1.270	2.902	0.004	Medium	(Su et al., 2013)
P 17	2.025	0.414	0.171	1.214	2.836	4.894	0.000	Large	(Yallihep et al., 2020)
P 18	0.451	0.251	0.063	0.041	0.944	1.796	0.073	Medium	(Zhang et al., 2020)

Note: Effect sizes are categorized as Small (d = 0.2), Medium (d = 0.5), and Large (d = 0.8) according to Cohen's (1988) criteria.

RESEARCH QUESTION 1: Is DGBL more effective in improving learning outcomes compared to traditional teaching methods in primary STEM education?

The meta-analysis of 18 studies, involving 1595 participants, revealed a significant positive impact of DGBL on primary school students' learning outcomes in STEM subjects. The overall large effect size (0.834, SE = 0.123) demonstrates the superiority of DGBL over traditional teaching methods. However, the individual study results varied, with 16 out of 18 studies showing statistically significant positive outcomes, while two studies reported nonsignificant effects. This variability underscores the importance of considering factors like game type, instructional design, and individual student differences when evaluating DGBL's effectiveness in primary STEM education.

5.6.2. The Impact of DGBL on Learning Outcomes Across STEM Subject Disciplines

RESEARCH QUESTION 2: Do students' learning outcomes differ based on the STEM subject discipline (Science or Mathematics) when using DGBL?

Research Question 2 explored the impact of DGBL on learning outcomes across STEM subject disciplines. The meta-analysis revealed significant differences in effect sizes among Mathematics, Science, and Language. Mathematics showed the strongest positive impact on students' learning outcomes (ES = 0.607, $p < 0.001$), followed by Language (ES = 0.740, $p < 0.001$), and Science (ES = 0.478, $p < 0.001$). No significant difference was found between studies in Science and Mathematics, suggesting that DGBL positively impacts both domains. Further details are available in Table 4 (See Table 4 for more details).

5.6.3. Impact of Gameplay Design on Learning Success

RESEARCH QUESTION 3: How does gameplay design (game type or game platform) impact learning outcomes in primary STEM education when employing DGBL?

Research Question 3 explored gameplay design's influence on learning outcomes in primary STEM education, examining game types and platforms. The meta-analysis showed significant effect size differences among game types, with board games having the largest effect size (ES = 0.658, $p < 0.001$). Immersive (ES = 0.483, $p < 0.001$) and tutorial games (ES = 0.646, $p < 0.001$) also demonstrated significant effects. The analysis suggested mobile devices and touch tablets positively impacted learning outcomes more than computers, though mixed findings indicated other factors might play a role (see Table 4).

5.6.4. Impact of Intervention Duration on Academic Attainment

RESEARCH QUESTION 4: What is the relationship between intervention duration and students' academic achievement in DGBL interventions?

Research Question 4 investigated the relationship between intervention duration and academic achievement in DGBL interventions. The results showed a significant impact of intervention duration on academic achievement, with brief interventions lasting less than one week demonstrating the strongest positive effect on learning outcomes (ES = 0.773, $p < 0.001$). Longer interventions yielded smaller effect sizes, indicating that shorter interventions might be more effective due to reduced novelty effects. Further information can be found in Table 4 (see Table 4).

5.6.5. Influence of Control Treatments on the Effectiveness of Digital Educational Games in Primary STEM Education

- **RESEARCH QUESTION 5:** Do control treatments (traditional teaching methods vs. multimedia or non-game-based interventions) influence the effectiveness of DGBL interventions in primary STEM education?

Research Question 5 explored the influence of control treatments on the effectiveness of DGBL interventions in primary STEM education. The meta-analysis showed a significant effect of control treatments on learning outcomes ($p < 0.05$), with DGBL interventions demonstrating greater improvement compared to traditional teaching methods. This suggests that DGBL can be more effective than conventional approaches. However, the difference in learning outcomes between DGBL interventions and multimedia or non-game-based interventions was less significant, emphasizing the importance of considering control treatments when assessing DGBL intervention effectiveness.

TABLE 4. The impact of moderator variables on effect size in the random-effect model≤

Moderator variables		N	Effect Size (ES)	Standard Error (SE)	Variance	95% CI		Q_b
						Lower limit	Upper limit	
Subject	Science	12	0.761	0.219	0.048	0.397	1.171	0.352
	Mathematics	6	0.571	0.233	0.054	0.357	1.248	
Control Treatment	Traditional	8	0.571	0.202	0.040	0.304	0.979	0.387
	Multimedia	10	0.768	0.242	0.059	0.497	1.422	
Game Type	Tutorial Games	7	0.646	0.244	0.059	0.337	1.271	0.388
	Board Games	4	0.658	0.329	0.108	0.987	2.239	
	Immersive Games	7	0.483	0.182	0.033	0.258	0.869	
Gaming Platform	Computer	10	0.618	0.195	0.038	0.347	1.025	0.285
	Mobile	8	0.802	0.283	0.080	0.467	1.552	
Intervention duration	<1 week	10	0.773	0.244	0.059	1.400	3.462	3.852
	1 week–1 month	2	0.381	0.27	0.073	1.209	2.468	
	1 month–3 months	5	0.432	0.193	0.037	0.891	2.142	
	≥3 months	1	0.18	0.18	0.032	1.240	4.950	

N Number of effect size; ES, effect size; SE, Standard Error; Q_b; Q Value of the heterogeneity test between the subgroups; CI, Confidence Interval; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

6. DISCUSSION

6.1. Comparison of DGBL Interventions and Traditional Teaching Methods

The meta-analysis conducted by the authors revealed a significant positive impact of DGBL interventions on primary school students' learning outcomes in STEM subjects compared to traditional teaching methods. This finding suggests that DGBL can provide an engaging and interactive learning environment, resulting in improved academic achievement. However, the authors also found that the difference in effectiveness between DGBL interventions and multimedia or non-game-based interventions was less distinct, indicating that the unique features of DGBL may offer a marginal advantage over other technology-enhanced learning approaches.

Student characteristics and game design features may moderate the relationship between DGBL interventions and learning outcomes. For example, students with different levels of prior knowledge or motivation may benefit differently from DGBL. Additionally, specific game design elements, such as feedback mechanisms or problem-solving tasks, could influence the effectiveness of DGBL in promoting STEM education, as highlighted in the analysis.

The findings reveal that DGBL interventions yield improved learning outcomes compared to traditional teaching methods, a finding supported by other research (Chen, 2020; Tsai & Tsai, 2020). These findings align with the understanding that DGBL approaches can provide an engaging and interactive environment, leading to increased motivation and enhanced academic achievement (Anderson et al., 2011; Khan et al., 2017). However, the difference in effectiveness between DGBL interventions and other technology-enhanced learning methods, such as multimedia or non-game-based interventions, was less distinct. This observation suggests that while DGBL can offer advantages over traditional teaching methods, their unique features may only provide a marginal benefit over other technology-enhanced learning strategies (Tsai & Tsai, 2020).

6.2. Influence of STEM subject disciplines on learning outcomes

The authors observed that learning success varied across subject disciplines in DGBL interventions, with mathematics demonstrating the largest effect sizes, followed by language and science. This finding suggests that some subjects may be more amenable to DGBL, possibly due to differences in content or learning processes.

For instance, mathematics frequently involves problem-solving and skill-building, which can be readily integrated into game mechanics. In contrast, science may necessitate a more complex conceptual understanding that might be more challenging to convey through games.

By examining the unique characteristics of each discipline and tailoring DGBL interventions accordingly, educators can optimize the effectiveness of DGBL in promoting learning success across various subject areas. This approach may contribute to a more comprehensive and targeted use of DGBL in primary STEM education.

This study indicates that the effectiveness of DGBL varies across different STEM subject disciplines, highlighting the importance of considering the specific learning context and objectives when implementing DGBL strategies (Bai et al., 2020; Tsai & Tsai, 2020). For instance, DGBL may be particularly effective in enhancing problem-solving skills in mathematics or promoting conceptual understanding in science. These findings emphasize the need to tailor DGBL interventions to the specific needs and learning objectives of each STEM subject discipline to maximize their effectiveness in promoting academic achievement (Brinson, 2015).

6.3. Impact of gameplay design on learning success

The findings demonstrated that gameplay design, including game types and platforms, had an impact on learning outcomes in primary STEM education. Notably, board games had the most significant effect on learning success compared to mobile devices, touch tablets, and computers. This result could be attributed to the collaborative and tactile nature of board games, which might enhance student engagement and facilitate peer-to-peer learning.

Educators and game developers should weigh the strengths and weaknesses of various gameplay designs when selecting or designing games for STEM education. While mobile devices and touch tablets offer portability and accessibility, board games may be more effective in promoting social interaction and collaboration among students.

The findings indicate that gameplay design significantly affects learning outcomes, which is consistent with previous research (Bai et al., 2020; Chen, 2020; Tsai & Tsai, 2020). The design elements in DGBL, such as feedback mechanisms, problem-solving tasks, and interactivity, can influence students' motivation, engagement, and learning performance (Jia et al., 2016). These findings emphasize the importance of integrating appropriate gameplay design elements in DGBL to enhance their effectiveness in promoting learning success. By thoughtfully incorporating game design features tailored to the needs and characteristics of learners, educators can optimize the potential benefits of DGBL strategies in STEM education (Brinson, 2015).

6.4. Influence of intervention duration on academic attainment

The meta-analysis conducted by the authors revealed a connection between intervention duration and students' academic achievement, with brief interventions showing the largest effect size. This finding supports previous research suggesting that shorter interventions may lead to better learning outcomes due to decreased novelty effects, as students may lose interest in DGBL over time. Consequently, educators should consider the optimal intervention periods to maximize the benefits of DGBL while maintaining student engagement.

Several factors could potentially moderate this relationship, including student characteristics (e.g., attention span or prior knowledge) and game design features (e.g., complexity or variability of game content).

By examining the interplay between intervention duration, student characteristics, and game design features, educators can make more informed decisions about implementing DGBL interventions in primary STEM education. This approach may contribute to enhanced learning outcomes and sustained student engagement in DGBL environments.

The findings from this study are corroborated by various research endeavors. As postulated by Anderson and Barnett (2011) and Khan et al. (2017), developmental barriers can impede academic success and induce negative attitudes, potentially leading to students abandoning their courses (Anderson & Barnett, 2011; Khan et al., 2017). These observations confirm findings, highlighting the impact of such barriers on students' learning outcomes. In addition, Bai et al. (2020) and Tsai & Tsai (2020) demonstrated that games, game mechanisms, competitive techniques, and gaming platforms significantly influence students' learning outcomes, further confirming the findings (Bai et al., 2020; Tsai & Tsai, 2020). These studies collectively emphasize the importance of addressing developmental barriers and leveraging effective DGBL strategies to enhance academic success.

6.5. Addressing Bias and Variability in Publications

In this meta-analysis, the authors aimed to provide a comprehensive understanding of the effectiveness of DGBL in primary STEM education. However, they acknowledged potential biases and variability in publications that needed to be addressed to ensure the validity of their findings.

One significant challenge faced was the limited number of studies included in the meta-analysis, which can hinder the detection of publication bias using conventional methods like funnel plots. Additionally, the methodological heterogeneity among the studies complicated the interpretation of the distribution of effect sizes. To overcome these challenges, the authors employed the fail-safe value method instead of the funnel plot technique to evaluate potential publication bias.

By using the fail-safe value method, the authors provided a transparent and comprehensive assessment of potential publication bias while accounting for the unique characteristics of the included studies. The calculated fail-safe value of 83 demonstrated the robustness of their meta-analytic findings, indicating that a substantial number of unpublished studies with null results would be required to negate the positive outcomes reported in their study.

Moreover, the overall consistency in study outcomes, with 16 out of 18 studies showing a statistically significant positive impact of DGBL on primary school students' knowledge acquisition in STEM subjects, further supported the effectiveness of DGBL in this context.

6.6. Contributions to the Field of DGBL

The present meta-analysis significantly contributes to the field of DGBL in primary education by:

- Consolidating evidence from 18 studies on the impact of DGBL on primary school students' learning outcomes in STEM subjects.
- Identifying the most effective types of DGBL and guiding educators in choosing appropriate game types to improve learning outcomes.
- Evaluating the effectiveness of different gaming platforms, such as computers and mobile devices, to help educators make informed decisions.
- Examining how intervention duration affects learning outcomes and providing insights into the ideal length of DGBL interventions.

- Emphasizing the role of DGBL in developing critical STEM skills and knowledge among primary school students.
- Identifying research trends and gaps to encourage further research and inform the development of more effective educational strategies.
- Offering practical guidance for educators and policymakers implementing DGBL in primary education, with recommendations on game types, platforms, intervention duration, and subject areas to improve learning outcomes and enhance educational experiences for students.

By addressing these aspects, the meta-analysis substantially contributes to the existing body of knowledge on DGBL in primary education and offers valuable insights to advance research and educational practices in STEM education.

6.7. Implications

The outcomes of this comprehensive study bear wide-ranging implications for diverse stakeholders within the STEM education ecosystem:

- **Educational Practice:** The results of this meta-analysis substantiate the efficacy of DGBL in augmenting students' learning outcomes in STEM disciplines. Educators can harness these insights to recalibrate their pedagogical methodologies, integrating DGBL into their STEM curricula to catalyze student engagement and optimize learning.
- **Game Developers:** The significance of refined game design and mechanics, as highlighted by the study, underscores the potential for game developers to engineer or refine DGBL with heightened educational efficacy and learner engagement. By addressing unique learning requirements and incorporating research-driven strategies, game developers can contribute to the advancement of STEM education.
- **Policy and Decision Makers:** The evidence-driven conclusions of this study can guide policymakers in formulating policies that promote investments in DGBL, advocate for the adoption of emerging technologies, and incentivize ongoing research in DGBL within STEM education. Policy decisions integrating DGBL as tools for elevating learning outcomes can incite enduring, positive transformations in education systems.
- **Researchers:** The identification of critical research domains within the realm of DGBL in STEM learning serves as a roadmap for researchers aiming to contribute to this burgeoning field. By pursuing evidence-based investigations and encouraging collaboration among education, technology, and design specialists, researchers can reshape the future of STEM education.
- **Students and Parents:** With the study establishing the potency of DGBL in bolstering academic outcomes, students and parents can consider assimilating these games into home-based learning pursuits. This incorporation not only supports STEM learning beyond traditional classroom settings but also cultivates affirmative attitudes towards technology and learning among young scholars.

7. CONCLUSIONS

This meta-analysis aims to explore the impact of DGBL on the academic achievement of primary school students in STEM subjects. Through a comprehensive analysis of 18 research studies, the study reveals a moderate yet positive effect of DGBL on learning outcomes, suggesting that these games have the potential to significantly enhance academic achievement when compared to traditional teaching methods. Furthermore, the study delves into the intricacies of DGBL by examining the influence of factors such as subject disciplines, control treatment, game type, platforms, and intervention duration on learning outcomes. The results indicate that integrating educational DGBL into STEM education can serve as a valuable teaching strategy, leading to measurable improvements in academic performance.

7.1. Limitations

This research investigation examines the potential advantages of incorporating educational DGBL into STEM education in primary schools, comparing their effectiveness to that of non-digital games. Despite its contributions, this meta-analysis has certain limitations. Firstly, the meta-analysis methodology required excluding relevant studies that did not meet specific criteria, resulting in the analysis relying on data from 18 empirical studies and effect estimates, while other pertinent studies may have been overlooked. Secondly, a random-effects model was employed instead of a more precise fixed-effects model. Furthermore, a comprehensive examination of all internal and external moderator variables was not feasible within the study's scope. Additionally, there is a noticeable gap in research investigating the impact of DGBL on cognitive abilities and emotional states. In light of these limitations, it is recommended that future research utilize diverse academic databases to explore the effects of DGBL with STEM instruction from multiple perspectives, particularly in primary school settings.

7.2. Future Work and Recommendations

As more studies on DGBL in primary STEM education become available, future meta-analyses should employ additional methods such as funnel plots, Egger's regression test, and trim-and-fill analysis to further explore potential biases and variability in publications.

Future research should focus on identifying the ideal duration for DGBL interventions in primary STEM education, considering factors such as game type, subject area, and student demographics. This will help educators and policymakers make informed decisions when implementing DGBL interventions in their curricula.

Further investigation into the potential of combining different gameplay designs to create a more holistic and effective learning experience is also encouraged. By considering the unique advantages of various game types and platforms, educators can optimize the use of DGBL in primary STEM education and foster a more engaging and collaborative learning environment.

In addition, future studies should delve deeper into the factors contributing to disciplinary differences in learning outcomes. This knowledge can be used to develop customized DGBL interventions that cater to the specific learning needs of each subject area.

Lastly, incorporating personalized learning strategies into DGBL designs, as well as investigating the integration of DGBL with other technologies, can further enhance the potential benefits of these interventions in primary education.

8. ACKNOWLEDGMENT

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