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Digital game-based learning in K-12 mathematics education: a systematic literature review

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Abstract

The application of mathematical skills is essential to our daily routine and is foundational for numerous disciplines. Among various computer-supported learning methods, Digital Game-Based Learning (DGBL) has been perceived as a promising method in teaching mathematics, promoting students' interest, and motivation. Therefore, the aim of this systematic literature review is to provide a detailed synthesis of literature regarding the effectiveness of DGBL applications in K-12 mathematics education and extend the findings of previous reviews. This study reviewed a total of 43 articles published in the Social Sciences Citation Index (SSCI) of Web of Science, and other top-ranked educational technology journals between 2008 and 2019. The findings were then evaluated according to the multi-dimensional framework and classified into three main categories: knowledge acquisition, perceptual and cognitive skills, and affective, motivational, and behavioral change. This revealed that most of the reviewed studies have reported positive gains in all categories, with the traditional method of teaching being the most popular comparison approach. Numerous scholars also demonstrated a particular interest in the subject of arithmetic operations. The study also found that a considerable number of DGBL applications were constructed based on a specific design feature or learning theory. Furthermore, this study highlighted a number of research gaps in this domain according to which more research is required to understand how different dynamics (e.g., collaborative/cooperative, competitive) influence students' learning. Additionally, more studies are required to address the lack of research on twenty-first-century skills such as creativity and critical thinking. The findings of this review could benefit researchers and educators who are interested in using educational computer games to teach mathematics.

Keywords Digital game-based learning · DGBL · Mathematics education · Systematic review

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Mathematical skills play an essential role in our daily lives, and they a provide solid foundation for numerous disciplines. Historical records show that humans have been experimenting with mathematics for over 4000 years (Huang et al., 2014; Ku et al., 2014).

Despite the importance of mathematics, the majority of students in K-12 education view mathematics unfavorably and recognize it as a frustrating and difficult subject that causes learning fatigue, pressure, and anxiety (Deng et al., 2020; Geist, 2010; Offer & Bos, 2009; Luhan et al., 2013; Sun et al., 2021). Therefore, mathematics is the subject with the highest student failure rate (Huang et al., 2014).

A number of factors have been attributed to students' mathematics problems, among these factors, the traditional method of teaching has been receiving growing criticism. For example, Paul (1992) argued that the traditional method promotes memorization and encourages students to keep practicing what they already know. Additionally, Skinner and Belmont (1993) stated that this method is incapable of motivating students to learn and engage in the learning process. Further, students' exposure to complex problems is very limited, hence, this method does not advance the development of students' problem-solving skills, conceptual understanding, or critical analysis (Bikić et al., 2016; Kinard & Kozulin, 2008; Voskoglou & Salem, 2020).

Due to substantial technological developments during the past decade, a growing number of researchers and educators are incorporating technology in education (Hussein, Ow, Cheong, & Thong, 2019; Hwa, 2018). Among the various technology-supported learning methods, Digital Game-Based Learning (DGBL) is perceived as an effective way to learn mathematics. For instance, Ke (2008) and Tsai et al. (2012) indicated that the use of DGBL applications in mathematics promotes students' perseverance and improves their engagement in the learning process. Martinovic et al. (2014) showed that gaming could contribute to young learners' cognitive development. However, despite DGBL's potential, prior research has not supported the notion that its use in mathematics education guarantees positive outcomes. For example, Ke (2008) reported that there is no significant evidence to support the premise that DGBL improves students' comprehension of mathematics or metacognitive skills. Similarly, Hung et al. (2014) articulated that DGBL applications are not always effective in managing students' anxiety towards mathematics.

Given the prevalence of gaming in education and the inconclusive findings in the literature, a growing number of scholars have conducted meta-analyses and reviews pertaining to the effectiveness of the DGBL approach. Abdul Jabbar and Felicia (2015), Boyle et al. (2016), Connolly et al. (2012), Hainey et al. (2016), and Vogel et al. (2006) argued that gaming results in improved academic performance, motivation, and attitudes towards learning. However, there are some other studies that do not show that the literature consistently supports DGBL's empirical effectiveness. For example, Young et al. (2012) stated there is limited evidence to support the effectiveness of gaming applications in the domain of mathematics. Additionally, in their meta-analysis, Wouters et al. (2013) stated no evidence suggests that computer games are better motivators in learning than the traditional teaching methods.

Although the earlier studies provide crucial insights into the effects of gaming in the context of learning; their scope was broad (e.g., covered several

curricular subjects) and their findings were inconsistent. As a consequence, Divjak and Tomić (2011), Byun and Joung (2018), and Tokac et al. (2019) conducted domain-specific reviews to examine DGBL's effectiveness in mathematics. Although their analyses showed that playing games contribute positively to students' knowledge comprehension and motivation, there are issues associated with the timelines of the studies or the type of publications reviewed. For example, Divjak and Tomić (2011) surveyed papers published between 1995 and 2010, while Byun and Joung (2018) examined papers published between 2000 and 2014. Therefore, there is a need to update their findings and demonstrate how this area of research has evolved after 2014. Further, out of the 24 research studies reviewed in Tokac et al., 2019) meta-analysis, nine publications were gray literature (including eight dissertations, and one conference paper). While the inclusion of such publications may significantly improve the comprehensiveness of findings and reduce publication bias (Paez, 2017), it is often a challenge to evaluate the rigor of the reviewing process, due to the lack of information on how this process has been performed with these publications (Garousi & Rainer, 2020; Noroozi et al., 2020). Furthermore, recent DGBL meta-analyses in K-12 mathematics education lack an in-depth analysis of individual papers. This causes different critical aspects of the learning process and different angles of students' learning outcomes to remain unclear. In addition, McLaren et al. (2017) stated that there is limited empirical evidence concerning the DGBL effectiveness, especially in the context of mathematics education. Therefore, McLaren et al. (2017) called for more studies to investigate whether the excitement behind using this method of instruction in mathematics education is justified.

As a consequence, the aims of this study are to extend the findings of previous reviews and provide an updated synthesis of evidence regarding the effectiveness of DGBL applications in the domain of K-12 mathematics education. This is achieved by utilizing a multi-dimensional framework to gain an in-depth understanding of the current status of DGBL research in K-12 mathematics education. To accomplish the above-mentioned objectives, this review poses the following research questions:

1. Do students learn mathematics more effectively when it is presented via DGBL applications, compared to other teaching methods?
2. How do students learn mathematics more effectively via DGBL applications?

The present study has two key contributions: first, providing an evidence-based discussion with regard to the effectiveness of DGBL in K-12 mathematics, synthesized from rigorously-reviewed academic journals, and second, providing detailed insights into the current trends in K-12 mathematics education. Therefore, it is believed that this review will provide useful information to aid researchers, educators, and game designers who are interested in using DGBL in K-12 mathematics education. This paper could also assist researchers and instructors from other knowledge disciplines in obtaining additional evidence pertaining to the impact of DGBL as a teaching method.

1 DGBL definitions

DGBL refers to a student-centered approach where educational objectives and material are embedded in gaming activities in an attempt to motivate students to learn and improve their skills and knowledge by providing them with an enjoyable and interactive learning environment (Prensky, 2001; Qian & Clark, 2016; Sung & Hwang, 2013).

However, some studies, particularly those employing a value-added design, have addressed at least two types of DGBL applications: value-added application and a base or simplified application. The former refers to a DGBL application enriched by a specific design or learning feature (Mayer, 2019), and the latter is similar to the value-added application with the sole exception that it does not have this specific design feature (Mayer, 2019). The significance of value-added comparisons lies in attempting to understand and investigate how a specific game design feature could foster students' understanding of a certain mathematical concept. This, in turn, could lead to an improved game design that might enhance the learning process.

2 Methodology

This study utilizes the classification method proposed in Connolly et al. (2012), which is useful for identifying similarities, differences, and limitations in DGBL studies. This method classifies outcomes into four categories:

- Knowledge acquisition
- Perceptual and cognitive skills
- Affective and motivational outcomes
- Behavior change outcomes

According to Connolly et al. (2009) and Hainey et al. (2014), the knowledge acquisition category is primarily about gains in factual knowledge and improvements in students' performance as a result of the DGBL intervention. The perceptual and cognitive category encompasses the learners' perceptions such as their flow experience or cognitive load; this assesses the effects of DGBL interventions on the students' cognitive competencies (e.g., problem-solving). The affective and motivational category concerns a number of aspects such as the learners' particular motivations for using the intervention as well as their level of interest in participation. Finally, the behavioral change category, as the name implies, relates to the effects of the DGBL interventions on the occurrence of change in the learners' behaviors and attitudes (All et al., 2016; Stewart et al., 2012).

3 Database

The Social Sciences Citation Index (SSCI) database of Web of Science was used to search for DGBL interventions in mathematics education in the Educational Research category. This online repository contains rigorously reviewed research and high impact studies (Zydney & Warner, 2016). In addition, to ensure wider coverage of high-quality journals, the researchers employed the Google Scholar metrics in a manner similar to that used in Nikou's and Economides' (Nikou & Economides, 2018) review to identify educational technology journals with the highest impact factors. Among the 20 publications in this subcategory, the following 13 journals were considered:

- Computers and Education
- British Journal of Educational Technology
- Educational Technology and Society
- Journal of Computer Assisted Learning
- Education and Information Technologies
- Educational Technology Research and Development
- Interactive Learning Environments
- Tech Trends
- Turkish Online Journal of Educational Technology
- Learning at Scale
- Learning, Media and Technology
- IEEE Transactions on Learning Technologies
- Australasian Journal of Educational Technology

Seven publications were not considered because their scope did not align with the scope of this study, as these publications either did not target students in K-12 education or did not include DGBL interventions in the subject of mathematics.

4 Search terms

The Boolean operator "OR" was utilized to combine all the keywords related to DGBL (i.e., serious game*", "game-based learning", "educational game*", "computer game*", "online game*", "digital game-based learning", "Digital game*", "gaming", "MMORPG", "augmented reality", "video games", "video gaming", "electronic games"). In a similar way, the Boolean operation "OR" was employed to combine all the keywords related to mathematics learning (i.e., "math* learning", "learning math*", "math* teaching", "teaching math*", "math* education", "math* instruction", "math* evaluation", "math* outcome", "math* skills"). Finally, the Boolean operator "AND" was used to combine DGBL and mathematics learning keywords.

5 Inclusion and exclusion criteria

To ensure the retrieved studies are relevant to the scope of the review, the researchers applied the following inclusion and exclusion criteria:

- Published in English, in a peer-reviewed journal, and between 2008 and 2019 (as DGBL research in mathematics education experienced a notable upsurge in 2008 (Byun & Joung, 2018)).
- Each intervention is related to mathematics learning and includes participants from K-12 education.
- Each DGBL application is clearly designated as a *game* and the term *game* must be included in the title or abstract of the publication†.[1]
- Eligible studies must incorporate at least one comparison of a DGBL application to a simplified game design, other e-learning tools, or the traditional method of teaching†.
- Upon completion, students received feedback (e.g., score points and/or a progress report)†.

The researchers applied the following exclusion criteria:

- Non-English publications.
- Interventions published in conference papers, book chapters, or PhD dissertations.
- Findings of qualitative studies.
- Findings of single-group interventions.

6 Article selection

The search process resulted in the retrieval of 1347 research articles, after excluding duplicates, inaccessible publications, and studies unrelated to DGBL in K-12 mathematics education. Two researchers conducted two in-depth screening rounds to finalize the search results according to the inclusion and exclusion criteria mentioned above.

During the first screening process, the two researchers independently rated the papers, they had inter-rater reliability of 88.5%, which was brought to 100% agreement after discussion. This process resulted in the inclusion of 70 research articles. During the second screening process, the same two researchers read the full text of the 70 articles to ensure that these studies truly satisfied the inclusion and exclusion criteria. The inter-rater reliability was 90.7% and then was brought to 100% after addressing all the inconsistencies and disagreements through discussion. Finally, a total of 43 research articles were included in the present review. Figure 1 details

[1] Conditions marked with (†) were adapted from (Clark et al., 2016).

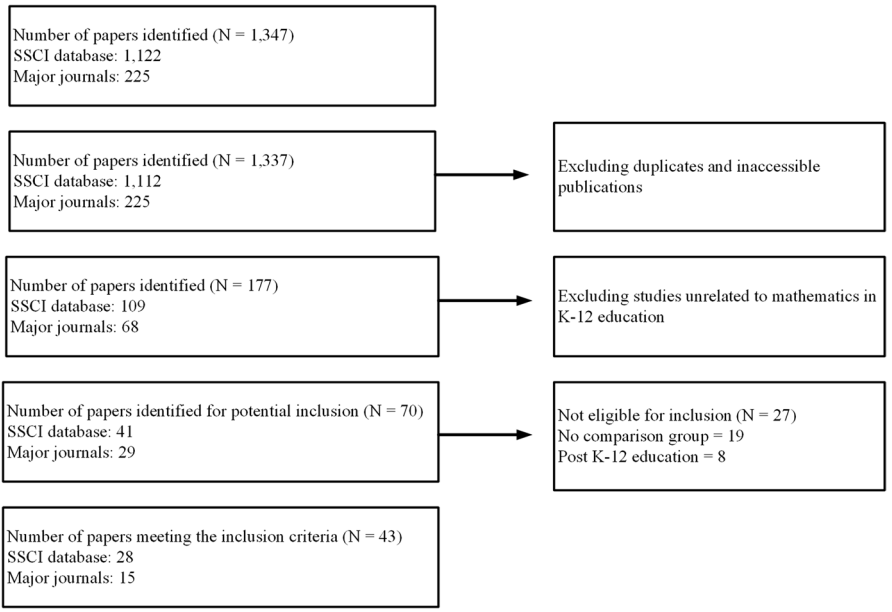

Fig. 1 Articles selection process

the various stages that this study followed during the data collection and evaluation processes.

7 Results

7.1 Analysis of game and study variables

This section highlights the findings of the analysis of variables related to the studies included in this review with a specific focus on the educational level of participants, the year of publication, and the genre of the DGBL application.

7.1.1 Participants

Figure 2 identifies the educational levels of students who participated in DGBL interventions in the domain of K-12 mathematics education. Twenty-eight of the 30 studies were focused on students at the primary level, while two studies had participants from primary and junior high schools. Eight studies were conducted at the high school level and seven were conducted at the junior high school level, while one study included participants from both junior and senior high school. Furthermore, four studies were performed at pre-vocational levels and one study was carried out at the vocational level. It should be noted that primary education refers to students who are in grades 1–6, junior high school refers to students in grades 7–9, and senior high school refers to students in grades 10–12. Prevocational and

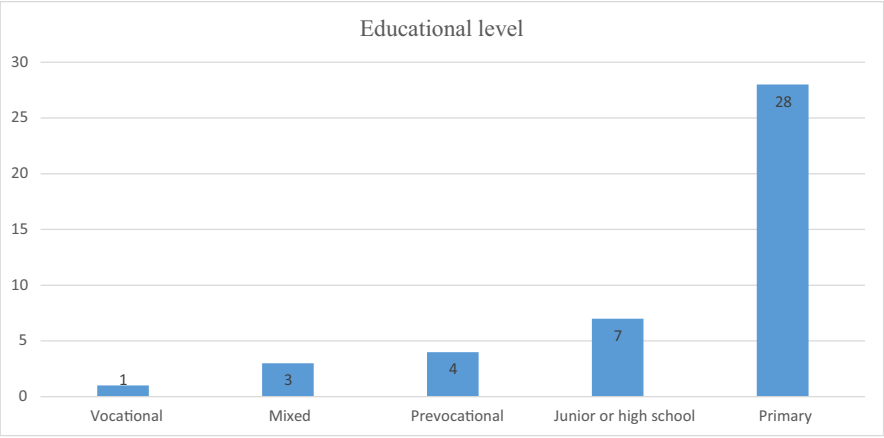

Fig. 2 Distribution of articles in K-12 mathematics education, according to participants' educational level.

vocational learning refer to students who are in a less advanced level of high school education that specifically prepares them for vocational learning (ter Vrugte, de Jong, Vandercruysse, et al., 2015).

7.1.2 Number of studies with respect to publication year

Figure 3 shows the number of articles published between 2008 and 2019, presented by the year of publication. The study of DGBL in mathematics learning has experienced two phases. In the first phase, from 2008 to 2013, the number of published articles was relatively limited. This indicates that the use of DGBL in K-12 mathematics was still in its early stages. In the second phase, from 2014 until the present

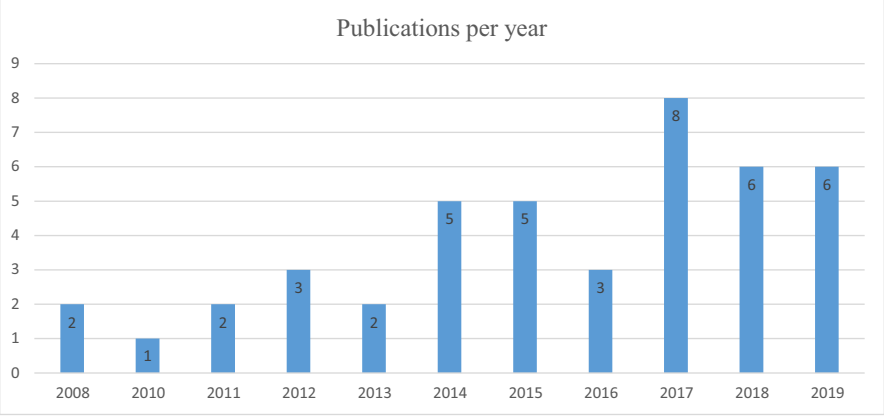

Fig. 3 Distribution of articles in K-12 mathematics education, according to year of publication.

time, the number of papers rapidly increased, showing a growing interest among researchers in utilizing DGBL applications in K-12 mathematics.

7.1.3 DGBL genres

Game genres are constantly evolving and changing (Lee et al., 2006), hence one DGBL application may belong to more than one genre (Ke, 2016), this study categorized the game genres based on the classifications suggested by Bontchev and Vassileva (2010), Carmigniani et al. (2011), Herz (1997), Ke (2016) and Minkkinen (2016). A brief description of these genres is provided in Table 1.

In this review, nine genres were identified, as shown in Fig. 4. These genres can be categorized into two distinct groups. The first group consists of frequently employed genres such as simulations (n = 13), puzzle and adventure (n = 8), role-playing (n = 7), and strategy (n = 4), whereas the second group involves board game, virtual reality, platform, and construction only once. There was also one study that did not present clear details regarding the DGBL application they used, hence, it was difficult to recognize its genre.

7.2 Analysis of methodologies and learning outcomes

This section reviews the articles with regard to the following considerations:

- Research design is primarily concerned with the type of methodology being used (e.g., Randomized Controlled Trial (RCT) and quasi-experimental).
- Effects of the intervention on learning outcomes (e.g., positive, neutral, mixed, or negative).

Table 1 Definitions of gaming genres

Genre	Definition
Simulation	A game where the learner interacts with and explores a simulated recreation of a location or situation.
Puzzle	Logic and thought during the process of puzzle-solving.
Adventure	A game involving constant exploring, overcoming long-term obstacles, solving puzzles, and collecting rewards in order to progress through the game world.
Strategy	Strategic deployment via systematic analysis and thinking.
Role play	The player assumes the role of a character (e.g., king/queen, wizard, elf), then, the protagonist will interact with other in-game characters, collect information, and make decisions.
Construction	The player designs, develops, and practices resource management.
Platform	Such games are based on a character that runs, jumps, and slides to overcome obstacles and defeat enemies.
Board game	Games where figures or pieces are manipulated on a surface based on some predefined rules.
Virtual reality	Gaming environments where students are immersed in an artificial environment.

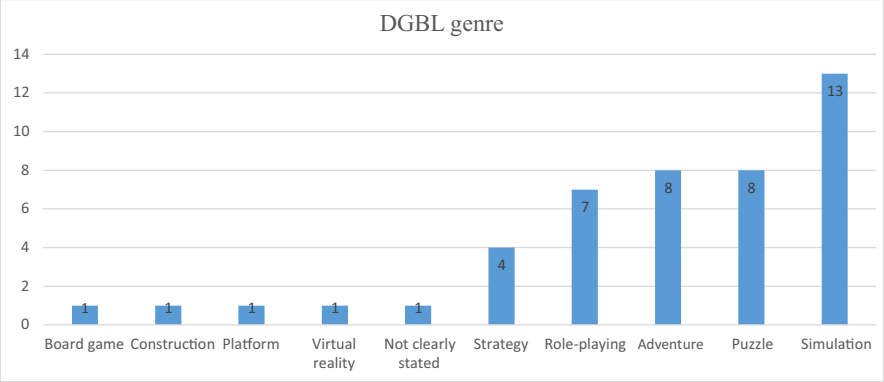

Fig. 4 Distribution of articles in K-12 mathematics education, according to genre of the DGBL application

- The comparison approach refers to the educational activities that students in the control group received during the intervention (e.g., traditional method, value-added, or other computer-enhanced learning methods).
- Areas of interest were concerned with which area of mathematics education a particular DGBL application is targeting (e.g., arithmetic operations, algebra, etc.).
- Learning dynamics were examined to explore which learning dynamic (e.g., individual, collaborative/cooperative, or competitive) is more effective in promoting students' mathematical knowledge in K-12.
- Design characteristics aimed at highlighting the design features and learning theories that guided the development of some DGBL applications.

After reviewing the articles that met the inclusion criteria, it was revealed that the studies that investigated the effects of DGBL applications on students' affective and motivational outcomes and behavioral change were very limited. Therefore, these two categories were combined together in one category known as affective, motivational, and behavioral change. It should be noted that similar approaches have been implemented by other reviews that have used the multi-dimensional framework to classify the learning outcomes of DGBL applications in science education (Hussein, Ow, Cheong, Thong, & Ebrahim, 2019) and digital storyline-enhanced learning (Novak, 2015).

7.2.1 Knowledge acquisition

It was revealed that 27 papers have investigated the effects of DGBL applications on students' construction of mathematical knowledge and concepts. Eight studies implemented an RCT design; among them, six papers reported positive outcomes (Barzilai & Blau, 2014; Denham, 2015; Kebritchi et al., 2010; Kim & Ke, 2017; Lin et al., 2013; ter Vrugte et al., 2017). Wouters et al. (2017) reported mixed findings from two experiments. The first demonstrated

Table 2 Summary of RCT studies investigating the DGBL effects on mathematics knowledge acquisition

Author(s)	Platform	Comparison	Area of interest	Learning dynamic
Barzilai and Blau (2014)	Web-based	Value-added	Financial skills	Individual
Denham (2015)	Computer	Value-added	Arithmetic operations	Individual
Gresalfi et al. (2018)	Hand-held device	Digital worksheets	Geometry	Collaborative
Kebritchi et al. (2010)	Computer	Traditional method	Algebra	Individual
Kim and Ke (2017)	Computer	A non-gaming application	Fractions	Individual
Lin et al. (2013)	Computer	Instructional videos	Fractions	Individual
ter Vrugte et al. (2017)	Computer	Value-added	Proportional reasoning	Individual
Wouters et al. (2017)	Computer	Value-added	Proportional reasoning	Individual

neutral outcomes, while the second showed positive outcomes. There was only one collaborative study that reported neutral outcomes (Gresalfi et al., 2018). Table 2 lists the studies that followed the RCT research design along the dimensions of the platform, comparison approaches, areas of interest, and learning dynamics.

In this category, 19 studies were included because they followed a quasi-experimental research design. Of these 19 studies, 16 papers revealed positive learning gains (Barros et al., 2019; Beserra et al., 2014, 2017; Huang et al., 2014; Hung et al., 2015; Hwa, 2018; Ke, 2008a; Kolovou et al., 2013; Masek et al., 2017; Pareto et al., 2012; Shi et al., 2019; ter Vrugte, de Jong, Vandercruysse, et al., 2015a; ter Vrugte, de Jong, Wouters, et al., 2015; Vandercruysse et al., 2017; Wang et al., 2018 and Yang et al., 2018). The results of the remaining studies were mixed. Two studies Ke (2008b) and Panoutsopoulos and Sampson (2012) reported neutral outcomes, and one study, Fokides (2018), reported mixed outcomes. The researcher in Fokides (2018) provided students with 15 learning exercises, and students in the experimental group who used the DGBL application significantly outperformed their counterparts in control group (A) who received instruction via the traditional method in all the 15 exercises. However, students in the experimental group achieved significantly better learning gains than the students in control group (B) who received instruction via contemporary teaching methods based on collaborative learning of the textbook as well as worksheets designed by the teachers in only four out of the 15 learning exercises.

The majority (n = 14) of studies were single-player and non-collaborative, with regard to different learning dynamics (e.g., individual, collaborative/cooperative, or competitive). Ke (2008, 2008a) looked at the same learning dynamics and reported interesting findings; Ke (2008) revealed that students from economically disadvantaged backgrounds who learned collaboratively and competitively made greater gains than their counterparts in the individualized

group. Conversely, students from better socio-economic backgrounds gained significantly more from individualized learning than other learning dynamics. In addition, with respect to the mathematics learning attitude, Ke (2008) reported that cooperative learning significantly improved students' learning attitude towards mathematics more than the individual and competitive learning dynamics. Ke (2008a) found that students who learned individually significantly outperformed their counterparts who learned cooperatively and competitively. As for learning attitude, students learning cooperatively demonstrated a better attitude than those who learned competitively, but not than their counterparts who learned individually.

In addition, Fokides' (2018) study found that collaborative learning via a DGBL application is significantly more effective than individual learning administered via the traditional method. Further details regarding the individual characteristics of quasi-experimental studies that focused on the students' knowledge acquisition category are demonstrated in Table 3.

7.2.2 Perceptual and cognitive skills

In the perceptual and cognitive skills category, nine studies were included. Among them, four studies (Castellar et al. (2015), Hulse et al. (2019), Ke (2019), and Lee and Ke (2019) have followed the RCT research design and reported positive outcomes. Table 4 highlights the key features of RCT studies that targeted the students' perceptual and cognitive skills.

Five studies followed a quasi-experimental research design, among which three studies (i.e, Brezovszky et al. (2019), Kiili et al. (2018), and Lee et al. (2014)) revealed positive outcomes. Eseryel et al. (2011) reported mixed findings from two learning interventions. Kiili and Ketamo (2017) is the only study that reported negative outcomes, whereby the effects of a DGBL application was compared to the traditional method. Table 5 details the key components of the quasi-experimental studies that emphasized promoting the students' perceptual and cognitive skills.

7.2.3 Affective, motivational, and behavioral change

This category included seven studies with only two articles following an RCT research design. One of these studies Habgood and Ainsworth (2011) reported positive learning outcomes, while the other one Kim et al. (2017) reported neutral outcomes.

The remaining five studies Chang et al. (2016), Chen et al. (2012), Garneli et al. (2017), Ku et al. (2014), and Mavridis et al. (2017) have followed a quasi-experimental design, and all of them obtained positive results. Due to the limited number of studies investigating affective, motivational, and behavioral change, both RCT and quasi-experimental studies are combined in one table. Thus, Table 6 summarizes the main aspects of this category and demonstrates the research design they followed.

Table 3 Summary of quasi-experimental studies investigating the DGBL effects on mathematics knowledge acquisition

Author(s)	Platform	Comparison	Area of interest	Learning dynamic
Barros et al. (2019)	Hand-held device	Traditional method	Arithmetic operations	Individual
Beserra et al. (2014)	Computer	Traditional method	Arithmetic operations	Individual
Beserra et al. (2017)	Computer	Traditional method, and value-added	Arithmetic operations	Individual
Fokides (2018)	Computer	Traditional, and contemporary methods	Basic math concepts	Collaborative
Huang et al. (2014)	Hand-held device	Value-added	Arithmetic operations	Individual
Hung et al. (2015)	Hand-held device	Multimedia comparison	Arithmetic operations	Individual
Hwa (2018)	Computer	Traditional method	General math concepts	Individual
Ke (2008a)	Web-based	Traditional method	Cognitive math concepts	Individual, collaborative, and competitive
Ke (2008b)	Web-based	Traditional method	Cognitive math concepts	Individual, collaborative, and competitive
Kolovou et al. (2013)	Web-based	Not clearly stated	Early algebra	Individual
Masek et al. (2017)	Computer	Traditional method	Fractions	Individual
Panoutsopoulos and Sampson (2012)	Computer	Traditional method	Linear functions	Individual
Pareto et al. (2012)	Computer	Traditional method	Arithmetic operations	Individual, and collaborative
Shi et al. (2019)	Computer	Traditional method	Quadratic functions	Individual
ter Vrugte, de Jong, Vandercruysse, et al. (2015)	Computer	Value-added	Proportional reasoning	Competitive, and collaborative
ter Vrugte et al. (2015a)	Computer	Value-added	Proportional reasoning	Individual
Vandercruysse et al. (2017)	Computer	Value-added	Proportional reasoning	Individual
Wang et al. (2018)	Computer	Online learning system	Speed and time	Individual
Yang et al. (2018)	Computer	Value-added	Arithmetic operations	Individual

Table 4 Summary of RCT studies investigating the DGBL effects on perceptual and cognitive skills*

Author(s)	Platform	Comparison	Area of interest
Castellar et al. (2015)	Computer	Traditional method	Mental arithmetic skills
Hulse et al. (2019)	Web-based	A non-gaming application	Algebra
Ke (2019)	Computer	Traditional method	Ratios and proportion reasoning
Lee and Ke (2019)	Computer	Value-added	Ratios and proportion reasoning

* This table did not include the learning dynamics dimension, as research studies in this section were only focused on individual studies

Table 5 Summary of quasi-experimental studies investigating the DGBL effects on perceptual and cognitive skills*

Author(s)	Platform	Comparison	Area of interest
Brezovszky et al. (2019)	Computer	Traditional method	Adaptive number knowledge
Eseryel et al. (2011)	Hand-held device	Traditional method, and dynamic modelling	Complex problem solving
Kiili and Ketamo (2017)	Web-based	Traditional method	Fractions
Kiili et al. (2018)	Hand-held device	Traditional method	Fractions
Lee et al. (2014)	Web-based	Value-added	Non-routine problems

* This table did not include the learning dynamics dimension, as research studies in this section were only focused on individual studies

7.3 Analysis of design features and learning theories

Among the 43 studies included in this review, only 20 studies detailed how the DGBL applications they used were designed. These 20 papers can be divided into two groups. The first group comprises 17 studies that focused on the effects of specific design features, and the second group consists of three studies that examined the impact of general learning theories.

In the context of K-12 mathematics, a number of design features were employed, which can be further classified into three groups based on the functions they perform and services they provide, namely, learning content representation, scaffolds, and question representation features. First, seven studies focused on how mathematical learning content is presented to students within the game world. For example, Denham (2015), Habgood and Ainsworth (2011), Ku et al. (2014), and Vandercruysse et al. (2017) examined intrinsic and extrinsic features. Chen et al. (2012) incorporated game quests, Garneli et al. (2017) embedded storyline narratives, and Wouters et al. (2017) investigated surprising events. Table 7 briefly defines these mechanisms and highlights their effectiveness.

Similarly, seven studies focused on scaffolding features, which are assistive mechanisms that aim to help students when they face difficulties or challenges during gameplay by providing prompts, clues, and hints (Barzilai & Blau, 2014). For example, Barzilai and Blau (2014) employed external conceptual scaffolds, Eseryel et al. (2011) embedded dynamic modeling in the DGBL application they used,

Table 6 Summary of studies investigating the DGBL effects on affective, motivational, and behavioral change*

Author(s)	Platform	Comparison	Area of interest
Chang et al. (2016)	Hand-held device	Traditional method	Fractions
Chen et al. (2012)	Computer	Value-added	Arithmetic operations
Garneli et al. (2017)	Computer, and web-based	Traditional method, and value added	Arithmetic operations
Habgood and Ainsworth (2011)	Computer	Value-added	Arithmetic operations
Kim et al. (2017)	Computer	A non-gaming application	Fractions
Ku et al. (2014)	Computer	Traditional method	Arithmetic operations
Mavridis et al. (2017)	Web-based	Traditional method	Multiple mathematical concepts

* This table did not include the learning dynamics dimension, as research studies in this section were only focused on individual studies

Table 7 Summary of studies investigating the learning content representation features

Study	Definition	Effectiveness
Chen et al. (2012)	Game quests are a goal-guiding mechanism incorporated in role-playing games, which direct students to conduct specific learning tasks, and promote students' persistence and their intensity in pursuing goals.	The game that includes game quest is more effective than the base version in improving students' goal intensity, goal orientation, and enjoyment.
Denham (2015)	The intrinsic and extrinsic approaches refer to the degree of integration the game story has with the instructional content. In the former, this relationship has been described as 'integral and continuing' (Malone & Lepper, 1987, p. 240); hence, the game story is endogenous to the learning content. Whereas in the latter, the instructional content being taught is outside the actual game; therefore, the relationship between these two elements is exogenous (Denham, 2016).	Students learning via the intrinsic version demonstrate greater learning gains than the students who play the other extrinsic and the base versions in terms of conceptual understanding of the associative property of multiplication.
Garneli et al. (2017)	Storyline DGBL application includes narrative elements aiming to enhance students' motivation. Students who were instructed via the coding mechanism not only played the game but also modified its code via Scratch programming environment.	The coding mechanism significantly impacts students' intention to participate (ITP), but not their immersion. The DGBL application with the story mode and the base application have no significant influence on students' ITP and immersion. The base application and the coding mechanism significantly influence low-performing students' ITP. The traditional method significantly benefits low-performing girls.
Habgood and Ainsworth (2011)	The intrinsic and extrinsic mechanisms have been defined earlier.	Students who used the DGBL application with the intrinsic mechanism learn more than students who utilize the extrinsic version and the base DGBL application. Students in their free time play the intrinsic version seven times more than the extrinsic version.
Ku et al. (2014)	The extrinsic mechanism has been defined earlier.	DGBL application is more effective in terms of improving confidence and computational performance. The confidence of high and low-performing students who use the DGBL application increases significantly. Low-performing students can significantly profit from DGBL application since it advances their computational performance.

Table 7 (continued)

Study	Definition	Effectiveness
Vandercruysse et al. (2017)	The intrinsic and extrinsic mechanisms have been defined earlier.	The extrinsic version of the game is significantly more effective than the intrinsic version in terms of learning gains, motivation, and perceived usefulness.
Wouters et al. (2017)	Surprising events are events that occur unexpectedly in a manner that prompts learners to re-examine their understanding of previous events and check whether they have missed something. In this process, learners retrieve, update, and reconstruct these events, thereby promoting their cognitive interest and improving their learning (Van der Spek et al., 2013).	In the first study, there was no overall difference between the experimental and control groups. However, in the second study, the utilization of surprising events resulted in significant effects when students' existing skills in proportional reasoning were taken as a factor.

Huang et al. (2014) utilized a diagnostic mechanism, and Lee et al. (2014) investigated the effectiveness of four types of scaffolds in two phases: first, single or multiple-solution, second, specific or generic prompts. Collaboration and competition facilities were examined by ter Vrugte, de Jong, Vandercruysse, et al. (2015), while ter Vrugte et al. (2017) addressed the faded worked examples. Finally, Yang et al. (2018) focused on progressive prompting. Table 8 briefly defines these mechanisms and highlights their effectiveness.

Finally, three studies have examined the question representation features. Such features are primarily concerned with how questions within the game world will be formatted and delivered to students. For example, Beserra et al. (2017) assessed fine-grained multiple-choice response format, Lee and Ke (2019) examined the effectiveness of iconic and symbolic prompting, and ter Vrugte et al. (2015a) focused on reflection prompts, procedural information, and reflection prompts plus procedural information. Table 9 briefly explains these mechanisms and highlights their effectiveness.

With regard to learning theories, there were three studies focusing on the impact of general learning theories in their DGBL interventions. For example, Kebritchi et al. (2010) addressed the experiential learning theory, Lin et al. (2013) employed the remedial mastery learning, and Pareto et al. (2012) used the master-apprentice theory. Table 10 briefly explains these learning theories and highlights their effectiveness.

8 Discussion

This study aimed to examine and provide insights into the DGBL effects on K-12 mathematics education. To this end, the Web of Science database and top-ranking educational technology journals indexed by Google Scholar were selected for review and analysis. This paper reviewed empirical research published between 2008 and 2019. The keywords used in this study produced 1347 research articles, which shows that DGBL in mathematics education is frequently addressed in high impact journals. The inclusion and exclusion criteria followed by this study resulted finally in the inclusion of 43 studies. The multi-dimensional framework proposed by Connolly et al. (2012) was used to identify and summarize the key trends of research in this domain.

The distribution of papers based on their publication year revealed that research in this area went through two periods. The first was from 2008 to 2013, when research into the DGBL effects on K-12 mathematics was receiving limited interest from the academic community. From 2014 onwards, it was noted that scholars' interest grew considerably and steadily, as more studies were found focusing on investigating the effectiveness of DGBL applications in K-12 mathematics education.

The findings showed that different researchers have used a number of game genres with a notable interest in simulation games. The frequent utilization of simulations is justified due to their ability to provide students with rich and compelling narratives (Abdul Jabbar & Felicia, 2015). Another justifiable explanation is that simulation games have been found beneficial in promoting students' mathematics

Table 8 Summary of studies investigating scaffolding features

Study	Definition	Effectiveness
Barzilai and Blau (2014)	This scaffolding mechanism was employed to aid students in bridging their intuitive understandings of the game and curricular knowledge.	Students' performance in the post-game assessment revealed that providing scaffolds before the game is significantly more effective than providing scaffolds after the game, or no scaffolds at all.
Eseryel et al. (2011)	Dynamic modeling is a useful cognitive regulation tool that aids students in learning complex problem-solving during gameplay.	In the first intervention, students who used the DGBL application and the traditional method experienced a decline in their problem-solving. In the second intervention, students who received their instructions via the DGBL application, equipped with the dynamic modeling scaffold also suffered a drop in performance, while students in the control group who received dynamic modeling only demonstrated significant gains. Further, when the performance of students in the second intervention was compared to the first one, there was a significant difference favoring the students of the second intervention regardless of their group.
Huang et al. (2014)	The diagnostic mechanism is a design feature that evaluates students' performance to ensure that their answers are not affected by issues such as carelessness in judgment. When students submit incorrect answers, the diagnostic mechanism will assess the incorrect answer and then present the student with flash content related to the nature of the problem they faced.	Students' responses confirmed the efficacy of the diagnostic mechanism over the simplified DGBL application.
Lee et al. (2014)	In the single-solution group, students received one solution per example, whereas students in the multiple-solution group were provided with at least two solutions and they were required to weigh the advantages and disadvantages of this mechanism. Generic prompts are structured on the delivery of procedural scaffolds to students that explain the general direction of the task at hand, while specific prompts provide generic prompts as well as specific and strategic direction for students when they are playing the game.	Specific prompting is significantly better than generic prompting in terms of generalization and justification of non-routine problem-solving. Multiple-solution is significantly better than single-solution in terms of the generalization and justification of non-routine problem-solving.

Table 8 (continued)

Study	Definition	Effectiveness
ter Vrugte, de Jong, Vandercruysse, et al., 2015a	In collaboration and competition group, students collaborated with and competed against other teams in their group. In the collaborative group, teams of two students collaborated. In the competition group, students played individually against each other, and against other teams in the collaboration and competition group.	No effects of collaboration and competition were observed on learning. Below-average students benefit from collaboration, where competition is not present. Conversely, above-average students are likely to benefit from collaboration, when competition is present.
ter Vrugte et al., 2017	In faded worked examples approach, students receive a fully-worked example; then, a partially-worked example is provided with one step missing; finally, as students progress in their learning, worked-out steps will be removed one by one until students become independently engaged in the problem-solving process.	Only students who played the DGBL application enriched with faded worked examples obtained significant learning gains, while students who played the simplified version achieved no significant progress.
Yang et al. (2018)	The progressive prompting strategy offers students two prompts that progressively proceed from abstract text description to concrete image description to aid students in forming the correct concepts and consolidating their knowledge foundations.	The DGBL application with progressive prompting is more effective than base DGBL. The progressive prompting is particularly helpful for students with low self-efficacy.

Table 9 Summary of studies investigating the question representation features

Study	Definition	Effectiveness
Beserra et al. (2017)	A mechanism where students build their answer, one element at a time, with each element specifically selected from a predefined set.	The fine-grained multiple-choice response is significantly more beneficial for students' learning than the simplified DGBL application. However, the simplified application is more successful in promoting interest and motivation.
ter Vrugte et al. (2015a)	Procedural information presents the students with possible procedures and the corresponding rules required to address the challenges they face while playing. Reflection prompts take the form of multiple-choice questions, which aim to direct students' attention to the most important steps while solving the problem at hand. Students in the reflection prompts plus procedural information group receive a combination of both techniques.	Students regardless of their group affiliation achieved significant learning gains.
Lee and Ke (2019)	In iconic prompting, the representation of the problem is depictive and specific as it involves iconic signs that share visual representation with the object to which they refer. In symbolic prompting, the characterization of the problem is general and abstract as it includes symbolic representations in the form of natural language, numerals, and formulations.	Symbolic prompting better supports students' mathematics comprehension, reflection and mathematical problem-solving skills, and qualitative understanding. Iconic prompting is more effective in terms of quantitative proficiency.

Table 10 Summary of studies investigating specific learning theories

Study	Definition	Effectiveness
Kebritchi et al. (2010)	According to Kolb (1984), the experiential learning theory refers to a cyclical and iterative process in which students improve their comprehension and expertise by cycling through the four stages of this theory: (a) concrete experience, (b) reflective observation, (c) abstract conceptualization, and (d) active experimentation. Concrete experience transpires when students are actively and directly involved in a learning activity. Reflective observation is usually triggered when students discuss and reflect on their hands-on experience and make judgments in relation to their performance. The abstract conceptualization stage is primarily concerned with students making adjustments to their prior concepts, incorporate new knowledge, and develop new understandings. Finally, during active experimentation, students determine how they will utilize the skills they gained from their hands-on learning experience in future scenarios (Burch et al., 2019; Lee et al., 2020).	The results revealed a significant improvement for the experimental group who learned via a DGBL application grounded in the experiential learning theory.
Lin et al. (2013)	In remedial mastery learning, the instructional content is divided into smaller units each with its own objectives, and only students who demonstrate the prerequisite level of mastery can advance to the next learning unit. However, students who do not achieve the desired level of mastery would receive remedial instructions.	Using a DGBL application based on remedial mastery learning is significantly more effective than using instructional videos.
Pareto et al. (2012)	The master-apprentice model was utilized by incorporating a Teachable Agent (TA) into the gaming application, where the student can teach the TA in two ways: First, the student plays and the TA questions the learner during the gaming experience. Second, the TA plays the game and the student gives feedback in relation to the TA's action.	The master-apprentice is significantly more effective than the traditional method. Competitive collaboration is recognized as a more effective strategy than the traditional method. However, in their study, students preferred more collaboration than competition in their learning.

learning experience (Wang et al., 2018) and enhancing their mathematical knowledge and problem-solving skills (Ke, 2019).

Twenty-nine studies followed a quasi-experimental research design, and only 14 implemented the RCT methodology. The quasi-experimental method was the most utilized research design in all three categories. The limited number of RCTs could be attributed to the challenges associated with finding an equally engaging and motivating learning activity for students in the comparison group (Gauthier & Jenkinson, 2016). This observation is in line with reports of previously conducted reviews that have recognized the quasi-experimental design as the most employed form of research in DGBL (Boyle et al., 2016; Connolly et al., 2012; Hainey et al., 2016; Hussein, Ow, Cheong, Thong, & Ebrahim, 2019).

With regard to the areas of interest, the results showed that DGBL was used to teach a wide range of mathematics-related topics, with a specific interest in arithmetic operations (14 studies). A possible explanation for this emphasis is that arithmetic operations are essential for advanced mathematical achievements (Geary, 2011; van der Ven et al., 2017). Another justification for this trend could be that students' interactions with DGBL may help them develop a better understanding of arithmetic operations (Denham, 2015).

Twenty-eight DGBL studies were delivered via computers, nine were web-based, and hand-held devices were used only in eight studies. One possible reason for the extensive use of computers is that the majority of schools and educational institutes are already provided with computer laboratories. Therefore, researchers and educators often utilize computers to deliver learning content to students.

With regard to participants' age, the majority (n = 30) of studies were devoted to primary education, with 28 studies conducted on the primary education level and two studies on students from primary and junior high school grades. One possible reason for this trend is that games are inherently joyful and pleasing, particularly for young learners; therefore, combining mathematics and games could successfully reduce students' fear of learning this subject (Chang et al., 2012; Huang et al., 2014; Mayer et al., 2002). According to Khan et al. (2017), high school teachers have acknowledged the potential benefits of using DGBL in improving students' learning and engagement. However, Proctor and Marks (2013) observed that the utilization of DGBL application at the high school level was limited compared to its application the primary education. The lack of DGBL studies at the high school level could be attributed to barriers and hindrances that teachers experience when they attempt to adopt DGBL in the classroom. Such barriers include a mismatch between the knowledge and skills embedded in the game and those explicitly identified by the curriculum, lack of ICT skills, and negative attitude towards using games in a classroom environment (Papadakis, 2018; Sánchez-Mena & Martí-Parreño, 2017). Further, Romero and Barma (2015) stated that educators in primary education enjoy greater flexibility in their teaching activities, hence, they are more willing to integrate serious games in their classrooms than educators at the high school levels. Furthermore, one could argue that researchers prefer to focus on students in primary education as learners in this age group are easier to please and less demanding than students in high school grades who might require sophisticated and advanced DGBL applications.

Only 20 out of 43 studies provided background information concerning the design features and theories behind the design of the DGBL applications they utilized in their learning

interventions. It could be argued that this is a small percentage, and a possible explanation for this is that earlier DGBL research has mainly focused on using DGBL applications in a proof-of-concept manner to examine whether this method of instruction could lead to better academic achievements (Young et al., 2012), and only recently researchers have called for investigating how specific design features and learning theories could influence students' learning outcomes (Clark et al., 2016). Another plausible explanation is that most studies that have explored the effects of a specific design feature utilized a value-added comparison, and such comparisons require designing at least two DGBL applications, which is a time-consuming and financially demanding task. As previously mentioned, numerous design features were utilized by the studies reviewed in this article, which suggests that the developers of these DGBL applications are experimenting with these design features and learning theories to ascertain their impact on promoting students' mathematical knowledge. However, there was some interest in intrinsic and extrinsic design features as they were employed three times. Although their utilization did not produce conclusive findings, the results suggested that students in two out of these three studies preferred DGBL applications with intrinsic design features. This observation is supported by a similar finding reported by Westera (2015) who argued that playing such games is intrinsically satisfying for students.

The main purpose of the first research question was to investigate whether students in K-12 mathematics education can learn mathematics more effectively via DGBL compared to other methods of instruction. Findings revealed that in the category of knowledge acquisition, 22 out of 27 studies reported positive outcomes. In perceptual and cognitive skills, seven out of nine studies obtained positive outcomes. While in the category of affective, motivational, and behavioral change, six out of seven studies reported positive outcomes. Taking all the results into consideration, we can conclude that there is a promising potential to use DGBL in K-12 mathematics education, especially at the primary level, and in the category of knowledge acquisition. These findings are in agreement with previous reviews that revealed that DGBL applications were mainly used to foster students' knowledge acquisition (Boyle et al., 2016; Connolly et al., 2012; Hainey et al., 2016; Hussein, Ow, Cheong, Thong, & Ebrahim, 2019; Li & Tsai, 2013).

The second research question focused on how students learn mathematics more effectively via DGBL. The results demonstrated that there is a reason to believe that DGBL applications based on specific design features and learning theories are more effective than the base version of the same application. This finding is supported by a similar finding reported by Wouters and Van Oostendorp (2017) and Young et al. (2012). Results also suggested that embedding a specific design feature or a learning theory into a DGBL application does not guarantee improved performance, as other factors such as students' prior knowledge, gender, and cognitive abilities could influence how they perceive and interact with games.

8.1 Future directions

It is essential to provide more evidence regarding the effectiveness of this relatively new method of teaching. Researchers and educators are advised to consider the following research directions:

- Additional research is necessary to investigate how different learning dynamics (e.g., collaborative/cooperative, and competitive) could influence students' learning of mathematics, as findings from these studies did not produce conclusive results.
- Only a fraction of the studies included in this review was focused on cognitive skills such as problem-solving, while other twenty-first century skills have received no scholarly interest from the academic community. Thus, to address this concern, upcoming studies are encouraged to focus on utilizing DGBL applications to promote students' creativity and critical thinking skills in the domain of K-12 mathematics education.
- DGBL studies investigating the effects of a specific design feature could play a key role in improving the instructional effectiveness of DGBL. However, evidence suggests that using such features does not always improve learning. Therefore, to maximize their effectiveness, future studies are recommended to consider a number of factors such as students' gender, cognitive development, and prior knowledge.
- Although this review covered all K-12 educational levels, there was a notable lack of research investigating the academic value of DGBL on senior high school students. To provide additional empirical evidence pertaining to the effectiveness of this approach, future studies are recommended to explore the effects of DGBL on the mathematical learning of senior high school students.

8.2 Limitations

As with previous reviews and meta-analyses, the findings reported here were limited by the search terms, journals indexed by Web of Science, and Google Scholar metrics, and papers published between 2008 and 2019. The second limitation concerns the research design, as only RCT and quasi-experimental studies were considered in this paper; therefore, the outcomes reported by surveys and one group studies were excluded. The final limitation concerns the publication type. As this study focused only on peer-reviewed journals, the concluding remarks of proceedings, book chapters, or PhD dissertations were excluded.

8.3 Implications

This study is important from both theoretical and practical perspectives. Theoretically, the present article addressed the paucity of qualitative analysis focusing on DGBL in K-12 mathematics; therefore, the findings present a more complimentary understanding to researchers and educators who are interest in DGBL research, particularly, in the context of K-12 mathematics. Practically, schools could utilize the popularity of video games among K-12 students and the recent wide employment of technologies in education to develop training programs for teachers. These programs are required to familiarize teachers with using DGBL and the potential advantages of utilizing this method in mathematics education.

In addition, the traditional method does not take the individual differences among students into account; consequently, a considerable number of students feel isolated and left out when learning via the traditional method. Conversely, when schools and teachers implement the DGBL approach, they could provide students with the opportunity to learn at their own pace and the freedom to reexamine the learning material multiple times at their own leisure.

9 Conclusion

The current paper reviewed the literature regarding the implementation of DGBL in K-12 mathematics education. The initial search process resulted in 1347 research articles, suggesting that significant research attention has been given to DGBL in mathematics education. However, despite this surge in interest, there is still a paucity of research offering a thorough analysis of the current state of literature. To address this issue, the present study employed the multi-dimensional framework to systematically review, classify, and analyze the findings of 43 studies published between 2008 and 2019. These articles were sourced from the SSCI database of Web of Science and major educational technology journals according to Google Scholar metrics. In K-12 mathematics education, most studies have reported positive learning gains, and researchers have primarily focused on using DGBL applications in the knowledge acquisition category. Although there is cause for optimism, other areas exist that still require additional research to provide more evidence on the effectiveness of DGBL in K-12 mathematics education. For example, more research is needed to examine the impact of different learning dynamics on students' mathematical achievements. Moreover, there is a notable lack of research addressing various twenty-first-century skills. Therefore, more research is required to ascertain if the DGBL approach is effective in promoting students' twenty-first-century skills such as creativity and critical thinking. It is expected that this review will offer useful guidance to researchers, educators, and game developers in the area of K-12 mathematics education as well as the scholars working in other domains who are also interested in DGBL.

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Declarations

Research involving human participants and/ or animals This research did not include human or animal participants, hence, for this type of study formal consent is not required.

Informed consent As a corresponding author, I confirm that this paper has been read and approved for submission by the all the name authors.

Conflicts of interest/competing interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

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