



A systematic review of the role of learning games in fostering mathematics education in K-12 settings

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ABSTRACT

In the recent decade, a number of literature reviews were conducted to examine the effectiveness of learning games. However, prior reviews typically focused on providing a synopsis of the overall research trends and the games' impact on cognitive and non-cognitive learning, without providing critical and contextual information of learning-gameplay integration or the game design features. The current review focuses on recent empirical studies that implement learning games for K-12 mathematics education during the time period of 2008–2021 via a systematic search of the databases. Forty-three papers were identified as the result of a three-stage data extraction process. We identified the trends of implementing learning games in mathematics education and the ways to designing and integrating math content in gameplay. We propose that more research is needed to examine the design and use of learning games for math learning in K-12 settings. Recommendations for future game-based learning design and research are presented.

1. Introduction

Learning games refer to games designed for teaching specific skills, knowledge, and attitudes other than simply entertainment through gamified exercises and simulations (Ritzhaupt et al., 2011; Van Eck, 2015). In the recent decade, over twenty major literature reviews have explored the effects of learning games on students' performances (e.g., Boyle et al., 2014; Byun & Joung, 2018; Connolly et al., 2012; Hainey et al., 2016; Ke, 2016; Lämsä et al., 2018; Qian & Clark, 2016; Young et al., 2012). The majority of these reviews synthesized learning games across a wide range of disciplines, such as science, technology, engineering, mathematics, languages, and social areas. Only six of these reviews focused on mathematics education (Byun & Joung, 2018; Divjak and Tomic, 2011; Hussein et al., 2021; Joung & Byun, 2021; Lämsä et al., 2018; Tokac et al., 2019). However, it is widely considered that mathematics is a basic compulsory discipline around the world, and it is indispensable and fundamental for many different disciplines, including engineering, physics, economics, accounting, and many others (Cooper, 1994). Mathematics educators generally agree that the teaching and learning of mathematics requires different skills compared with that of other subject matters. As such, games designed and employed for mathematics education can differ from those for other subject matters.

Earlier review studies focused on evaluating the impact of games on math learning. For example, Divjak and Tomie (2011) conducted a systematic review of 27 identified studies published in 1995–2010 on game-based learning (GBL) for mathematics education. They concluded that math learning games not only promoted the targeted learning outcomes (with 21 out of 27 studies showing

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positive results), but also fostered students' motivation and positive attitudes toward math learning (14 out of 17 studies confirmed positive effects). To critically evaluate and statistically combine results of comparisons, Tokac et al. (2019) conducted a quantitative meta-analysis review of 24 studies to examine the effects of learning games on math achievement in PK-12 settings. The results showed that compared to conventional instructions, learning games led to better improvements for math learning ($d = 0.13$, $p = .02$). Along with Clark et al. (2016)'s emphasis of studying the relationships between game design and learning outcomes, Tokac et al. (2019) suggested that future studies should focus more on *why* and *how* such features of game design contribute to specific learning outcomes in the domain of mathematics. Recently, Joung and Byun (2021) evaluated the quality of 23 math learning games, with the aim of investigating whether the content embedded in the game is aligned to the Content and Process Standards proposed by the National Council of Teachers of Mathematics (NCTM, 2000). Nevertheless, this exploratory review study mainly investigated to what extent these learning games relate to NCTM without reporting critical and contextual information of game design methods and features governing learning-gameplay integration. Research examining how math content is characterized in the game, as well as how game design and implementation features affect learning, is warranted to strengthen the body of knowledge.

Therefore, this systematic literature review focuses on examining how games are used for math learning purposes and identifying game design elements that promote effective math learning. Specifically, it aims to address these questions: (1) What research methodologies are adopted to investigate the use of the learning games in mathematics education? (2) What are the trends of using learning games for mathematics education? (3) What are the salient approaches to integrating learning in the game world and game mechanics?

2. Methodology

2.1. Procedure

Two major sources were used to gather sufficient data to address the research questions. The previous reviews and articles served as the first source and the corresponding references were further investigated as the second source. Multiple online databases were employed to search and collect relevant articles, including JSTOR, ERIC, EBSCO, Psych Info, Dissertation Abstracts, and ACM.

The keywords used for searching relevant articles in this study include both single terms (e.g., computer games, video games, serious games, instructional games, game-based learning, math learning, and mathematics education) and their combinations (e.g., computer games for math learning, game-based learning for mathematics education).

A three-stage data extraction process (e.g., Läämsä et al., 2018), including screening, eligibility, and inclusion, was applied to select the appropriate articles for a rigorous systematic analysis. The detailed selection criteria for each stage are presented in Fig. 1 below.

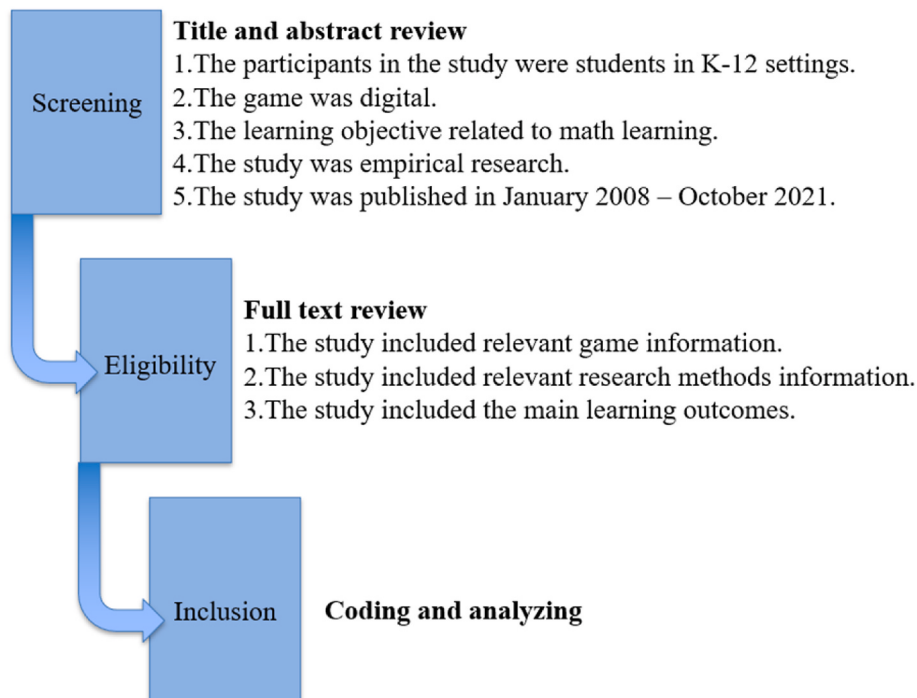


Fig. 1. The three-stage process for the systematic analysis.

2.2. Data coding

The constant comparative method (Strauss & Corbin, 1990) was adopted and used for coding the selected articles that met the inclusion criteria. The coding scheme included five phases. *First*, we focused on the features of math learning games in the selected studies. This coding focused on exploring (1) what the game genre is, based on the categories identified in Ke (2016), (2) what the platform for delivery is (i.e., video console, online game, VR, mobile, PC), (3) what the game functions are (e.g., drill and practice, application, learning tool), and (4) what the originality of the game (i.e., adopted from existing games or created/modified by the researchers). The coding of the *second* phase embraced (1) whether the game is played individually or collaboratively, (2) what the content is (e.g., algebra, arithmetic, geometry, mixed), (3) what standard or regulation the content is aligned (e.g., curriculum, standard), and (4) what the game-based task design is. In the *third* phase, our aim was to identify research methods used to examine math learning games in K-12 settings. We examined five main characteristics of the studies included in the review: (1) the research design (e.g., randomized control trial, (quasi-)experimental study, survey, correlational design, qualitative design), (2) the number and school levels of the participants, (3) the setting (classroom, after-school program), (4) the length of the intervention period, and (5) the moderating and independent variables of the study. The *fourth* phase emphasized the learning outcomes of the studies (e.g., knowledge acquisition, affective and motivational outcomes, perceptual and cognitive outcomes, and behavior change). In the *final* phase, we paid special attention to the game design features, particularly on how math content is integrated in the gameplay to impact the learning outcomes. The initial coding matrix was refined as the analysis process proceeded and a cross-case pattern analysis was conducted ultimately.

2.3. Quality of the studies

The quality of all the selected articles was gauged using the five-dimension criteria created by Connolly et al. (2012): (1) the appropriateness of the research design with respect to the research questions, (2) the appropriateness of the methodology and data analysis, (3) the generalizability of the findings, (4) the alignment of the study focuses and the research questions, and (5) the trustworthiness of the findings. All selected articles fulfilled such criteria.

2.4. Articles identified and selected

Table 1 shows the number of identified papers in each database using the search terms mentioned above. 1,370 studies in total were collected through the initial keyword-based search, among which 10 were found duplicated in the list after examining the search results synthetically. Consequently, 1,360 articles were used for the following three-stage selection process. Overall, 35 papers were identified after applying the inclusion criteria. Since we also employed the “snowball method” (Berg, 1988), in which the references of the previous reviews and relevant articles were further investigated, another 8 articles were included in the study. Thus, 43 papers were used for data coding and data analysis.

3. Results

3.1. Settings, participants, and intervention period

The most common learning setting described in the reviewed articles were regular school classes and after-school programs ($n = 38$), compared with the much smaller number of settings being at home or educational centers ($n = 4$). One study did not specify any information about its learning setting ($n = 1$). Of the 38 studies taking place in the formal school setting, 31 (81.58%) were performed in regular school classes and 7 (18.42%) took advantage of after-school programs to conduct the relevant research activities. Studies taking place in the regular school classes seemed relatively more effective than those performed in after-school programs as 3 out of 31 (9.68%) and 1 out of 7 (14.29%) respectively reported negative findings.

It was too dispersive to sort participants in terms of their age and grades because some studies did not report participants' age, or they recruited participants across the grades. Therefore, only the participants' grade level was analyzed. About half of the studies ($n = 20$) examined the effects of math learning games on elementary school students, with fewer studies on middle school students ($n = 15$), high school students ($n = 5$), or the crossed school levels ($n = 3$).

In the reviewed articles, the lengths of the intervention period varied. Slightly more than half of the studies ($n = 24$; 55.81%) used

Table 1

The numbers of papers identified in each database, identified following the screening, and selected for meeting the inclusion criteria.

Database	# of papers identified	# of papers identified after the screening	# of papers selected that meet the inclusion criteria
ERIC	157	49	25
JSTOR	708	14	2
Psych Info	67	21	2
ACM	290	7	1
Diss Abs	138	19	5
Snowball	78	21	8
Total	1,438	131	43

relatively longer intervention periods, ranging from 100 minutes to 2160 minutes. Approximately a quarter of the studies ($n = 10$; 23.26%) used shorter intervention periods, ranging from 15 minutes to 90 minutes. Several studies ($n = 9$; 20.93%) did not even report the intervention period.

3.2. Research design adopted

We found both experimental and non-experimental designs among the reviewed studies. The experimental design was prevalent in the reviewed 43 studies ($n = 40$; 93.02%), while a few others used non-experimental design, which consisted of qualitative inquiries ($n = 2$; 4.65%) and design-based research (DBR, $n = 1$; 2.33%). Among the 40 studies using experimental designs, quasi-experimental design ($n = 28$; 70.00%) was more prevalent than true experimental design ($n = 9$; 22.50%) and pre-experimental design ($n = 3$; 7.50%). Pretest and posttest group compare was the most popular design ($n = 37$; 92.50%) which included comparisons of game versus nongame conditions (i.e., media comparisons; $n = 26$; 70.27%), comparisons of augmented games versus standard game designs (i.e., value-added comparisons; $n = 9$; 24.32%), and comparisons of effects caused by individual difference on game play (e.g., players' characteristics; $n = 2$; 5.41%). Besides, the mixed-method ($n = 6$) and the repeated measure design ($n = 4$) were selected more than the factorial design ($n = 1$).

As shown in Table 2, about 80% of all the studies were conducted with a medium to large sample size, ranging from 50 to 435. A qualitative design study is normally conducted with small samples, with less than 30 participants, though one study (i.e., O'Rourke et al., 2013) used a sample size of 69 participants.

3.3. Research moderating variables and learning outcome

According to the research purpose, we categorized these studies into three clusters, including game play effects (i.e., pre-and-posttest one group comparison, media comparison, qualitative inquiry, and design-based research), game feature effects (i.e., value-added comparison), and effects of individual differences. Table 3 presents the summary of study designs focusing on game play effects, and it shows the results of the measures in terms of moderators and learning outcomes. The most investigated cognitive learning outcome was knowledge and skills acquisition ($n = 30$; 73.17%), followed by learning engagement ($n = 4$; 9.76%), meta-cognitive skills ($n = 2$; 4.88%), and learning behaviors ($n = 2$; 4.88%). The intervention of game play was most effective for improving students' learning behaviors ($n = 2$; 100%) and working memory ($n = 1$; 100%), followed by knowledge and skills acquisition ($n = 21$; 70%). Compared to conventional instruction approaches or non-game play conditions, the effects of game play on metacognitive skills ($n = 2$; 100%) and knowledge transfer ($n = 1$; 100%) were limited. Regarding the non-cognitive learning outcomes, the most frequently investigated dependent variables were students' motivation, attitudes, and self-efficacy towards math learning. More than 75% dependent outcomes were associated with positive results. The effects of game play were most effective for improving students' self-efficacy and least for decreasing math anxiety. In addition, prior studies also investigated how individual differences moderated the learning outcomes. The most popular moderators included gender, socioeconomic status (SES), prior knowledge of mathematics, and prior knowledge of gaming experience. For one third of learning outcomes ($n = 6$; 33.33%), individual differences were found to positively moderated the effects of game play learning.

Table 4 summarizes the studies on the effects of game features ($n = 9$) and individual differences ($n = 2$). Among the studies of value-added comparisons, all investigated the effects of three important game elements (i.e., user experience, learning, and gameplay) on students' cognitive and non-cognitive learning outcomes. Three components of the user experience were explored, including game embellishments, play mode, and feedback. Results indicated that the components of play mode and feedback effectively impacted students' cognitive and non-cognitive learning outcomes (i.e., Plass et al., 2013; Huang et al., 2014), but the effects of the embellishments on students' performance and motivational variables were very limited (i.e., Sedig, 2008). Incorporating learning supports in games led to significantly different and improved math performance but had no impact on the perception of game flow (i.e., Pan, 2019; Yang et al., 2018). Three components of the gameplay, including prompting strategy, surprise strategy, and adaptive system, were investigated. The research findings suggested that changing the design of these three gameplay strategies would cause significantly different cognitive and non-cognitive learning results, but not for knowledge transfer and math anxiety (i.e., Chen et al., 2012; Chu et al., 2021; Wouters et al., 2017; Vanbecelaere et al., 2021). Compared to students' motivation for math learning, students' SES had more significant impacts on the learning outcomes.

Table 2
Sample size by research design.

Research design	Sample size		
	Small (<50)	Medium (50–200)	Large (>200)
Pre-experimental design	2		1
True experimental design	1	8	
Quasi-experimental design	4	14	10
Qualitative design	1	1	
Design-based research	1		
Total	9	23	11

Table 3*Study Design with Game Play Effects in Terms of Dependent Variables and Moderating Variables.*

Variables	Pre-experimental N = 3	True experimental N = 6	Quasi-experimental N = 20	Qualitative N = 2	DBR N = 1
DV					
Cognitive					
Knowledge/skills	3(1-2-0) ^a	6(5-1-0)	20(14-6-0)		1(1-0-0)
Metacognitive skills	1(0-1-0)		1(0-1-0)		
Knowledge transfer		1(0-1-0)			
Working memory		1(1-0-0)			
Learning engagement		2(1-1-0)	1(1-0-0)	1(1-0-0)	
In-game performance			1(0-1-0)		
Learning behaviors		1(1-0-0)			1(1-0-0)
Non-cognitive					
Perception			2(2-0-0)	1(0-1-0)	
Attitude	3(3-0-0)	2(2-0-0)	3(1-2-0)		
Motivation		2(1-1-0)	6(6-0-0)	1(0-1-0)	
Anxiety			2(1-1-0)		
Self-efficacy	1(1-0-0)	1(1-0-0)	2(2-0-0)		
Moderator					
Individual differences					
Gender	1(0-1) ^b	1(0-1)	1(0-1)		
Age/grade			1(0-1)		
Ethnicity	1(1-0)				
SES	1(0-1)		2(1-1)		
Prior knowledge		1(0-1)	2(2-0)		
Prior computer experience	1(0-1)				
Prior gaming experience	1(0-1)	2(0-2)			
Language skill		1(0-1)			
Attitude	1(1-0)				
Playing time	1(1-0)				

Note.

^a A(B-C-D): A represents the total number of studies that measured the variable; B represents the number of measures with positive results; C represents the number of measures with no significant different results. D represents the number of measures with negative results.

^b A(B-C): A represents the total number of studies that measured the variable; B represents the number of measures with positive results; C represents the number of measures with negative results.

Table 4*Research on the effects of game features and individual differences with dependent variables and moderating variables.*

Variables	Embellish- ments N = 1	Feedback N = 1	Play mode N = 1	Learning support N = 2	Prompting N = 1	Surprise N = 1	Adaptive N = 2	SES N = 1	Motivation level N = 1
Cognitive									
Knowledge/skills	1(0-1) ^a	1(1-0)	1(1-0)	2(2-0)		1(1-0)	2(1-1)	1 (1-0)	
Knowledge transfer						1(0-1)	1(0-1)		
Cognitive load							1(1-0)		
In-game performance				1(0-1)		1(1-0)			1(0-1)
Learning behaviors				1(1-0)					
Non-cognitive									
Perception				1(1-0)	1(1-0)				
Attitude					1(1-0)		1(1-0)		
Motivation	1(0-1)		1(1-0)					1 (1-0)	1(0-1)
Anxiety		1(1-0)				1(0-1)	1(1-0)		
Self-efficacy				1(1-0)			1(1-0)		
Flow				2(0-2)					

Note.

^a A(B-C): A represents the total number of studies that measured the variable; B represents the number of dependent variables (learning outcomes) with positive results; C represents the number of dependent variables with negative results.

3.4. Game variables related to the research

3.4.1. Game genre

When the same game was used for different studies, or a study used a series of minigames that employed the same learning theory, we counted them as one game. In consequence, 33 games were found among the identified 43 articles. Puzzle games ($n = 13$) was the

most popular genre, closely followed by strategy games ($n = 6$), adventure games ($n = 5$), role-playing games ($n = 4$), action games ($n = 3$), simulation games ($n = 1$), and construction games ($n = 1$).

3.4.2. Game platform

Personal computer (PC) ($n = 38$), accounting for almost 88% of all the studies, was still the most popular platform for the delivery of math learning games. The rest were tablets ($n = 4$), and handheld game console ($n = 1$).

3.4.3. Game function

In the reviewed articles, most math learning games were designed and used for regular school class students ($n = 40$), and a few was purposefully designed for low-performing students whose math performances achieved were below the levels of their state exams or grade requirements ($n = 3$). Among these studies, only a few studies ($n = 4$) chose math learning games for the purpose of presentation and construction of novel knowledge, whereas the rest of them ($n = 39$) were designed and used as supplemental tools for instruction, such as a tool of drilling and practicing the prior/learned knowledge ($n = 16$) and a tool of developing and applying the learned knowledge ($n = 23$).

3.4.4. Game play mode and origin

With regard to the type of play mode, the studies were divided into three major categories: individual play mode ($n = 35$), collaborative play mode ($n = 5$), and mixed way play mode ($n = 3$). Individual play mode is still the primary choice among the reviewed articles, comprising 81.40% of the total studies, followed by collaborative play mode (11.63%) and mixed play modes (6.98%).

Games used in the reviewed studies, based on their originality, can be categorized into adoption (direct use without any change), and creation (use with modification or build from scratch). The results showed that more researchers preferred developing a new game from scratch or modifying an existing game based on the research purpose ($n = 22$) to directly using an existing math game (e.g., a commercial off-the-shelf game, an online game, etc., $n = 19$). The others did not specify a game source ($n = 2$).

3.4.5. Game-based math learning content

Games have been used to promote learning of various mathematics topics, including arithmetic, algebra, geometry, and mixed knowledge. More than half of the studies ($n = 24$; 55.81%) examined the effects of math learning games on students' arithmetic learning, whereas the number of studies that investigated the topic of geometry was the smallest ($n = 3$; 6.98%). Most of these studies ($n = 33$; 76.74%) asserted that the learning content embedded in the math games was aligned with educational standards, such as state curriculums, state assessment standards, as well as national council standards, with a few not reporting this information ($n = 10$; 23.26%).

3.5. Game design for learning

3.5.1. Game type, function and learning outcomes

As shown in Table 5, most of the math learning games in the target studies were frequently used as a supplemental tool for instruction ($n = 29$; 87.88%). Only a few studies ($n = 4$; 12.12%) employed games as a tool for novel knowledge construction. Table 5 indicates that most action games ($n = 2$; 66.67%), over half of the puzzle games ($n = 8$; 61.54%), and one third of strategy games ($n = 2$; 33.33%) were used as drill-and-practice tools. They were used to improve math proficiency, including conceptual understanding (e.g., Beserra et al., 2019; Hung et al., 2014; Vanbecelaere et al., 2021, 2021), and procedural fluency (e.g., Chang et al., 2015; Del Moral Pérez et al., 2018; Hoffman et al., 2021; Plass et al., 2013) that fall in the category of low-order cognitive learning. In these games, players were prompted to answer the corresponding math questions quickly to reach the game goals or sub-goals. Therefore, players were expected to activate prior knowledge and apply it to answer questions, thus engaging in reinforced knowledge application or drill-and-practice through gameplay. Particularly, if the learning goal was to improve students' computational fluency, time-limited in-game competitions with either computers or peer game players appeared to be the dominating game mechanic. For example, students were required to accurately and quickly complete the tasks by shooting the object (e.g., Castellar et al., 2015; Ku et al., 2014; Siew, 2018), choosing answers from multiple-choice questions (e.g., O'Rourke et al., 2013), or answering short questions (e.g.,

Table 5

Game types by functions, learning theory employed, and learning outcomes.

Game Type	Function		Learning Theory Employed			Math Knowledge	
	Application	Acquisition	Behaviorist	Constructivist	Experiential	Low-order cognitive	High-order cognitive
puzzle	X (12)	X (1)	X (12)	X (1)		X (8)	X (5)
strategy	X (4)	X (2)	X (3)	X (3)		X (2)	X (4)
action	X (3)		X (2)		X (1)	X (2)	X (1)
role-play	X (4)		X (1)		X (3)		X (4)
adventure	X (4)	X (1)	X (1)		X (4)		X (5)
simulation	X (1)				X (1)		X (1)
construction	X (1)				X (1)		X (1)

Abrams, 2008, p. 3296751) under limited time constraints. When the learning goal was to obtain a high-order cognitive learning outcome (e.g., proportional reasoning, and math problem solving), role-playing games ($n = 4$; 100%), adventure games ($n = 5$; 100%), simulation games ($n = 1$; 100%), and construction games ($n = 1$; 100%) were frequently adopted to engage students in solving math-related game missions (e.g., Chu et al., 2021; Fiorella et al., 2019; Ke et al., 2019; Swearingen, 2011; Yang et al., 2018). In these games, time constraint was not the emphasized element of game mechanics. Players were given relatively sufficient time to tackle the game mission. They were typically expected to complete an adventure-themed mission that required the application of math problem solving skills.

3.5.2. Learning theories for game design

Game designers often borrowed the elements from the perspectives of behaviorism, experiential learning, constructivism, or a combination of them, in the design of games for math learning. In this review, to reflect the dominating learning theory that guided the game design, we classified a game to one learning theory only.

Game developers frequently modeled game mechanics on psychological hooks where individuals learn to react in a certain way in response to a particular stimulus (Filsecker & Bündgens-Kosten, 2012). Players were required to use repetitive actions to complete game tasks and encouraged with reinforcement or rewards. We found that quite a few game designers ($n = 19$; 57.58%) employed behaviorist elements in the design of games for math learning (see Table 5). Surprisingly, games that illustrated a natural association between learning and play were sparse. Of the 19 games, only 2 (10.53%) games, *FactorReaction* (Plass et al., 2013) and *MATERIAL* (Es-Sajjade & Paas, 2020), portrayed the natural way of association between math learning and gameplay. For example, *FactorReaction* challenged the learner to transform a given number (center number) via appropriate arithmetic operations into a targeted number (surrounding numbers). In its essence, the game took a behaviorist approach by repetitions of the number transformation actions. The player's response to this challenge involved the selection of a specific number from a set of numbers and allowed for some flexibility in the combination with different numbers to achieve the game and learning goals. The game provided instant feedback to an incorrect attempt in such a visual form that the given number (center number) would immediately glow and jiggle. The task itself was an alternative format of answering arithmetic questions, but the game mechanics of converting numbers with arithmetic operations into a new number made learning and play intrinsically integrated. Students in the experimental group showed significant positive improvement in math performance (Plass et al., 2013). The major game mechanic for the games featuring extrinsic association between learning and play ($n = 17$; 89.47%) was to answer questions to earn game rewards (e.g., coins, or scores) or progresses. In these games, there were no innate connections between the learning task and the game fantasy. Players only clicked or chose the correct answer from multiple choices attached to the moving objects (e.g., balls, balloons, animals, aircrafts) in a fast-paced state to compete with either a computer or a real game player. We found (see Table 5) that almost all of the puzzle games ($n = 12$; 92.31%) employed behaviorist elements in the game mechanics, and the majority of them ($n = 8$; 61.54%) aimed to improve students' low-order cognitive skills, such as computational fluency (e.g., Beserra et al., 2019; Del Moral Pérez et al., 2018; Es-Sajjade and Paas, 2020; O'Rourke et al., 2013).

We found that the games targeting the high-order cognitive learning skills (e.g., math-related problem solving) frequently endorsed the experiential learning approach in game design ($n = 10$; 30.30%). To create a game world that fits for situated learning, game designers normally developed an adventure-themed mission in an authentic context. For example, a construction game *E-Rebuild* (Ke, 2019; Ke & Clark, 2020; Pan, 2019) depicted the mission of rebuilding a disaster-damaged space by applying math knowledge and solving context-rich math problems. In a role-playing game *Dimension-M* (e.g., Gillispie et al., 2010), players needed to escape from a deserted island by solving various problems in a military bio-technology facility. Players were immersed in a context to learn math knowledge and skills by solving game missions and accomplishing game objectives.

Proponents of constructivism believe that learning will occur through interactions with the environment (Vygotsky, 1978). In the games driven by constructivism, learners needed to construct their own mental model of the math content through interactions with the game system. Frequently, these games modeled a context in which learners could experiment on their math explorations with immediate feedback (Obikwelu & Read, 2012). Among the studies reviewed, there were 3 strategy games (i.e., Barreto et al., 2017; Kolovou et al., 2013; Pareto et al., 2012) and 1 puzzle game (i.e., Sedig, 2008) employing the learning theory of constructivism. For instance, the game *Hit the Target* (Kolovou et al., 2013) was created to teach early algebra for sixth grade students. In the game, to obtain a specific total score, the players needed to actively interact with the game environment by selecting appropriate combinations of the shooting option (user shooting vs. computer shooting) and the scoring option (user-defined scoring rule vs. computer-defined scoring rule). Specifically, the player needed to dynamically 'construct' their own gaming strategies to interact with the game mechanism in order to achieve the scoring goals, during which their mental model of the corresponding math solutions could be established. It is noticed that in these four studies driven by constructivism, three reported positive findings on both cognitive and affective learning, but one study (Barreto et al., 2017) reported that students gained limited math knowledge from game play, and they were not always motivated to play the game.

3.5.3. Math content integration via contextualization, representation, and simulation

Three kinds of meaningful math content integrations were found in the literature – contextualization, representation, and simulation. Contextualization is aimed at engaging a game player in a game world via empowering the player as a specific character completing an adventure-themed mission (Ke, 2016). In the reviewed articles, contextualization was frequently employed to apply learned math knowledge to solve problems in a simulation of authentic learning situations so that they would feel that mathematics was a part of their daily life, which further motivated them to master the math content because of the established relevancy ($n = 18$). Among these 18 games, we further differentiated them into both intrinsic ($n = 11$) and extrinsic ($n = 7$) contextualization in terms of

the relevancy between the content and the gameplay. The intrinsic contextualization refers to games in which the content being used is closely associated with the storyline or fantasy (Ke, 2008a). For example, *Speedy World* (Wang et al., 2018) was a role-playing game designed to teach arithmetic multiplication with the story of “Tortoise and the Hare”. Students playing the role of the tortoise were requested to catch up with the hare using math knowledge that was intrinsically integrated into the game mechanics. This study found a positive impact of the game on both cognitive and non-cognitive learning. Over half of the studies with intrinsic contextualization ($n = 7$; 63.64%) reported that learners in the experimental group showed significant improvements in math achievement. In contrast, the content in an extrinsic contextualization is only weakly related to the game mechanic. For example, the mission of the game *One Piece* (Chu et al., 2021) was to get the treasure and power to defeat the evil, which did not have an intrinsic connection with the learning actions of answering math word problems. Nevertheless, most of these games ($n = 5$; 71.43%) were still associated with positive impacts on cognitive learning.

Conceptual representation refers to the embodiment of the concept in game objects that is purposefully designed (Ke, 2016). In the selected papers the games fostered meaning-making between the abstract math concepts and the concrete objects in the game world. For example, Pareto and his team developed board games (e.g., *Find Pair*, *Pack Many*, *Remove All* and *Divide*) to teach a basic arithmetic topic, such as the base-10 number system for elementary school students (Pareto, 2014; Pareto et al., 2012). Math content was embedded in the game action of translating symbolic representations to graphical representations. For instance, the number 87 was represented by 8 orange and 7 red squares, ordered left to right to portray different decimal positions. Additionally, Riconscente (2013) used *Motion Math: Fraction* to teach novel knowledge of how fractions, proportions, and percentages were related to the number line with 122 5th graders who played the game 20 minutes per day over 5 consecutive school days. Students learned new knowledge through locating the right position on a given number line and maneuvering various representations of fractions, percent, decimals, or pie charts. The relation between the fraction and the number line was visually presented and illustrated, making conceptual understanding an innate action of gaming. The results of this study indicated that students who played the game exhibited significant improvement in the knowledge test of fractions as well as attitudes toward math learning (Riconscente, 2013). Learning integration via conceptual representation was found in multiple math learning games (e.g., Barreto et al., 2017; Vanbecelaere et al., 2020, 2021; $n = 7$). These studies generally reported positive impacts of GBL.

Simulation, defined as a way to simulate a scientific and/or complex system (Ke, 2016), was another approach used to intrinsically embedding the math-specific content in the GBL environment ($n = 1$; 3.03%). For example, in the study of Panoutsopoulos and Sampson (2012), the researchers used a commercial business game called *Sims2 - Open for Business* to simulate the professional business activities to teach complex math problem solving skills for high school students. Players needed to run a business and keep customers satisfied by applying data monitoring, strategic thinking, and decision making. Empirical research findings suggested that using this simulation game in lecturing improved math problem solving skills for students but there was no impact on the attitudes toward math learning and teaching.

3.5.4. Learning embedded in the game

3.5.4.1. Learning embedded in game world. In-game references, remedial instruction, and cues/hints were the most frequently used approaches that enabled the association of learning with the game world. In-game references could be embedded as a game object situated in the game world, such as a “guidebook” (e.g., Wale, 2013, p. 3606018) or a “journal” (e.g., Gillispie et al., 2010) that summarized game dialogue and math concepts. In other cases, in-game references were integrated into the game world via an ever-present learning support panel that allowed players to review the math-relevant information whenever they needed (e.g., Ferguson, 2014, p. 3613196). Remedial instruction was built as a section that presented the explicit in-game math content instruction when students failed to complete a game level or a quest (e.g., Huang et al., 2014; King, 2011, p. 3468187; Lin et al., 2013). Cues/hints were presented through the head-up display (e.g., Kolovou et al., 2013), task-oriented display (e.g., Abrams, 2008, p. 3296751; Yang et al., 2018), or an end-of-level performance summary (e.g., Del Moral Pérez, 2018; Ferguson, 2014, p. 3613196).

The in-game math content was presented via text messages, graphical illustration, animations/videos, and often various combinations of them, in the design of the game world. A good example was *Ko's Journey* that provided multimedia presentations of key math concepts in the form of diagrams, photographs, and texts, so that students were able to consult them when needed. Students acquired novel knowledge through the process of collecting, organizing, and integrating the relevant information to solve the scientific quest. Learners were challenged with math-oriented game quests and had to locate useful information by exploring the background knowledge (Wale, 2013, p. 3606018).

3.5.4.2. Learning embedded in game mechanics. Learning with Game Actions. In the reviewed games, two different approaches - in-game prompts and learning scaffolds - were used to embed learning in game mechanics, especially in game actions. In-game prompts urged players to reflect on their game actions, thus stimulating math learning processes during gameplay. For example, Pareto and his team (Pareto, 2014; Pareto et al., 2012) designed a math game to serve as a supplement to the class instruction for the base-ten addition and subtraction. In the game a teachable agent provided in-game prompts to stimulate meta-cognitive reflection (e.g., strategic use, and reflective use) to promote math learning. The findings reported that the game-playing group had significant math learning gains and self-efficacy, but not for attitude.

Learning scaffolds aimed to assist players in tackling the game task by providing instructional hints as needed. The game *Motion Math: Fraction* (Riconscente, 2013) exemplified how learning scaffolds were designed to strengthen students' conceptual understanding of the relation between fractions, proportions, and percentages to the number line. Repeated failed game actions triggered

instructional scaffolds with an increasing level of elaborations on the underlying math concepts, in both visual and symbolic forms. The study found that both math comprehension scores and students' attitude toward math learning increased significantly for the game-playing group.

Learning with Agent Interaction. This review identified 8 papers featuring the use of pedagogical agents within the game world. Generally, the results presented in these studies showed that students perceived immersed (Pareto, 2014; Wang et al., 2018), became confident (Pareto et al., 2012), developed self-efficacy (Pareto et al., 2012), and became more motivated and eager to play more (Chen et al., 2012; Pareto, 2014; Wang et al., 2018). Students acquired knowledge by interacting with computerized agents (or game characters) because agents could engage them either cognitively or affectively (e.g., Huang et al., 2014; King, 2011, p. 3468187; Pareto et al., 2012; Wang et al., 2018). For example, in a role-playing game called *Zeldenrust* (Wouters et al., 2017), the hotel manager delivered not only the task information and learning prompts, but also feedback on the task performance. The content presented by the agents encompassed multimedia math content presentation and problem solving guidance.

3.5.4.3. Learning embedded in assessment mechanics. End-of-level performance summary was the most frequently used learning feature associated with the assessment mechanics. In general, the game gave summative feedback on the player's performance along with a reference link for the task-related, math content review (e.g., Del Moral Pérez et al., 2018; Ferguson, 2014, p. 3613196).

The game *Hit the Target* (Kolovou et al., 2013) exemplified a way to integrating learning in assessment. Students evaluated and refined their game actions based on instant feedback. As the game proceeded, a player would decide the numbers of missing, hitting, or at-random shots on a control panel before shooting the arrows. The player could either set all the numbers at once and let the computer finish all the shots, or set some numbers first and then drag an arrow to shot, and then repeat such an action. In either way, players were able to calculate the corresponding scores shown on the scoreboard based on the shooting results, and to evaluate and refine their game actions (arrow shooting) according to such instant feedbacks. By adjusting varied combinations of missing and hitting shots, and also calculating the corresponding scores out of the shooting performance, players could practice math operations, such as adding and subtraction, in an intuitive and interesting approach during the game play. This game was reported to produce significant learning gains for the intervention group (Kolovou et al., 2013).

4. Discussion and conclusion

This paper has presented a systematic literature review of the math learning games in K-12 settings over a 13-year period from January 2008 to October 2021. A three-stage process (e.g., Lämsä et al., 2018) was applied to select the appropriate articles for rigorous systematic analyses. The 43 selected articles that met the inclusion criteria were coded. Using the aforementioned systematic analyses, we highlight and discuss the emerged salient aspects among these studies as follows.

4.1. Methodology in studying the impact of learning games on mathematics

4.1.1. Research design

Although we observed different research designs applied in the reviewed research, a large quantity of studies ($n = 37$; 86.05%) opted for the pretest and posttest experimental design, which is recognized as the best practice for game-based learning studies (All et al., 2016). According to different research purposes, these reviewed articles can be categorized into three types: (a) game play effects (i.e., pre-and-posttest one group comparison, media comparison, qualitative inquiry, and DBR), (b) game feature effects (i.e., value-added comparison), and (c) effects of individual differences. The findings showed that comparisons of game versus nongame conditions were still prevalent ($n = 26$; 60.47%), indicating that proving the effectiveness of learning games is still a big concern in the field. Meanwhile, one fourth of the studies ($n = 11$; 25.58%) investigated the effects of specific game design features (e.g., user experience, learning, and gameplay) and learner characteristics (e.g., SES and motivation), showing that some researchers identified the importance of studying the relation among game design, individual characteristics, and learning outcomes. The majority of these studies reported significant results of these independent variables on cognitive and non-cognitive learning outcomes. However, the lack of replicated studies makes it challenging to generalize the research findings. Therefore, we argue that empirical and theoretical research about the design and use of learning games on students' math learning is still limited. We recommend that researchers extend studies by applying variant research designs and conducting more value-added comparisons.

4.1.2. Characteristics of participant and setting

The majority of the studies (88.37%) used elementary and middle school students as the target subjects. This finding is consistent with the recent systematic review conducted by Gao et al. (2020), where they found that 86.67% reviewed studies in the field of mobile game-based learning for STEM education were conducted with elementary and middle school students. Some reasons may underlie such a finding. First, students in elementary schools may be the most accessible target subjects for researchers (Byun & Joung, 2018). It may also be due to the fact that math content at the low grade level is easier to be incorporated into the game than those at the high school levels, because mathematics becomes more abstract as the school level increases. Therefore, we suggest that game developers should contribute more design effort to GBL for math topics in higher school levels (e.g., algebra and geometry).

With respect to the sample size, we observed that most studies, especially quantitative studies, tended to use medium to large sample sizes to achieve higher accuracy and more persuasive results. This finding is different from prior research of Petri and von Wangenheim (2017) who found that most studies were conducted with very small sample sizes.

Regarding the selection of learning settings, formal learning was still preferred, indicating that researchers tended to be more interested in investigating the use of GBL in formal than informal educational contexts. From another point of view, GBL is still new compared to other learning methods (e.g., computer-based instruction, computer-supported collaborative learning, online learning, etc.) in the domain of mathematics education. It may explain why most studies in our articles pool chose school classrooms as the intervention setting.

4.1.3. Learning outcome and moderating variables

The reviewed studies used content-specific (i.e., math) learning games rather than content-generic ones to examine if the games could enhance students' math performance, including math problem solving, algebra skills, strategic and reasoning abilities, mental computation skills, critical geometry skills, and arithmetic procedures. Consequently, students' knowledge acquisition and content understanding were the most prevalent dependent variables investigated in these reviewed studies.

Positive effects of game play on students' math learning performance were consistently shown in the reviewed studies. However, this finding should be interpreted with caution. For example, it is worth noting that the number of studies examining the effects of GBL on students' learning behaviors and working memory is still small, even though a positive impact of GBL was reported. Likewise, there was no enough evidence suggesting the benefits of game play for metacognitive skills and knowledge transfer. Future research is warranted to examine whether and how GBL will impact these learning outcomes.

Students' non-cognitive learning outcomes, such as motivation, self-efficacy, attitudes, and sense of flow, were frequently examined across the studies. Most of the studies had at least two measures on these non-cognitive learning outcomes and the majority (73.17%) found positive results, especially for self-efficacy toward math learning.

Regarding studies investigating the association between individual differences, game play, and the learning outcomes, only one third of the measures found that individual differences positively moderated the effects of GBL on the learning outcomes. Similar results were reported in prior studies (e.g., Tokac et al., 2019), where they found that whether individual differences moderated game play or game-based learning was still inconclusive. A better understanding of how specific characteristics of game players affect learning experience is needed.

4.1.4. Generalizability issue

This review indicates that one needs to be cautious to generalize the results to different populations or implementation settings. It remains misty as to why the same game used in different studies would lead to contradictory results (Wale, 2013, p. 3606018). An interpretation is that the use of math learning games was mediated or moderated by a series of different compounding factors, including but not limited to individual characteristics, learning environment features, and learning content. This may explain the inconclusive effects of GBL on students' learning and motivation. Research on *DimensionM* is an example. Three studies (Bai et al., 2012; Gillispie et al., 2010; Kebritchi et al., 2010) indicated that middle and high school students who played *DimensionM* showed significant improvement in math achievement but lacked enhancement in motivation. However, one study conducted by Ritzhaupt et al. (2011), investigating the effects of *DimensionM* with 225 low-SES middle school students, found no significant change in students' math performance but significant progress in students' attitudes towards math learning and self-efficacy.

4.2. Trends of using games for math education

In this review we found that learning games with different genres were employed in math learning, but the puzzle game was still the most frequently used game genre ($n = 13$; 39.40%). Similar results were reported in Byun and Joung (2018), where they found that the puzzle game (e.g., drill and practice game) was the predominant game genre in the reviewed 33 empirical studies published in the years of 2000–2014 relevant to digital game-based math learning. In addition, we found that over the half of the puzzle games ($n = 8$; 61.54%) were applied to improve students' low-order cognitive skills.

Individual play mode ($n = 35$, 81.40%) was mostly used in the reviewed articles. However, it should be noted that all of the studies that employed the collaborative play mode ($n = 5$, 11.63%) reported the significant improvement of the math knowledge gains or positive attitude toward math learning.

The current study finding on the selected math topics embedded in the game design is consistent with prior reviews (Byun & Joung, 2018; Joung & Byun, 2021): the largest number of studies investigated the effect of GBL on arithmetic, followed by algebra and geometry. We found that math learning games are frequently designed and used as a practice tool or a supplement to regular class instruction, which is consistent with what Ke (2016) discovered in the systematic review of the GBL in general. Learning games are considered as a planned application or a pedagogical instrument for in-class instruction rather than a stand-alone teaching-learning approach (Ke, 2016).

Notably, this review has a different discovery from a previous finding (e.g., Ke, 2008b) that learning games used in prior research lacked the connection to school curricula. We found that the majority of the studies employed curriculum aligned content in the games used or designed. In addition, this review demonstrates that half of the studies ($n = 22$) used self-modified or self-developed math learning games. These two findings suggest that more researchers have emphasized the importance of integrating education into games rather than integrating games into education as a prior review claimed (Kebritchi et al., 2010).

4.3. Game design for math learning

Our observation governing how math content is characterized in the game world is consistent with prior research (i.e., Ke, 2016).

Contextualization and representation are more frequently employed than simulation as an approach to integrating math content in the game world. The former approaches are more frequently used to improve players' cognitive and emotional learning than the latter one. It is possibly due to the fact that mathematics heavily relies on signs, numeral expressions, algorithms, and their endless combinations, thus it is difficult to simply simulate math calculations. Meanwhile, it is a common sense that mathematics exists everywhere in our daily life and is easily contextualized into different scenarios. Hence, games could act as a dynamic platform to transform abstract math knowledge into concrete and visual objects or representations (Pan et al., *in press*), as well as into easy-to-understand contexts.

To create an effective game-based learning environment, math content should be intrinsically embedded in the game world, game mechanics, and/or assessment mechanics. In-game references, remedial instruction, and cues/hints are the most frequently used approaches that enable the association of learning with the game world. In-game prompts, learning scaffolds, as well as agent interactions are usually incorporated in the game mechanics. End-of-level performance summary is frequently used to incorporate the content for remedial purposes. In addition, learning can be created by mapping learning actions onto game assessment mechanics. In future studies, researchers are encouraged to explore how these approaches influence students' math performance.

In our review, we found that behaviorist elements (57.58%) were most frequently used in the design of games for math learning, followed by experiential learning and constructivism. It is worth mentioning that many games employed the combination of these learning theories. Quite a few researchers argued that learning needs to be embedded in a game's core mechanics rather than acting as an add-on. Specifically, gameplay cannot be used as a reward for question answering; vice versa, questions cannot be forced into unrelated gameplay (e.g., King, 2011, p. 3468187; Wale, 2013, p. 3606018). Games, particularly those that serve as drill and practice tools for improving students' computational fluency, are usually considered less effective than other game genres. However, our review with the empirical studies did not support this claim. The majority of those studies that employed games as drill and practice tools reported positive findings on both cognitive and non-cognitive learning. A potential reason could be that the improvement derives from computer-aided learning (CAL) rather than game-based learning. CAL provides multimedia information and instant feedback that has been proved to be an effective way to enhance math learning.

Furthermore, the current review indicates that the learning goal is critical in determining the use of the game genre and game mechanics. When the learning goal is to improve students' computational fluency, the puzzle games that emphasize competitions with computers or a peer game player with time constraints tend to be the first preference. If the learning goal is about high-order cognitive learning, role-playing games, adventure games or simulation games have been used, by promoting the application of the acquired knowledge in math-related game missions. This finding supports the proposition by Byun and Joung (2018) that a specific game genre might be better for certain math content. We assume that there is an association between learning goal, math content, and game genre.

5. Implications, limitations and future research

The review findings provide an initial insight into the design and implementation approaches of GBL for mathematics education in K-12 settings during the years 2008–2021. Consistent with prior review studies (e.g., Byun & Joung, 2018; Clark et al., 2016; Gao et al., 2020; Hussein et al., 2021; Tokac et al., 2019), the current study partially supports the feasibility of the employment of GBL in K-12 school settings, but more research is warranted to recommend the use of GBL for teaching different math topics. The review indicates a set of implications for game developers, educators, and teachers. First, game developers should ensure that the game is designed as a pedagogical instrument or a planned application tool. Second, game activities should be aligned with students' preferred modes of gameplay, their prior knowledge, as well as the learning tasks. In addition, the embedded content should be aligned with the target curriculum or content standards to promote knowledge transfer. Teachers will then choose the game based on learning goals and math content. For instance, puzzle games might have positive impacts on participants' procedural fluency in mathematics but do not necessarily enhance students' high-order learning outcomes. Lastly, teachers should provide students who lack sufficient prior knowledge of mathematics with instructions on how to identify, transform, and coordinate math information embedded in the game world. For example, teachers can provide exercises and examples of math representational transformations before game play and encourage students to share their learning experiences after game play.

We must point to a few limitations in the study. First, it was limited by the search terms used and the databases used. Second, the review excluded studies that did not provide sufficient information of the game design due to our intent to understand the features governing learning-gameplay integration. Third, this review included studies of different research design approaches. It should be noted that some studies provided limited description of equivalence between the treatment and control group, particularly lacking explanation on how students in the control group were given alternative instructions.

Our review raises several opportunities for future research to refine and elaborate on the investigation of GBL. First, it is recommended that researchers should provide a detailed description of game mechanics, learning mechanics, assessment mechanics, as well as the rationales for game selection or game development. Second, longitudinal and systematic research on learning games is warranted. For example, scholars have started to realize the impact of time on GBL and attempt to extend the game-playing duration. Future research could elaborate on this point, providing critical information on whether the time of game-playing influences the results. Future research is also needed to investigate the add-on value of GBL in comparison with CAL in math education. Research on math learning games have emphasized the acquisition of in-game math content without examining knowledge transfer. Future studies could explore whether and how students with low competency will transfer the knowledge gained in the game to external math tasks. Lastly, future research on what and how game features will contribute to effective learning is warranted. We recommend that researchers should endorse more rigorous research design in conducting value-added comparisons with game design and implementation features.

CRedit authorship contribution statement

YanJun Pan: Idea construction, data collection, data analysis, writing, and editing. **Fengfeng Ke:** Supervision, reviewing and editing. **Xinhao Xu:** Idea development, data collection, reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.edurev.2022.100448>.

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