J. Comput. Educ. (2022) 9(3):455–476
https://doi.org/10.1007/s40692-021-00210-y

Three decades of game-based learning in science and mathematics education: an integrated bibliometric analysis and systematic review

Pei-Ying Chen[1] · Gwo-Jen Hwang[1] · Ssu-Yin Yeh[1] · Yi-Ting Chen[1] · Ting-Wei Chen[1] · Chih-Hsuan Chien[1]

Received: 18 July 2021 / Revised: 19 October 2021 / Accepted: 24 October 2021 /
Published online: 31 October 2021

Abstract Digital game-based learning research has received increasing attention in recent years due to advances in technology. A systematic review was conducted to understand the current status and potential of game-based learning (GBL) research in science and mathematics. This study reviewed articles on GBL in science and mathematics education published in the Web of Science (WoS) database from 1991 to 2020. The 146 articles were selected for content and bibliometric analysis. After a systematic analysis of the trends and overviews, we present discussions and insights for the future. The study raised relevant research questions to analyze authors, regions, applied subjects, educational stages, research methods, game types and devices, performance issues, and author keywords. The results revealed that the majority of the published research in this field has been carried out in Taiwan, followed by the United States. GBL is currently applied in mathematics and science to increase learner motivation and engagement and reduce learning anxiety. The results also revealed that higher order thinking skills such as problem solving, group

✉ Gwo-Jen Hwang
gjhwang.academic@gmail.com

Pei-Ying Chen
chvicky@gmail.com

Ssu-Yin Yeh
future3031@gmail.com

Yi-Ting Chen
yiting19961221@gmail.com

Ting-Wei Chen
kiwichen0911@gmail.com

Chih-Hsuan Chien
sharonchien2020@gmail.com

[1] Graduate Institute of Digital Learning and Education, National Taiwan University of Science and Technology, #43, Sec.4, Keelung Rd., Taipei 106, Taiwan

collaboration, and critical thinking, have become an increasingly important focus of research in recent years. The systematic review also found that researchers have been engaged in the field since 1993 and have conducted a large number of studies since 2011. In terms of keywords, game-based learning and interactive learning were the most used keywords in the articles, indicating that they were the most explored topics by researchers, while learning behaviors and competition were relatively new directions to explore. This study analyzed and summarized GBL in science and mathematics education in the hope that it may contribute to future research.

Keywords Game-based learning · Science · Mathematics · Bibliometric analysis · Systematic review

Introduction

Science learning lags behind other subjects in early education. Scholars have found that exposure to science learning can be a great help for students' future long-term achievement (Herodotou, 2018). Natural science is a required subject for students in compulsory education (Wang & Zheng, 2021), and scientific literacy is also considered a core literacy of students' learning (Valladares, 2021). The understanding of natural science, the realization of personal goals, and emphasis on the development of intelligence and communication skills are all related to each other (Holbrook & Rannikmae, 2007). Some scholars have also mentioned that science education will further affect students' attitudes towards science, indirectly affecting the degree of understanding of learning a concept (Alsop & Watts, 2003), with their problem-solving skills and advanced thinking skills. Li and Tsai (2013) published a review of empirical research articles on games-based science learning (GBSL), exploring the development of digital games in the field of science from 2000 to 2011. Traditional teaching methods focus on the views of the teacher and the textbook, with less consideration given to motivating students to engage in scientific exploration activities. Therefore, compared with technology-supported learning, traditional learning methods are more likely to lead to a lack of interest and motivation in learning science (Song et al., 2016).

Since the twentieth century, with technology development, games have been integrated into the educational world. In the early twenty-first century, learner-centered educational games began to emerge rapidly, and many researchers believe that digital games can help learners learn. From an educational standpoint, digital games are suitable for various themes, subjects, and different age groups (Annetta et al., 2009). The lesson and new knowledge from digital games often tend to stay with students because of the interactive nature of the learning experience (The New Media Consortium [NMC], 2005). For example, digital games improve conceptual understanding and problem handling (Ke, 2014). They also help learners discover new rules and ideas for themselves instead of memorizing, as well as improving students' learning performance and enjoyment (Hung et al., 2015). The issue of game-based learning (GBL) has been gaining attention and research in recent years (Gee, 2014). GBL is divided into digital game-based learning (DGBL) and traditional game-based learning, with types of serious games, contextual games, and immersive games. GBL is a learning style that presents learning content digitally, incorporates game features into the teaching content, and uses these features to stimulate learners' interest in learning and to enhance their confidence in learning (Kuet al., 2014). GBL creates a comfortable learning environment, and then enables learners to actively participate in learning to enhance learning motivation and learning effectiveness (Chen et al., 2012). Prensky (2007) also noted that the characteristics of DGBL include entertainment, playfulness, rules, goals, human–computer interaction, outcomes, and feedback, appropriateness, sense of victory, competitive conflict and challenge, problem solving, social interaction, images, and emotionality. When learners consider it fun, feel challenged, and are willing to learn on their own, it increases their self-efficacy and learning persistence (O'Rourkeet al., 2017).

Game-based learning is an approach that has shown to have the potential to transform science teaching and learning (Wang & Zheng, 2021). Digital games have been shown to increase learners' motivation and learning effectiveness; it is hoped that this will change the teaching drawbacks by eliminating the use of memory or other traditional teachings that reduce the willingness to learn in science education (Honey & Hilton, 2011; Mayo, 2007). To allow students to acquire knowledge and twenty-first century competencies (e.g., critical thinking and problem-solving skills) through digital games, many scholars have proposed a variety of educational games for science learning (Barab & Dede, 2007; Maxmen, 2010; Mayo, 2007). Divjak and Tomić (2011) reviewed game-based learning for learning mathematics and found that GBL has a positive impact on students' learning outcomes, motivation, and attitude towards mathematics. Mathematics is also considered a key discipline in higher education and a foundation for other fields of study such as science, engineering, or technology. Although mathematics is a critical part of learning, many learners still report that mathematics courses are not easy to learn, that they are prone to difficulty and risk of failure, that negative performance ratings are high, and that learners often experience intense stress and anxiety (Roick & Ringeisen, 2018).

This study includes literature from the fields of science education and mathematics education. Researchers have suggested that learners' attitudes toward mathematics, including their feelings and perceptions of mathematics, originate from and are influenced by memories of past failures and successes, interactions with the environment, the teaching methods they receive, the types of mathematics they are exposed to, and the learning environment they are in (Martinez, 1996). It has been shown in past studies that the application of GBL in science and mathematics education not only enhances learners' learning outcomes but also increases their motivation (Alrehaili & Al Osman, 2019; Chen et al., 2016). Moreover, GBL in science and mathematics education improves learning attitude (Chiang & Qin, 2018), enhances engagement (Bressler & Bodzin, 2013), improves technology acceptance (Hwang et al., 2012; Lin & Hou, 2016), raises self-confidence (Pareto et al., 2012), and decreases learning anxiety (Verkijika & De Wet, 2015). In this study, GBL is examined in the fields of science and mathematics education to measure learning issues and the 5C key competencies including communication and collaboration

(Gil-Doménech & Berbegal-Mirabent, 2019), problem solving (Ke, 2019), critical thinking, and creativity for further review and analysis of learning outcomes.

GBL has an enormous influence on current education. The GBL research in science and mathematics education is also growing and developing more widely. In this study, we reviewed the literature on the application of GBL in science and mathematics education. The analysis is divided into three time periods: 1991 to 2000, 2001 to 2010, and 2011 to 2020. A systematic review of GBL in science and mathematics education was conducted by searching the Web of Science (WoS) database to understand the current state and potential of GBL in science and mathematics education. The research questions of this study are as follows:

1. Who are the most influential authors in the field of GBL in science and mathematics education in the last 30 years?
2. Which regions have made the most contributions in the field of GBL in science and mathematics education in the last 30 years?
3. What are the most popular platforms/devices and game genres used in the field of GBL in science and mathematics education in the last 30 years?
4. What are the most popular subjects in the field of GBL in science and mathematics education in the last 30 years? What is the education level of the learners?
5. What are the research methods and measurement issues in the field of GBL in science and mathematics education in the last 30 years?
6. What is the cluster analysis of keywords in the field of GBL in science and mathematics education in the last 30 years?

Research methods

Data collection journal database from 1991 to 2020

Considering the purpose of this study, we drew on previous literature and developed two groups of keywords to identify articles for the main analysis: (a) keywords covering games, such as game-based learning, GBL, learning games, serious games, educational games, game for learning, video games, gamification, digital games, game, gaming, gameful, gameplay; and (b) keywords related to science and mathematics for subjects and competencies, such as science, sciences, biology, chemistry, physics, science education, environmental education, ecological science, and mathematics. Consequently, the Boolean expression ("game-based learning" or "GBL" or "learning games" or "serious games" or "educational games" or "game for learning" or "video game" or "gamification" or "digital games" or "game" or "gaming" or "gameful" or "gameplay") AND ("science" or "sciences" "biology" or "chemistry" or "physics" or " science education" or "environmental education" or "ecological science" or "mathematics") were applied to search the publications (Gao et al., 2020; Hwang & Chen, 2021). Next, according to several literature reviews, it is important to conduct a review based on quality publications in relation to education and technology with high impact factors, the journals were limited to the following seven: the British Journal of Educational Technology (BJET), Computers and

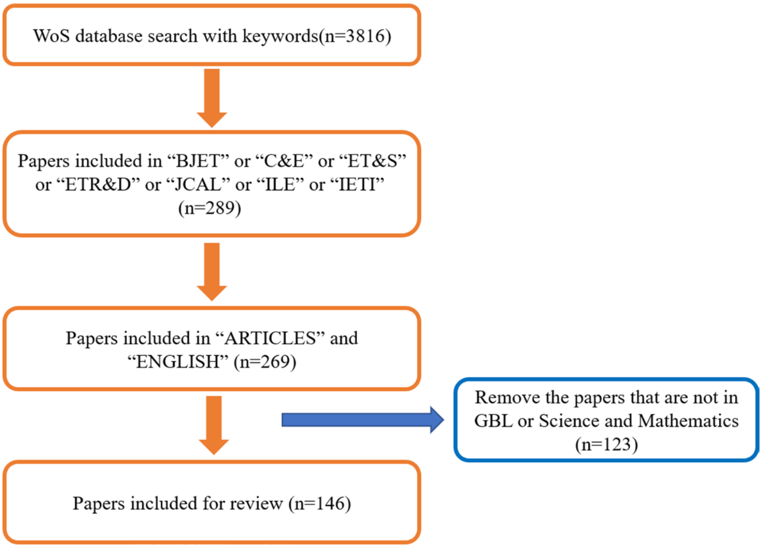


Fig. 1 WoS database searching steps

Education (C&E), Educational Technology & Society (ETS), Educational Technology Research & Development (ETR&D), the Journal of Computer Assisted Learning (JCAL), Interactive Learning Environments (ILE), and Innovations in Education and Teaching International (IETI) (Hwang et al., 2012; Tsai & Tsai, 2020). This study collected literature published in seven educational technology journals in the field of GBL in science and mathematics education from 1991 to 2020 from the WoS database, to analyze the research trends in the field.

Figure 1 indicates the process of searching, filtering, and selecting eligible literature for this study. The search task was performed in March 2021 using the WoS database to identify all potentially relevant literature from 1991 to 2020.

The search underwent a two-stage manual filtering process. First, all researchers read all titles and abstracts, deleting those that were screened out as irrelevant articles. Second, the remaining literature was read to verify that the selection adequately met the inclusion criteria, and the deleted literature was categorized as non-science and mathematics education areas, non-GBL, irrelevant, and literature review. The number of retained papers and their publication years are listed in Table 1, and all papers included in the criteria were coded and analyzed using content analysis, the results of which are presented with Microsoft Excel and the VOSviewer software.

Theoretical model and coding schemes

In order to analyze the literature on the application of GBL in science and mathematics education, a coding scheme was developed regarding the previous technology-based learning model adopted by Lin et al., (2018) as shown in Table 2.

Based on the characteristics of the science and mathematics education domains, this study used a multi-item model of game-based learning and a

Table 1 Distribution status of journal publications from 1991 to 2020

Journal titles	1991–2000 ($N = 1$)	2001–2010 ($N = 11$)	2011–2020 ($N = 134$)	1991–2020 ($N = 146$)
C&E	1	6	47	54
ILE	0	1	23	24
ETR&D	0	1	18	19
BJET	0	1	17	18
JCAL	0	1	14	15
ETS	0	0	14	14
IETI	0	1	1	2

developmental profile of learning in the science and mathematics education domains. The model represents the factors that need to be taken into account in the learning environments in science and mathematics education, including learners, technology, and subjects. In addition, the following issues were considered such as research issues (e.g., subjects and education level), interaction issues (e.g., platforms/devices and game genre), and measurement issues (e.g., learning performance, and affective or psychological state) to meet the study's research objectives as shown in Fig. 2.

During the analysis process, the coding was first conducted by two researchers who read, categorized, and analyzed the literature according to the coding scheme. If there was any disagreement during this phase, a group discussion was conducted until a decision was reached. In the second coding phase, the discrepancies were resolved by consensus through discussion and necessary modifications to the existing coding work. Finally, the coding consistency was agreed upon by all researchers. Two other researchers then conducted a meta-analysis using the revised coding scheme and supervised all coded data, allowing a close check of the suitability of the analysis. The final check was conducted by all researchers simultaneously.

Data distribution

As shown in Fig. 3, there was only one article from 1991 to 2000, which shows that research on GBL was still developing, and 11 articles from 2001 to 2010, indicating that researchers were beginning to invest in research. The earliest application of GBL in science and mathematics education, written by Lingefjärd (1993), was published in 1993 in the C&E Journal. It examined the use of tutorial games integrated with mathematics. Figure 3 shows that the related research began to increase in the next few years, the number of publications in 2012 was triple than that of 2011. It also shows that most of the papers were published between 2015 and 2020; in particular, from 2018 to 2010, which indicates that the GBL application in science and mathematics education is becoming a popular research trend.

Table 2 The coding scheme for analyzing the GBL research in science and mathematics education

Category	Aspects	References
Platforms/devices	Five aspects: Console or video games; Computer or online games; Mobile or ubiquitous games; Wearable devices; Others	Wouters and Van Oostendorp (2013)
Game genre	Nine aspects: Serious games; Simulation games; Role-playing games; Tutorial games; Puzzle games; Exer-games; Board games; Hybrid genre; Others	Wouters et al. (2013)
Research methods	Three aspects: Quantitative method; Qualitative method; Mixed method	Li and Tsai (2013); Chen, Huang, & Hwang (2019)
Subject	Seven aspects: Science; Mathematics; Biology; Chemistry; Physics; Ecological science; Mixed	Hwang et al. (2012); Chen, et al. (2019)
Education level of learners	Five aspects: preschool or kindergarten; elementary education; secondary education; tertiary; cross-levels	Hung, Yang, Hwang, & Wang (2018)
Learning outcomes-performance	Five aspects: problem solving; critical thinking; creativity; communicative competence; collaboration/cooperation	Hwang et al. (2015)
Learning outcomes- affective or psychological state	Nine aspects: general perceptions or attitudes; satisfaction; motivation/interest; engagement/flow; technology acceptance/evaluation; self-efficacy/confidence; cognitive load; learning anxiety; learning achievement	Cheng et al., (2020)

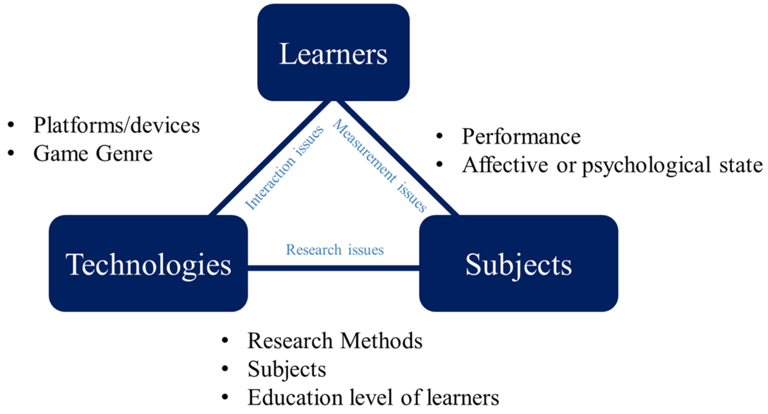


Fig. 2 Game-based learning model

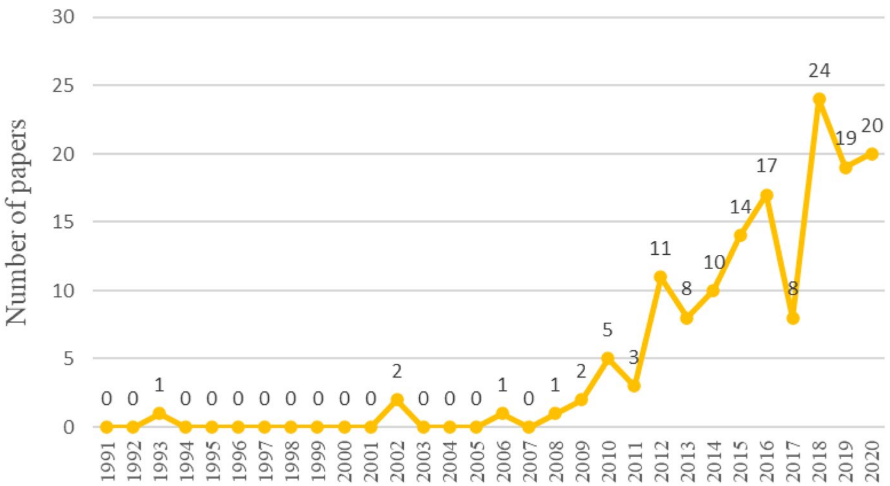


Fig. 3 Distribution status of GBL in science and mathematics education from 1991 to 2020

VOSviewer

In this study, the bibliometric analysis was conducted using VOSviewer. The results are presented in the form of a network map showing the relationship of keywords, the most cited authors, and regions in science and mathematics education on GBL. In the network map, each keyword is represented by a circle. The diameter of the circle indicates the frequency of the keyword, where the larger the circle, the more frequently the keyword appears. The distance between the circles represents the association of two keywords, and the line represents the connection between the two keywords, where the more frequently they appear together, the thicker the line between them.

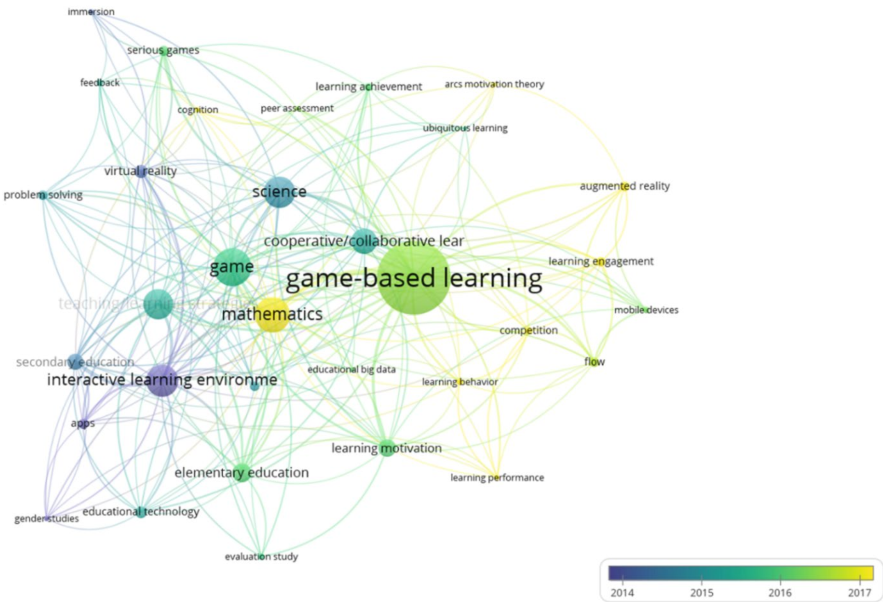


Fig. 4 Distribution of the number of papers using the keywords from 1991 to 2020

Results

Bibliometric mapping analysis

Keywords

According to Fig. 4, game-based learning and interactive learning environment are the keywords that appear more frequently, which also means that they have been the keywords that researchers have been exploring the most. By contrasting the color of the chronological diagram at the bottom of the figure, it is seen that the more the color tends to be yellow, the more recent the keywords are. The game-based learning, interactive learning environment, and cooperative/collaborative learning have received attention by earlier studies, while the ARCS (Attention, Relevance, Confidence, Satisfaction) motivation theory, competition, and learning behavior have been increasingly researched and explored in recent years.

Author publications

Table 3 and Fig. 5 show that Professor Hwang, Gwo-Jen has published the most papers with a total of 10. His research is mainly on natural science education in elementary school. The primary type of game is role-playing. He is followed by Professor Chen, Ching-Huei who has published a total of seven articles. Moreover, the most-cited author is Professor Hwang, Gwo-Jen with 844 citations, followed by Professor Sung, Han-Yu with 385. The analysis of author publication shows that

Table 3 Number of authors' documents and citations

Author	Documents	Citations
Hwang, Gwo-Jen	10	844
Chen, Ching-Huei	7	89
Ke, Fengfeng	4	140
Sung, Han-Yu	3	385
Hung, Chun-Ming	3	241

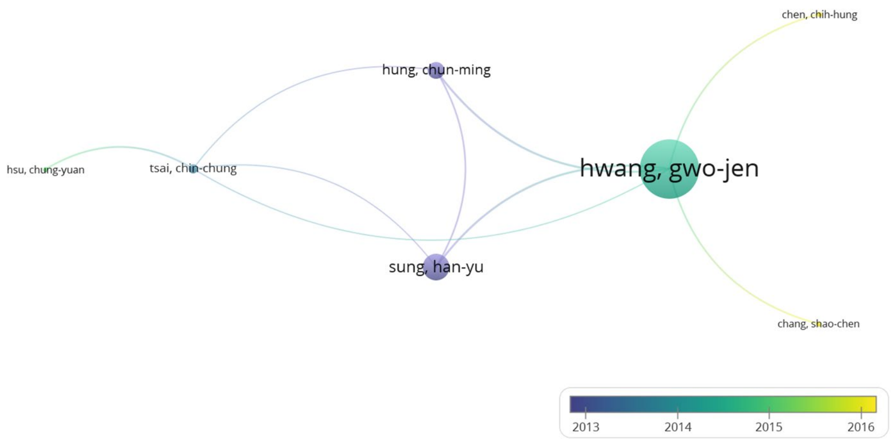


Fig. 5 Most cited authors from 1991 to 2020

Table 4 Number of documents and citations of each region

Region	Documents	Citations
Taiwan	60	2229
U.S.A	40	1374
Chinese Mainland	8	53
England	7	160
Greece	6	772

Professor Hwang, Gwo-Jen has made great contributions and has been a very influential researcher on GBL in science and mathematics education.

Region distribution

Table 4 and Fig. 6 present that Taiwan accounts for the majority of GBL research in science and mathematics education with 60 publications, followed by the United States with 40. Moreover, the most-cited region is Taiwan, with 2229 citations, followed by the United States with 1374. The thickness of the line between Taiwan and the United States in Fig. 6 also shows the close relationship between them. In

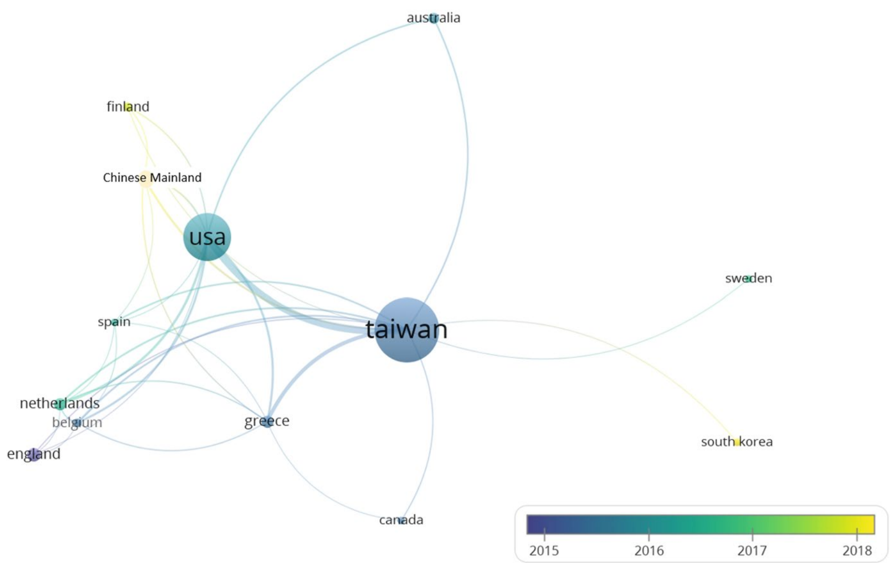


Fig. 6 Most cited regions from 1991 to 2020

this field, Greece has published six articles, but with a high number of 772 citations, indicating that its research is worth attention. In addition, the Greek researcher Papastergiou (2009) published a paper using quantitative research and combining computer science with simulation games not only investigated the high school students' effectiveness and motivation in learning computer memory concepts, but also examined gender differences in the learning performance. The results showed the gaming approach promoted students' knowledge of computer memory concepts and motivated learning without gender differences. This study has been cited 682 times, which means it is a significant contribution and a very influential paper. The color comparison of the chronological diagram also shows that in recent years, Finland, South Korea, and Chinese Mainland have started to explore this field as well.

Content analysis

Adopted types of platforms/devices and game genres

Table 5 shows the most used devices and types of games in science and mathematics education. The data show that the GBL process is mainly computer or online assisted (N=71). However, mobile learning (N=34) has gradually become mainstream due to the rapid development of mobile technology in the last decade, which provides both convenience and immediacy. The ranking of game types in the last decade is in the order of simulation games (N=51), tutorial games (N=41), and role-playing games (N=12). When learners learn by simulation games, they can participate in the process of discovery and autonomy, which can facilitate the learning experience

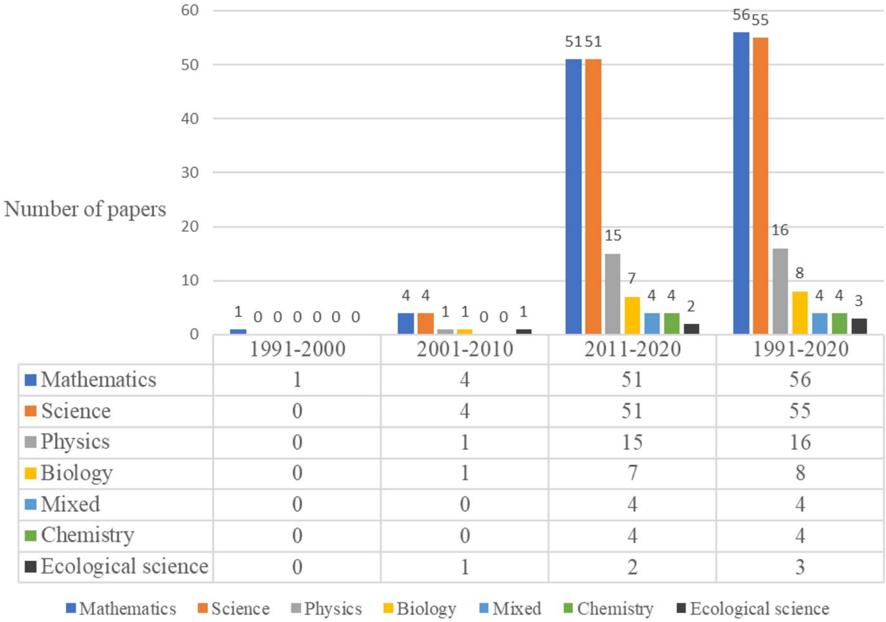
Table 5 Adopted types of platforms/devices and game genre

	Category	1991–2000 (N=1)	2001–2010 (N=11)	2011–2020 (N=134)	1991–2020 (N=146)
Platforms/devices	Computer or online games	1	7	63	71
	Mobile or ubiquitous games	0	0	34	34
	Console or video games	0	3	23	26
	Wearable devices	0	1	9	10
	Others	0	0	5	5
Game genre	Simulation games	0	4	51	55
	Tutorial games	1	5	41	47
	Role-playing games	0	0	12	12
	Serious games	0	1	11	12
	Puzzle games	0	0	8	8
	Hybrid genre	0	0	6	6
	Others	0	1	2	3
	Exer-games	0	0	2	2
	Board games	0	0	1	1

and enhance intrinsic learning motivation. Research has also found a strong correlation between learning experiences and problem-solving strategies (Liu et al., 2011). Besides, tutorial games have been widely used in research because of their relative ease of production and ease of use (Chang et al., 2010; Khoo, 2016).

Adopted research subjects

Figure 7 presents the research subjects chosen by the current studies. They are science, mathematics, physics, biology, mixed, chemistry, and ecological science, in which science includes natural science and computer science. Data from the last 10 years show that most of the areas of study were "Science" (N=51), followed by "Mathematics" (N=51) and "Physics" (N=15). GBL has been extensively used to support science learning (Nietfeld et al., 2014). One of the potentials of GBL in science learning is the ability to provide an emotional environment that promotes cognitive learning in science. Also, learners can enhance their collaboration and problem-solving abilities during the process of GBL (Li et al., 2013). Mathematics is considered a critical discipline in higher education, and most fields of study, such as science, engineering, or technology, are based on mathematics as an extension (Ke, 2014; Yang et al., 2018). Although mathematics is an important part of learning, many researchers report that mathematics is not easy to learn. Learners are prone to difficulty and risk of failure, negative performance ratings are high, and they often experience intense stress and anxiety (Roick & Ringeisen, 2018). Therefore, researchers and educators have worked to improve the learners' learning experience of mathematics to enhance their intrinsic motivation, interest, and learning outcomes with GBL (Chang et al., 2012; Yang et al., 2018).



	1991-2000	2001-2010	2011-2020	1991-2020
Mathematics	1	4	51	56
Science	0	4	51	55
Physics	0	1	15	16
Biology	0	1	7	8
Mixed	0	0	4	4
Chemistry	0	0	4	4
Ecological science	0	1	2	3

Fig. 7 Number of research subjects from 1991 to 2020

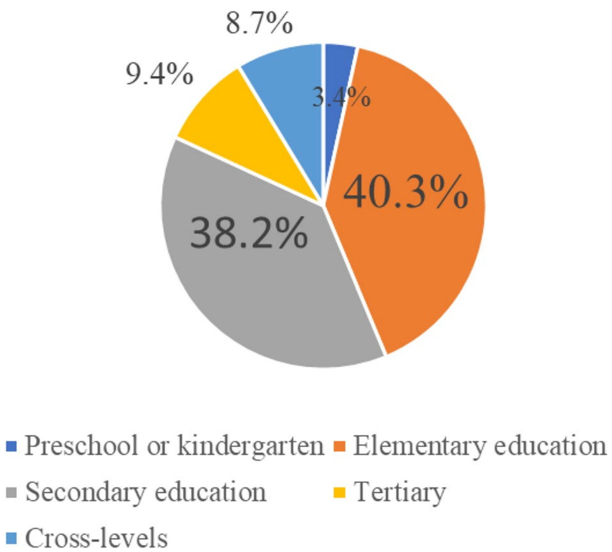


Fig. 8 Number of research participants from 1991 to 2020

Fig. 9 Research methods used from 1991 to 2020

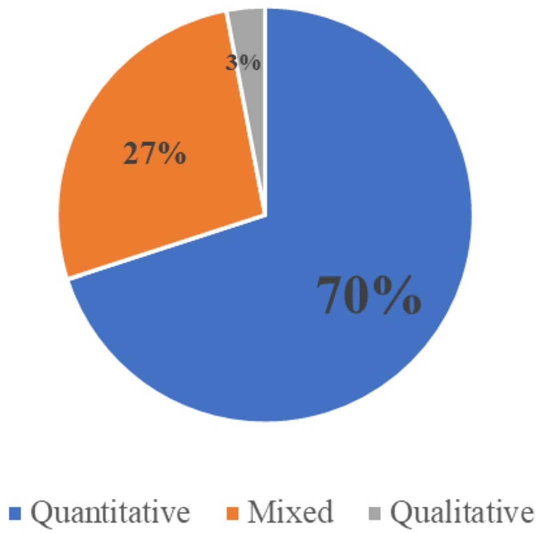


Table 6 Research methods used from 1991 to 2020

Research methods	1991–2000 (N = 1)	2001–2010 (N = 11)	2011–2020 (N = 134)	1991–2020 (N = 146)
Quantitative	0	8	94	102
Mixed	0	3	36	39
Qualitative	1	0	4	5

Adopted research participants

Figure 8 shows the sample size of GBL learning among learners at different educational levels and found that elementary education (40.3%), and secondary education (38.2%) accounted for the majority, and tertiary education accounted for 9.4%. The study also found that nearly 9% of the research was conducted across educational levels, and 3.4% involved preschoolers. This means that secondary and elementary school students are the primary sample for GBL in science and mathematics education. It also implies that most researchers consider children and adolescents to be the primary learners of GBL.

Adopted research methods

In Fig. 9, quantitative research is currently the most dominant research method, accounting for 70% of the total. This research method is the most intuitive way to present research data and explore the current research state. More than half of the research is first to present the research hypothesis and understanding of the learning area, then to conduct research and quantify the results for statistical analysis. This is followed by mixed research, accounting for 27%, and finally, qualitative research accounting for 3%. It is also evident from Table 6 that in the last decade, researchers have begun to pay more attention to learners' subjective ideas and have used mixed or quantitative research methods to investigate the data. The literature also shows that more in-depth and informative findings can be collected through interviews or focus group meetings with study participants, enriching the findings (Bressler & Bodzin, 2013; Laine et al., 2016; Wilkinson et al., 2020).

Number of measured issues used

As shown in Table 7, GBL was used to examine whether the measured issues in the last 30 years have changed or improved significantly. Between 1991 and 2000, only one paper focused on learning achievement, motivation/interest, and technology acceptance. Between 2001 and 2010, the main issues discussed were learning achievement (10 articles), motivation/interest (5 articles), and engagement (4 articles). In the past 10 years, from 2011 to 2020, the main issues discussed were learning achievement (119 articles), motivation/interest (52 articles), and general perceptions or attitude (37 articles), which shows that achievement, motivation, and attitude have always been important issues for researchers.

From 2001 to 2010, researchers began to emphasize the development of higher order thinking, such as cooperation/collaboration ($N=4$), problem-solving skills ($N=1$), and critical thinking ($N=1$). From 2011 to 2020, cooperative/collaborative learning (27 articles), problem-solving skills (24 articles), and communication skills (4 articles) were beginning to be explored in a large body of literature. This means that researchers emphasized interaction, mutual evaluation, and team competition in group learning activities. Moreover, researchers stressed the learners' problem-solving skills and expected them not only to learn the knowledge but also to learn actively and deal with different problems and crises to help improve their self-efficacy.

Discussion and conclusions

This study analyzed the literature on GBL in science and mathematics education from 1991 to 2020, and divided it into three time periods, 1991 to 2000, 2001 to 2010, and 2011 to 2020, respectively. Furthermore, the study summarized the current state of research and suggested potential trends for future research. For nearly 2 decades, GBL has been a common learning method used by many researchers and educators. Many researchers have found the benefits of adopting GBL in science and mathematics education. For example, the study indicated that for elementary students, the application of tutorial games in mathematics can effectively improve engagement, self-efficacy, and learning achievement (Ku et al., 2014), and for secondary students, the application of puzzle games in science can effectively improve collaboration skills, attitudes, motivation, and engagement (Bressler & Bodzin,

Table 7 Number of measured issues from 1991 to 2020

	Category	1991–2000 ($N=1$)	2001–2010 ($N=11$)	2011–2020 ($N=134$)	1991–2020 ($N=146$)
Affective or psychological state	Learning achievement	1	10	119	130
	Motivation / interest	1	5	52	58
	General perceptions / attitudes	0	1	37	38
	Engagement / flow	0	4	30	34
	Technology acceptance / evaluation	1	1	15	17
	Self-efficacy / confidence	0	1	12	13
	Cognitive load	0	0	8	8
	Satisfaction	0	0	8	8
	Learning anxiety	0	0	6	6
Performance	Collaboration / cooperation	0	4	27	31
	Problem solving	0	1	24	25
	Communicative competence	0	0	4	4
	Creativity	0	0	4	4
	Critical thinking	0	1	0	1

2013). Researchers also indicate the importance of integrating GBL into the teaching curriculum. For example, it strengthens the learner's initiative and enhances his or her learning motivation and effectiveness (Chen, 2020). In addition, mobile technology has become increasingly advanced in recent years. Applying mobile game-based learning (MGBL) can help learners have more flexible learning time and ubiquitous learning to improve their learning activity; for example, several researchers have reported that MGBL have great potential in improving students' learning achievement and motivation (Daungcharone et al., 2020; Shiratuddin & Zaibon, 2010; Su & Cheng, 2015) as well as their learning engagement (Karoui et al., 2020; Komalawardhana & Panjaburee, 2018).

Besides, this study analyzed the GBL literature by content analysis and bibliometric analysis. The study revealed keyword clusters, the most influential authors, and the regions that have contributed the most to GBL in science and mathematics education. According to the research results, Taiwan has the highest number of research papers and citations, showing its contribution. The most influential author is Prof. Hwang, Gwo-Jen. He promotes the integration of learning and technology, designing a diverse and innovative learning model, and changing the traditional learning mode. The second contributing is the United States, and the relationship between Taiwan and the United States is intensive. As mentioned in previous literature, learners who use GBL learn much more effectively than those who do not. Therefore, the use of GBL can have a positive impact on learners' performance. In addition, GBL learning provides learners with a fun learning experience and helps them develop their ability of higher order thinking, reduces their cognitive load, and enhances their flow experience and participation in the learning program (Es-Sajjade & Paas, 2020; Deng et al., 2020). GBL not only increases the fun of learning but also increases learners' participation and motivation through self-testing, game participation, and feedback (Syal & Nietfeld, 2020).

The most commonly used types of games in GBL are simulation games. These games have the effect of enhancing learners' game experience and participation. Learners increase their experience and learning skills and have the opportunity to work as a team to improve their collaboration skills (Hanghøj et al., 2018). GBL has greatly enhanced entertainment and shows that it motivates learners to have positive performance, participation, and interest in the learning process. After a thorough analysis, we learned that science and mathematics are the two subjects that educators most often integrate with GBL. The results are consistent with previous research (Tokac et al., 2019; Tsai & Tsai, 2020).

This study also investigates the benefits of GBL in various aspects of the learner's learning process. The learners' collaborative learning and problem-solving skills through game-based learning have received considerable attention from researchers in the past decade. Researchers have placed more emphasis on the core competencies of 5C for learners. Moreover, researchers have found that learners' ability to collaborate and comprehend was enhanced during team interaction in game-based learning (Lindström et al., 2011), the process of discussion and reasoning also helps the construction of knowledge (Hsu et al., 2016), and cultivates critical thinking (Hwang & Chang, 2020; Lim et al., 2006). The research found that higher order thinking tends to influence the learning process, such as improving peer-to-peer communication skills in group discussions and strengthening analytical skills through problem solving. During the collaborative activities, communication skills (Chang & Hwang, 2017), creativity (Lindström et al., 2011), and problem-solving skills (Sánchez & Olivare, 2011) are significantly enhanced in GBL. The 5C competencies are vital abilities in various subjects. It is expected that educators could develop creativity and critical thinking of students in the curriculum to foster their high-order thinking (Lederman et al., 2014), and enhance their engagement (Akman & Çakır, 2020; Ding et al., 2018).

Several previous studies have reviewed the early applications of information technology in education, including Computer Assistant Instruction (CAI), Online Learning, Mobile learning (M-learning), and numerous future trends of immersive learning, for example, Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), X-Reality, and Cross Reality (XR). Accordingly, researchers have indicated that mobile technology and its education and entertainment applications have gradually expanded to mobile learning (Karoui et al., 2020). They have also reported the need of integrating learning strategies with new technologies to enhance learner motivation and satisfaction as well as improving their understanding of concepts (Herrington et al., 2007; Prit Kaur et al., 2019).

In sum, the advantages and trends of GBL have been investigated through the literature review by content analysis and bibliometric analysis in this study. It explored the impact of different platforms/devices and game genres on learners and performed coding analysis of the measure issues for learners in various areas such as the core 5C competencies. We found that there were some limitations to this study, and so we offer the following suggestions for future research:

(1) Add more retrieval databases, such as SCOPUS, IEEE, and a greater volume of the literature for analysis.
(2) Increase exploration of co-citation relationships between authors.
(3) Investigate the number of co-citation relationships between regions.
(4) Explore in-depth collaborative relationships between authors.

Therefore, the results of this study confirm the current status of GBL in science and mathematics education. For future researchers who intend to explore this field, this study can be an informative and valuable reference. This research significantly improves the research knowledge and provides a better understanding of GBL trends in science and mathematics education. It is expected to serve as a reference for researchers in planning curriculum activities in the technological era.

Acknowledgements This study is supported in part by the Ministry of Science and Technology of Taiwan under contract numbers MOST-109-2511-H-011-002-MY3 and MOST-108-2511-H-011-005-MY3.

References

Akman, E., & Çakır, R. (2020). The effect of educational virtual reality game on primary school students' achievement and engagement in mathematics. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2020.1841800

Alrehaili, E. A., & Al Osman, H. (2019). A virtual reality role-playing serious game for experiential learning. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2019.1703008

Alsop, S., & Watts, M. (2003). Science education and affect. *International Journal of Science Education, 25*(9), 1043–1047.

Annetta, L. A., Minogue, J., Holmes, S. Y., & Cheng, M. T. (2009). Investigating the impact of video games on high school students' engagement and learning about genetics. *Computers & Education, 53*(1), 74–85.

Barab, S., & Dede, C. (2007). Games and immersive participatory simulations for science education: An emerging type of curricula. *Journal of Science Education and Technology, 16*(1), 1–3.

Bressler, D. M., & Bodzin, A. M. (2013). A mixed methods assessment of students' flow experiences during a mobile augmented reality science game. *Journal of Computer Assisted Learning, 29*(6), 505–517.

Chang, K. E., Wu, L. J., Weng, S. E., & Sung, Y. T. (2012). Embedding game-based problem-solving phase into problem-posing system for mathematics learning. *Computers & Education, 58*(2), 775–786.

Chang, S. C., & Hwang, G. J. (2017). Development of an effective educational computer game based on a mission synchronization-based peer-assistance approach. *Interactive Learning Environments, 25*(5), 667–681.

Chang, Y. C., Peng, H. Y., & Chao, H. C. (2010). Examining the effects of learning motivation and of course design in an instructional simulation game. *Interactive Learning Environments, 18*(4), 319–339.

Chen, C. H. (2020). Impacts of augmented reality and a digital game on students' science learning with reflection prompts in multimedia learning. *Educational Technology Research and Development, 68*(6), 3057–3076.

Chen, C. H., Liu, G. Z., & Hwang, G. J. (2016). Interaction between gaming and multistage guiding strategies on students' field trip mobile learning performance and motivation. *British Journal of Educational Technology, 47*(6), 1032–1050.

Chen, C. K., Huang, N. T. N., & Hwang, G. J. (2019). Findings and implications of flipped science learning research: A review of journal publications. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2019.1690528

Chen, Z. H., Liao, C. C., Cheng, H. N., Yeh, C. Y., & Chan, T. W. (2012). Influence of game quests on pupils' enjoyment and goal-pursuing in math learning. *Journal of Educational Technology & Society, 15*(2), 317–327.

Cheng, S. C., Hwang, G. J., & Lai, C. L. (2020). Critical research advancements of flipped learning: a review of the top 100 highly cited papers. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2020.1765395

Chiang, F. K., & Qin, L. (2018). A Pilot study to assess the impacts of game-based construction learning, using scratch, on students' multi-step equation-solving performance. *Interactive Learning Environments, 26*(6), 803–814.

Daungcharone, K., Panjaburee, P., & Thongkoo, K. (2020). Implementation of mobile game-transformed lecture-based approach to promoting C programming language learning. *International Journal of Mobile Learning and Organisation, 14*(2), 236–254.

Deng, L., Wu, S., Chen, Y., & Peng, Z. (2020). Digital game-based learning in a Shanghai primary-school mathematics class: A case study. *Journal of Computer Assisted Learning, 36*(5), 709–717.

Ding, L., Er, E., & Orey, M. (2018). An exploratory study of student engagement in gamified online discussions. *Computers & Education, 120*, 213–226.

Divjak, B., & Tomić, D. (2011). The impact of game-based learning on the achievement of learning goals and motivation for learning mathematics-literature review. *Journal of Information and Organizational Sciences, 35*(1), 15–30.

Es-Sajjade, A., & Paas, F. (2020). Educational theories and computer game design: Lessons from an experiment in elementary mathematics education. *Educational Technology Research and Development, 68*(5), 2685–2703.

Gao, F., Li, L., & Sun, Y. (2020). A systematic review of mobile game-based learning in STEM education. *Educational Technology Research and Development, 68*(4), 1791–1827.

Gee, J. P. (2014). An introduction to discourse analysis: Theory and method. *Routledge UK*. https://doi.org/10.4324/9781315819679

Gil-Doménech, D., & Berbegal-Mirabent, J. (2019). Stimulating students' engagement in mathematics courses in non-STEM academic programmes: A game-based learning. *Innovations in Education and Teaching International, 56*(1), 57–65.

Hanghøj, T., Lieberoth, A., & Misfeldt, M. (2018). Can cooperative video games encourage social and motivational inclusion of at-risk students? *British Journal of Educational Technology, 49*(4), 775–799.

Herodotou, C. (2018). Mobile games and science learning: A comparative study of 4 and 5 years old playing the game Angry Birds. *British Journal of Educational Technology, 49*(1), 6–16.

Herrington, J., Reeves, T. C., & Oliver, R. (2007). Immersive learning technologies: Realism and online authentic learning. *Journal of Computing in Higher Education, 19*(1), 80–99.

Holbrook, J., & Rannikmae, M. (2007). The nature of science education for enhancing scientific literacy. *International Journal of Science Education, 29*(11), 1347–1362.

Honey, M. A., & Hilton, M. L. (2011). *Learning science through computer games*. National Academies Press.

Hsu, C. Y., Tsai, C. C., & Wang, H. Y. (2016). Exploring the effects of integrating self-explanation into a multi-user game on the acquisition of scientific concepts. *Interactive Learning Environments, 24*(4), 844–858.

Hung, C. Y., Sun, J. C. Y., & Yu, P. T. (2015). The benefits of a challenge: Student motivation and flow experience in tablet-PC-game-based learning. *Interactive Learning Environments, 23*(2), 172–190.

Hung, H. T., Yang, J. C., Hwang, G. J., Chu, H. C., & Wang, C. C. (2018). A scoping i review of research on digital game-based language learning. *Computers & Education, 126*, 89–104.

Hwang, G. J., & Chang, S. C. (2020). Facilitating knowledge construction in mobile learning contexts: A bi-directional peer-assessment approach. *British Journal of Educational Technology, 52*, 337–357.

Hwang, G. J., & Chen, P. Y. (2021). Interweaving gaming and educational technologies: Clustering and forecasting the trends of game-based learning research by bibliometric and visual analysis. *Entertainment Computing*. https://doi.org/10.1016/j.entcom.2021.100459

Hwang, G. J., Lai, C. L., & Wang, S. Y. (2015). Seamless flipped learning: A mobile technology-enhanced flipped classroom with effective learning strategies. *Journal of Computers in Education, 2*(4), 449–473.

Hwang, G. J., Wu, P. H., & Chen, C. C. (2012). An online game approach for improving students' learning performance in web-based problem-solving activities. *Computers & Education, 59*(4), 1246–1256.

Karoui, A., Marfisi-Schottman, I., & George, S. (2020). JEM Inventor: a mobile learning game authoring tool based on a nested design approach. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2020.1753214

Ke, F. (2014). An implementation of design-based learning through creating educational computer games: A case study on mathematics learning during design and computing. *Computers & Education, 73*, 26–39.

Ke, F. (2019). Mathematical problem solving and learning in an architecture-themed epistemic game. *Educational Technology Research and Development, 67*(5), 1085–1104.

Khoo, K. Y. (2016). Enacting viewing skills with apps to promote collaborative mathematics learning. *Journal of Educational Technology & Society, 19*(2), 378–390.

Komalawardhana, N., & Panjaburee, P. (2018). Proposal of personalised mobile game from inquiry-based learning activities perspective: Relationships among genders, learning styles, perceptions, and learning interest. *International Journal of Mobile Learning and Organisation, 12*(1), 55–76.

Ku, O., Chen, S. Y., Wu, D. H., Lao, A. C., & Chan, T. W. (2014). The effects of game-based learning on mathematical confidence and performance: High ability vs. low ability. *Journal of Educational Technology & Society, 17*(3), 65–78.

Laine, T. H., Nygren, E., Dirin, A., & Suk, H. J. (2016). Science Spots AR: A platform for science learning games with augmented reality. *Educational Technology Research and Development, 64*(3), 507–531.

Lederman, J. S., Lederman, N. G., Bartos, S. A., Bartels, S. L., Meyer, A. A., & Schwartz, R. S. (2014). Meaningful assessment of learners' understandings about scientific inquiry—The views about scientific inquiry (VASI) questionnaire. *Journal of Research in Science Teaching, 51*(1), 65–83.

Li, M. C., & Tsai, C. C. (2013). Game-based learning in science education: A review of relevant research. *Journal of Science Education and Technology, 22*(6), 877–898.

Lim, C. P., Nonis, D., & Hedberg, J. (2006). Gaming in a 3D multiuser virtual environment: Engaging students in science lessons. *British Journal of Educational Technology, 37*(2), 211–231.

Lin, C. J., Hwang, G. J., Fu, Q. K., & Chen, J. F. (2018). A flipped contextual game- based learning approach to enhancing EFL students' English business writing performance and reflective behaviors. *Journal of Educational Technology & Society, 21*(3), 117–131.
Lin, Y. H., & Hou, H. T. (2016). Exploring young children's performance on and acceptance of an educational scenario-based digital game for teaching route-planning strategies: A case study. *Interactive Learning Environments, 24*(8), 1967–1980.
Lindström, P., Gulz, A., Haake, M., & Sjödén, B. (2011). Matching and mismatching between the pedagogical design principles of a math game and the actual practices of play. *Journal of Computer Assisted Learning, 27*(1), 90–102.
Lingefjärd, T. (1993). The use of computers in teaching mathematics—Beliefs and misbeliefs. *Computers & Education, 21*(1–2), 77–87.
Liu, C. C., Cheng, Y. B., & Huang, C. W. (2011). The effect of simulation games on the learning of computational problem solving. *Computers & Education, 57*(3), 1907–1918.
Martinez, J. G. (1996). Math without fear: *A guide for preventing math anxiety in children*. Allyn & Bacon.
Maxmen, A. (2010). Video games and the second life of science class. *Cell, 141*(2), 201–203.
Mayo, M. J. (2007). Games for science and engineering education. *Communications of the ACM, 50*(7), 30–35.
Nietfeld, J. L., Shores, L. R., & Hoffmann, K. F. (2014). Self-regulation and gender within a game-based learning environment. *Journal of Educational Psychology, 106*(4), 961.
O'Rourke, J., Main, S., & Hill, S. M. (2017). Commercially available Digital Game Technology in the Classroom: Improving Automaticity in Mental-maths in Primary-aged Students. *Australian Journal of Teacher Education, 42*(10), 50–70.
Papastergiou, M. (2009). Digital game-based learning in high school computer science education: Impact on educational effectiveness and student motivation. *Computers & Education, 52*(1), 1–12.
Pareto, L., Haake, M., Lindström, P., Sjödén, B., & Gulz, A. (2012). A teachable-agent-based game affording collaboration and competition: Evaluating math comprehension and motivation. *Educational Technology Research and Development, 60*(5), 723–751.
Prensky, M., & Thiagarajan, S. (2007). *Digital Game-Based Learning* (p. 17). St. Paul MN: Paragon House.
Prit Kaur, D., Mantri, A., & Horan, B. (2019). Design implications for adaptive augmented reality based interactive learning environment for improved concept comprehension in engineering paradigms. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2019.1674885
Roick, J., & Ringeisen, T. (2018). Students' math performance in higher education: Examining the role of self-regulated learning and self-efficacy. *Learning and Individual Differences, 65*, 148–158.
Sánchez, J., & Olivares, R. (2011). Problem solving and collaboration using mobile serious games. *Computers & Education, 57*(3), 1943–1952.
Shiratuddin, N., & Zaibon, S. B. (2010). Mobile game-based learning with local content and appealing characters. *International Journal of Mobile Learning and Organisation, 4*(1), 55–82.
Song, D., Karimi, A., & Kim, P. (2016). A Remotely Operated Science Experiment framework for under-resourced schools. *Interactive Learning Environments, 24*(7), 1706–1724.
Su, C. H., & Cheng, C. H. (2015). A mobile gamification learning system for learning improving the learning motivation and achievements. *Journal of Computer Assisted Learning, 31*(3), 268–286.
Syal, S., & Nietfeld, J. L. (2020). The impact of trace data and motivational self-reports in a game-based learning environment. *Computers & Education, 157*, 103978.
The New Media Consortium. (2005). The Horizon Report (No ISBN 0–9765087–0–2). Stanford CA.
Tokac, U., Novak, E., & Thompson, C. G. (2019). Effects of game-based learning on students' mathematics achievement: A meta-analysis. *Journal of Computer Assisted Learning, 35*(3), 407–420.
Tsai, Y. L., & Tsai, C. C. (2020). A meta-analysis of research on digital game-based science learning. *Journal of Computer Assisted Learning, 36*(3), 280–294.
Valladares, L. (2021). Scientific Literacy and Social Transformation. *Science & Education*, 1–31.
Verkijika, S. F., & De Wet, L. (2015). Using a brain-computer interface (BCI) in reducing math anxiety: Evidence from South Africa. *Computers & Education, 81*, 113–122.
Wang, M., & Zheng, X. (2021). Using game-based learning to support learning science: A Study with middle school students. *The Asia-Pacific Education Researcher, 30*(2), 167–176.
Wilkinson, K., Dafoulas, G., Garelick, H., & Huyck, C. (2020). Are quiz-games an effective revision tool in Anatomical Sciences for Higher Education and what do students think of them? *British Journal of Educational Technology, 51*(3), 761–777.

Wouters, P., & Van Oostendorp, H. (2013). A meta-analytic review of the role of instructional support in game-based learning. *Computers & Education, 60*(1), 412–425.

Yang, K. H., Chu, H. C., & Chiang, L. Y. (2018). Effects of a progressive prompting-based educational game on second graders' mathematics learning performance and behavioral patterns. *Journal of Educational Technology & Society, 21*(2), 322–334.

Pei-Ying Chen is a postdoctoral research fellow at the Graduate Institute of Digital Learning and Education, National Taiwan University of Science and Technology. Her research interests include digital learning in education, flipped learning and digital game-based learning.

Gwo-Jen Hwang is a chair professor at the Graduate Institute of Digital Learning and Education, National Taiwan University of Science and Technology. His research interests include mobile learning, digital game-based learning, flipped classrooms and AI in education.

Ssu-Yin Yeh is a Master student at the Graduate Institute of Digital Learning and Education, National Taiwan University of Science and Technology. Her research interests include self-directed learning and game-based learning.

Yi-Ting Chen is a Master student at the Graduate Institute of Digital Learning and Education, National Taiwan University of Science and Technology. Her research interests include virtual reality and digital game-based learning.

Ting-Wei Chen is a Master student at the Graduate Institute of Digital Learning and Education, National Taiwan University of Science and Technology. Her research interests include STEM and digital game-based learning.

Chih-Hsuan Chien is a Master student at the Graduate Institute of Digital Learning and Education, National Taiwan University of Science and Technology. Her research interests include digital game-based language learning and flipped classrooms.