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RESEARCH ARTICLE

Narrative-supported math problem solving in digital game-based learning

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Abstract
Narrative as a game design feature constantly yields mixed results for learning in the literature. The purpose of this exploratory mixed-methods case study was to examine design heuristics and implications governing the role of narratives in a digital game-based learning (DGBL) environment for math problem solving. We collected data via observation, semi-structured interviewing, and video recording with twenty-seven college students with diverse demographic backgrounds. Video logging resulted in 2276 behavioral events for quantitative analysis. The study indicated: (1) 11 narrative-governed actions for game-based math problem solving; (2) the positive correlations between narrative usage and successful game-based math problem solving; and (3) the gender effects: girls are supported by game narratives designed with intrinsic integration (i.e., object-oriented narrative) for math problem solving more than boys. The study findings highlighted the critical role of game narratives in a sandbox DGBL environment for math problem solving as well as gender-inclusive design of narratives. A set of data-driven design heuristics and implications for the game narrative in DGBL were delineated and suggested.

Keywords Game-based learning · Narratives · Math problem solving · Designing learning environments

Introduction

Digital game-based learning (DGBL) has been widely examined for its educational affordances and effectiveness (Ke, 2016). In a recent meta-analysis, Tokac et al. (2019) found a small but significant effect of digital learning games ($\overline{d}=.13$, $p=.02$) on students' mathematical learning compared to traditional instructions in PreK-12 settings. Prior research suggests that DGBL presents an immersive and experience-oriented learning space for students to experiment, explore, and apply gained knowledge (Ke, 2019). However, there is still no consensus on the effects of *DGBL design features*. Particularly, narrative, a game

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design feature that shapes and entails a series of learning tasks in DGBL, attracts researchers' attention (Dickey, 2020; Ke, 2016). Ke (2016) reported that 94% of the 69 reviewed educational game systems adopted a sort of narrative. However, research on the role of narrative as a key feature in DGBL consistently yielded mixed results (e.g., Adams et al., 2012; Ferguson et al., 2020; Novak, 2015).

Narrative in DGBL may tap into individual learners' prior experience to promote problem solving (Dickey, 2020; Ke, 2016). As such, Salen and Zimmerman (2003) proposed that when narratives are designed to be emergent, it can yield rich and compelling narrative experiences connecting to learners' prior experience for flexible thinking and distributed problem solving. However, there is still a lack of deep understanding of the characteristics and functions of various game narratives and how to integrate them in the learning-play processes (Dickey, 2020; Novak, 2015). Examining the processes and experiences of the gameplay with a specific focus on students' interactions with various types of game narratives to formulate design implications is essential for math education. Specifically, it is important to explore game narratives for math problem solving because both math problem solving and game narratives emphasize the role of learners' prior experience and in-game interactions with the environment. For example, it is argued that the processes of mathematical problem solving are the interactions between students' prior experience, their problem-solving attempts, and thinking behaviors; that is, students are supposed to experience math thinking as *sense-making activities* (Schoenfeld, 2016) in DGBL with game narratives.

Gender is another critical variable that is of interest to researchers in DGBL with game narratives (cf. Admiraal et al., 2014; Yang & Quadir, 2018). Earlier research (Yang & Quadir, 2018) has indicated that gender difference could influence individual interactions with the game features and their learning processes. Thus, it is important to explore the designs for gender inclusive narrative in DGBL (Admiraal et al., 2014). However, such studies are scarce.

The purpose of this exploratory mixed-methods study is to investigate the design implications and impacts of narrative in DGBL to inform the pedagogically sound and meaningful designs for game-based math problem solving. We focus on the types of game narratives and its impacts in relation to math problem solving and associated gender differences. Specifically, the research questions (RQs) guiding the exploration of this study are:

RQ1 What and how are the different types of game narratives used in game-based math learning for problem solving?

RQ2 What are the correlations between students' use of game narratives and their successful/failed problem solving in game-based math learning?

RQ3 Is there a gender difference on the use of game narratives in game-based math problem solving?

Narratives in DGBL

DGBL is an ideal vehicle that accommodates multimodal representations for "the embodiment or concretization of an idea for math problem solving" (Bruner, 1960, p. 614). In this study, our exploration of game narratives is centered on the form of *symbolic representation* coupled with *enactive and iconic representations* (Bruner, 1964). To elaborate, the learners' active exploration (i.e., enactive representation) is based on the semiotic information (i.e., symbolic representation) and pictorial compositions (i.e., iconic representation) in the interactive game system and *narrative play* (Salen & Zimmerman, 2003). In line with this, prior research has demonstrated that well-coordinated multimodal representations support learners' mental development (Ainsworth, 2006, 2014). These multimodal representations, which focus on game narratives, coordinate with game objects and environmental storytelling, can connect with players' prior experience. Symbolic immersion (Dede, 2009), occurs when learners interpret game narratives in the situated experience of gameplay, can associate learners' prior experience to facilitate problem solving and learning.

Narrative-supported symbolic immersion prompts learners to organize information from various sources and engage in problem-solving tasks to complete a narrative-framed enactive exploration (Dickey, 2006a; Polkinghorne, 1988). Likewise, Jenkins (2004) argued that game design *is* narrative architectural design because it enables "the story-constructing activity of players" (p. 29). It is suggested that narrative design features should foster action-based explorations or inquiries (i.e., enactive representations) in DGBL environments, through narratives inscribed on game components (e.g., objects, plots, feedback), and/or narratives situated in the game environment. Therefore, these narratives are considered as environmental storytelling that coherently promote learning (Dai et al., 2020; Pan et al., 2022).

Based on the literature (Bruner, 1964; Darejeh et al., 2021; Dickey, 2006a; Gresalfi & Barnes, 2016; Jenkins, 2004; Ke, 2016), we define *narrative* in this study as a series of events, tasks, and consequential feedback in simulated real-world scenarios that is used to frame learners' inquiry (enactive representation) for learning in a systematic environmental storytelling fashion.

Game narrative as an integral part of DGBL environmental design has shown to be effective in facilitating learning. Previous studies have focused on the impact of game narrative for cognitive learning, the results were mixed. For example, as proponents of narrative in DGBL, Dickey (2006a) asserted that adding narrative in a DGBL environment would assist problem-solving processes, enhance engagement, and provide feedback. Consistently, Gresalfi and Barnes (2016) suggested that "immersive games can also offer feedback in the form of a narrative outcome within the storyline" (p. 66). Their results revealed that feedback designed within a narrative-based learning environment supports math thinking and engagement. Particularly, feedback can be designed as environmental narratives to signal the consequences of learners' decision making. Ferguson et al. (2020) found that the implicit narrative structure contributes to higher retention of spatial information in a serious game. In alignment with Barab et al.'s (2007) argument, they suggested that game narratives should *not* be designed with a fixed sequence so that it won't demote the benefits of open and active explorations in DGBL environments.

Barab et al. (2007) proposed a *narrative*, *inscriptions*, and *inquiry* model in which narrative is described as interactive instead of a linear feature. They suggested that narrative, composed of inscriptions (e.g., graphs, tables, and diagrams), drives the inquiry and exploration to facilitate learning. To effectively design such narrative-based inquiry and exploration, intrinsic integration of the narrative in the game system has been promoted (Denham, 2015; Habgood & Ainsworth, 2011). To elaborate, the learning-gameplay integration of game mechanics, game world, and learning objectives is critical for the design of the learning game system (Ke, 2016). Although the effectiveness of intrinsic game mechanics design has been studied, how to design intrinsic integration of narrative features in DGBL is still lacking in the literature.

Despite the effectiveness of narrative for cognitive learning, some studies, when examining learning in modality-rich and discovery-oriented environments (e.g., DGBL) with cognitive load theory (Sweller et al., 2011), argued that narrative could increase extraneous cognitive load and then cause negative effects on learning (Adams et al., 2012). For instance, Fanfarelli (2020) found drawbacks of using game narrative for learning with a controlled experimental design. Wouters and van Oostendorp (2017)'s research reported positive effects of narrative on motivation, but not for learning. In addition, a recent study examined the connections between tasks and task narratives on cognitive load in an e-learning system (Darejeh et al., 2021). Their findings suggested that learners' cognitive load will be reduced only when they are familiar with the narrative and thus improve their task performance. Another study in the e-learning context (Recke & Perna, 2021) found that emergent narratives can engage learners and contribute to narrative-driven learning experience design as a potential way to reduce cognitive load. We continue on this line of research and explore what types of game narrative design work in interactive game-based math problem solving and for whom.

Gender difference with the game narrative in DGBL

Gender difference with the game narrative in DGBL has attracted researchers' attention (Dickey, 2006b). For the gender difference with the game narrative, seminal work (Malone, 1981) suggested that girls preferred intrinsic fantasy—intrinsic integration of game narratives with learning content in games—compared to the extrinsic fantasy. Other earlier studies also maintained that girls were more involved in the game narratives than boys (Dickey, 2006b; Inal & Cagiltay, 2007), though recent studies of the gender effect for the game narrative design are tremendously lacking. DGBL studies that investigated gender differences in relation to the overall game design features can inform the gender-related design of the game narratives. For example, Yang and Quadir (2018) explored the experience of game flow and rewards among boys and girls in a narrative-based learning game. They found that girls demonstrated a higher level of game flow than boys, but boys attained more interactive rewards than girls. Prior study (Admiraal et al., 2014) suggested the importance of designing equally-appealing game features for boys and girls in DGBL. Specifically, game designers and scholars have promoted gender-inclusive design (Admiraal et al., 2014; Dickey, 2006b) to attenuate traditional game designs that favor boys, but empirical studies on gender difference with the game narrative in DGBL are needed.

DGBL for mathematical problem solving

Researchers argued that DGBL could act as an innovative learning platform to enhance students' mathematical problem solving because it affords *problem solving by design* in a simulated context (Liljedahl et al., 2016). For example, an architecture-themed DGBL environment could provide students with opportunities for mathematical problem solving situated in architectural design/building (Ke, 2019). In such a learning environment, students produced initial solutions for contextualized mathematical problems based on their prior knowledge and experiences, then constantly *refined their solutions* through the exertion of meticulous evaluations until they found the optimal ones (Liljedahl et al., 2016). Thus, the students are actively involved in the process of constructing meaningful artifacts to build in-action knowledge.

DGBL promotes the development of problem-solving skills via a unique combination of *game actions*, *narratives*, and *rules* (Ke, 2016). Game actions and narratives can be considered as components of external representations that are not only memory aids but also as integral components of problem solving (Zhang, 1997). Previous research indicated that students' meaning-making abilities toward relevant mathematical concepts could be enhanced when they interact with multiple external representations framed by game narratives and mechanics in DGBL (Ainsworth, 2014; Pan et al., 2022). Some researchers suggested that text comprehension of written narratives (i.e., symbolic representations) in reality-based tasks is critical for the math problem solving processes because it determines the decision making that follows (Leiss et al., 2019). High complexity and linguistic convolutions of written task narratives oftentimes lead to problem-solving failure. In addition to symbolic representations for mathematical problem solving, researchers also emphasized the importance of iconic representations (i.e., pictorial compositions) that promotes holistic mathematical conceptual understanding (Moyer-Packenham et al., 2021). However, it is unclear what representation would yield the best learning outcomes in a specific context. For instance, Bennett et al. (2019) suggested that for math learning, using multiple iconic representations (e.g., five bricks) is not necessarily leading to better learning outcomes than using symbolic representations (e.g., five dots or arrays); whereas Moyer-Packenham et al. (2021) claimed that iconic representations (i.e., images) in DGBL may yield positive results for math learning. Given these arguments, text-based game narratives and narratives embedded in the game objects (or environmental storytelling) should be considered holistically when examining narrative design for DGBL.

One of the concerns for designing a holistic narrative system in DGBL for math problem solving is that learners may not perceive these narrative elements as instructional content to directly benefit from it (cf. Kapur & Bielaczyc, 2012). Learners also have to transform and coordinate different forms of narratives or representations during math problem solving (Moyer-Packenham et al., 2021). The process of mathematical problem solving along with a variety of transformations might cause cognitive overload and result in the failure of problem solving. Notably, some argued that productive failure can be considered as a catalyst for learning. For instance, Kapur and Bielaczyc (2012) suggested that students' experience of productive failure could facilitate the activation of (1) prior knowledge, (2) noticing features of the target concepts, (3) elaborating on the features, and (4) organizing the features into multiple representations for the target concepts. In a game narrative system, students can use multimodal narrative elements to iteratively experiment with and refine their solutions, and gradually attune to the target math concepts. Studies on productive failure suggested that it was the process of learning from failure, not the failure per se, that contributes to productive and successful learning (e.g., Kapur & Bielaczyc, 2012).

Method

Research design

The current study examined the design of game narratives in DGBL for learning math problem solving. We adopted a mixed-methods case study with an exploratory sequential design (Creswell & Plano Clark, 2018, see Fig. 1 for the research design flowchart). We

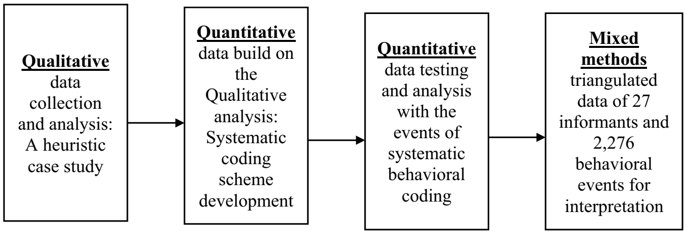

Fig. 1 The flowchart of exploratory sequential design in this study. Adapted from Creswell and Plano Clark (2018)

designed a qualitative heuristic case study followed by a quantitative systematic video coding analysis in this mixed-methods study to examine the correlations between the usage of game narratives and the process of mathematical problem solving in DGBL.

Participant and sampling strategy

Given our exploratory purpose to pursue design-based knowledge and avoid the influence of prior knowledge, we used purposeful sampling strategy (Creswell & Poth, 2017) in this study to recruit college students with diverse demographic backgrounds and of different genders to explore narrative design in game-based math learning. We collected and analyzed the data from twenty-seven college students ($M_{age}=19$ years, $SD=1.83$) recruited from a southeastern U.S. public university. Fifty-nine percent of the participants were female and 41% were male. Fifty-five percent of the participants were Caucasian, 26% were African American, and 19% were Latino.

Students participated in this study were recruited from different undergraduate and graduate-level courses at the college of education. Each participant was identified as a unique case in the current qualitative heuristic case study. The individual case was bounded by space and time as they provided their insights in an individual session (see Creswell & Poth, 2017). Each participant completed a two-hour game session and semi-structured interviewing. In this study, participant recruitment and data analysis were iterative. After collecting data from a participant/case, the researcher used it to build up and clarify the following data collection process until the data reached saturation (Creswell & Poth, 2017).

Data collection and analysis

The participants completed the sessions individually. Nine participants completed an on-campus session while other participants completed an online session through Zoom video conferencing tool. Individual sessions were important in this exploratory study, because as articulated by Schoenfeld (2016), "individual students' thought patterns matter" (p. 501) in math teaching and learning. Data were collected from four sources: (1) screen recordings of gameplay, (2) participatory observations, (3) semi-structured interviewing, and (4) reflective journals/analytic memos. All sources of data contributed to data triangulation (Creswell & Poth, 2017). All the screen recordings of gameplay were collected after the consent of the participants (names were all pseudonyms). For the participatory observations, we focused on the participants' behaviors and interactions with the game's narrative system. Semi-structured interviews were conducted with a protocol consisting of four aspects (cf. Dai et al., 2020): *ease of use* (e.g., do you feel that the narratives were easy to understand?), *experience* (e.g., did the narratives help you solve the math problem? If so, how? If not, why?), *perceived engagement* (e.g., did you feel engaged? why or why not?), and *math problem thinking processes* (e.g., describe your thought process approaching the most impressive game level). The researchers kept reflective journals and analytic memos throughout the data collection and analysis cycles for confirmability (Miles et al., 2020). Moreover, trustworthiness and credibility were established by using triangulation of multiple data sources, data saturation for thick descriptions, and audit trail (Miles et al., 2020).

Finally, we used a behavioral annotation software for a systematic behavioral analysis (Suen & Ary, 2014). We used a coding scheme developed based on the antecedent qualitative analysis (see Table 2 for the coding results). After we had a shared understanding of the scheme, we coded 20% of all the videos, and reached a high inter-rater reliability (coefficient α = .97) (Landis & Koch, 1977). Finally, we coded the rest of the videos independently. We then used multiple regressions and Chi-square test of independence (also called the Pearson Chi-square test) to address the research questions on correlations between narrative usage and math problem solving (RQ2) and gender differences on narrative usage (RQ3).

Materials

The game-based math learning environment used in the current study is *E-Rebuild* (Ke et al., 2019). *E-Rebuild* is the chosen DGBL environment for this study because the game narratives play an important role in the design of this type of strategic problem-solving game (Dickey, 2006a). The background story of this architecture-themed game is rebuilding after a natural disaster: learners need to help the habitants to rebuild their homes and facilities. Based on prior theoretical perspectives, we designed and investigated systematic (Jenkins, 2004; Salen & Zimmerman, 2003), multi-representational (Barab et al., 2007; Bruner, 1964), and multimodal (Mayer, 2009; Sweller et al., 2011) game narratives in the current study. Game narratives were carefully designed to control cognitive overload. Specifically, we created different math tasks to obtain the variability effect (Sweller et al., 2011). We followed multimedia design principles of coherence, signaling, spatial and temporal contiguity (Mayer, 2009) in designing the presentation and layout of the visual cues,

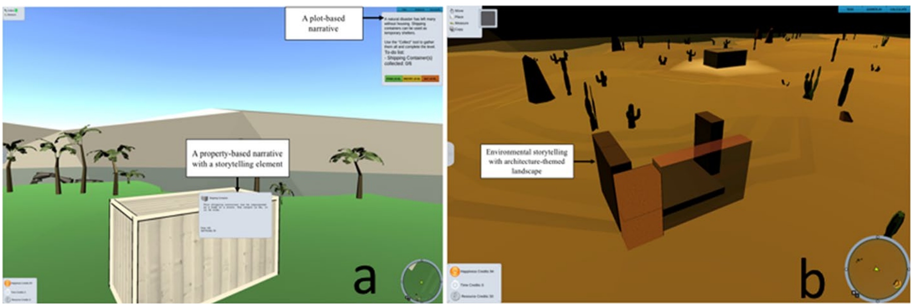

Fig. 2 **a** and **b** The user interface and game features in E-Rebuild

written texts, and math symbols in the virtual game world. We also tried to ensure that only essential information is presented in the game narratives.

In each episode of *E-Rebuild*, students are given a plot-/text-based narrative presented via a panel in the upper right corner of the user interface (see Fig. 2a). These narratives highlight the main storyline of rebuilding for disaster relief and describe the game missions to be completed. When inquiring about the game environment, participants can also inspect the interactive game objects as the embodiment of game narratives (see Fig. 2b).

Results

RQ1: What and how are the different types of narrative used in game-based math learning for problem solving?

Qualitative analysis, guided by both theory-driven (Barab et al., 2007; Bruner, 1964; Jenkins, 2004), and data-driven approaches, revealed three major narratives that the students interacted with, including plot-based narrative, property-based narrative, and

Table 1 The classification of narratives and their description in this study

The overarching definition of the game narratives in this study			
A series of events, tasks, and consequential feedback in simulated real-world scenarios that is used to frame learners' inquiry (enactive representation) for learning in a systematic environmental storytelling fashion			
Representation format	Narrative types	Narrative subtypes	Description
Symbolic	Plot-based narrative	Plot-based narrative	Texts/symbols in the panel integrated by an initiating story/plot with problems to be completed
Enactive, Iconic, and symbolic	Property-based narrative	Object-oriented narrative	Texts/symbols/tables inscribed on and are inherent to the game creates/objects as a part of *E-Rebuild* story, displayed via the interactive mouseover feature
		Tool-retrieved narrative	Parameters/numbers inscribed on the game creates/objects, retrieved by the measuring tool
Enactive, Iconic, and symbolic	Environmental narrative	Environmental landscape	Narrative elements in the environment and the game world such as walls, stadium seats, or adobe houses
		Environmental cues	Narrative elements in a form of consequential cues embedded in the game world, e.g., "the container is full."

environmental narrative, aligning with our design conjecture that interactive narratives are multimodal in DGBL (see Table 1).

From the gameplay observations, students appeared to use the plot-based narrative as a cognitive framing tool as well as a bridge for symbolic immersion. The plot-based narrative that supported cognitive framing also mediated explorations of game actions, as the following two examples illustrated:

> Almost all participants started their gameplay by reading the plot-based narrative and subsequently explored the game world. The plot-based narrative drew the participants' attention in the game world for *narrative-based exploration* while framing the math task.
> Caroline was observed to use the plot-based narratives to guide her math problem solving processes. There were *15 observed behavioral turns*, of which she repeatedly switched between "Reading Plot-Based Narrative" and "Collapsing Plot-Based Narrative." She carefully read plot-based narrative, followed by collapsing Plot-Based Narrative panel, and purposefully exploring the game world.

These two examples illustrated the role plot-based narrative played in introducing the math problem-solving tasks for engagement in the game world. In addition, the function of the plot-based narrative for cognitive framing is illustrated by the observations that Caroline repeatedly collapsed the plot-based narrative panel after opening and reading it. It appeared that after reading the plot-based narrative, Caroline has encoded and stored the necessary information from the narrative; she can engage in the game-based math problem solving without narrative being displayed (as observed with Plot-Based Narrative panel being collapsed). Participants also suggested that if the storyline of plot-based narratives are removed, "that will be a lot more boring…it increases engagement."

In addition to the use of five narrative subtypes in Table 1, we also found some special cases in which participants used the environmental narratives for math problem solving. For example:

> Marcus was observed constantly exploring, evaluating, and measuring the interactive game narrative objects when he was engaged in a task of building a wall for the villagers; he used the adjacent wall panel (consisting of *four* $2 \times 2 \times 1$ blocks) in the game environment to determine the size of the target wall to be built. He measured the adjacent wall (he got *4* m) and the target wall (he got 6 m). Using *ratio*, he figured out he needs 6 blocks to build the wall to play the story.

The observations of participants using environmental narratives informed us to further classify the behavioral code of "Integrating environmental narratives" into two subtypes: "Integration of environmental objects" and "Evaluation of environmental objects" (see Table 2 for the definitions).

Based on the classification of narratives outlined in Table 1, we conducted a systematic behavioral analysis. It resulted in a total of 2,276 behavioral events. The descriptive statistic of the systematic behavioral analysis is displayed in Table 2, showing narrative-governed actions ordered in the sequence of general math problem-solving behavioral patterns based on the narrative subtypes.

In terms of the frequency of the narrative-governed actions, we found that "Successful problem solving" was the most frequent narrative-governed actions, accounting for 24% ($n=539$) of the total behaviors, followed by "Reading narratives" 22% ($n=512$), "Revisiting narratives" 15% ($n=335$), "Exploring the game world" 10% ($n=232$), "Integrating

Table 2 Frequency and percentage of the narrative-governed actions based on narrative subtypes

Narrative-governed actions Description	Narrative subtypes*	Freq	%	Total
Reading narratives[X] Look at and comprehend the narratives	Plot-based narratives	144	28%	512
	Object-oriented narratives	223	44%	
	Tool-retrieved narratives	N/A	N/A	
	Environmental landscape	32	6%	
	Environmental cues	113	22%	
Ignoring narratives Perform other actions irrelevant to exploring the narratives	Plot-based narratives	1	3%	33
	Object-oriented narratives	15	45%	
	Tool-retrieved narratives	0	0%	
	Environmental landscape	0	0%	
	Environmental cues	17	52%	
Revisiting narratives Reread and re-comprehend the narratives	Plot-based Narratives	94	28%	335
	Object-oriented narratives	211	63%	
	Tool-retrieved narratives	1	0%	
	Environmental landscape	29	9%	
	Environmental cues	N/A	N/A	
Collapsing plot-based narratives Collapse the Plot-Based Narrative panel	Plot-based narratives	30	N/A	30
Exploring the game world Navigate in the game world	Object-oriented narratives	232	N/A	232
Retrieving narratives with the tool Use the measuring tool to inspect parameters and properties of game objects	Correct	37	62%	60
	Incorrect	23	38%	
Misinterpretation Interpret the narratives in a way that cannot successfully solve the math problem	Plot-based narratives	33	45%	74
	Object-oriented narratives	29	39%	
	Tool-retrieved narratives	N/A	N/A	
	Environmental landscape	10	13%	
	Environmental cues	2	3%	

Table 2 (continued)

Narrative-governed actions Description	Narrative subtypes*	Freq	%	Total
Integrating environmental narratives^{X} Combine different environmental narratives to solve the math task	Integration of environmental objects**	68	32%	215
	Evaluation of environmental objects***	147	68%	
Refining solutions^{X} Purposefully improve the solutions for a math problem	Plot-based narratives	28	27%	102
	Object-oriented narratives	49	48%	
	Tool-retrieved narratives	2	2%	
	Environmental landscape	15	15%	
	Environmental cues	8	8%	
Successful problem solving^{Y} Successfully completing a math task/problem in a game level	Plot-based narratives	185	34%	539
	Object-oriented narratives	245	45%	
	Tool-retrieved narratives	18	3%	
	Environmental landscape	76	14%	
	Environmental cues	15	3%	
Failed problem solving^{Y} Fail to complete a math task/problem in a game level	Plot-based narratives	65	45%	143
	Object-oriented narratives	60	42%	
	Tool-retrieved narratives	2	1%	
	Environmental landscape	15	11%	
	Environmental cues	1	1%	

*For the descriptions of *Plot-based narratives, Object-oriented narratives, Tool-retrieved narratives, Environmental landscape,* and *Environmental cues*, please see Table 1

****Integration of environmental objects*** refers to learners' use of related or adjacent game objects integrally to practice mathematical problem solving

****Evaluation of environmental objects*** refers to the observation that learners constantly monitored or checked game objects to make decisions on the next problem-solving actions

^{X}Predictors for RQ2

^{Y}Dependent variable for RQ2

environmental narratives” 9% ($n=215$), “Failed problem solving” 6% ($n=143$), “Refining solutions” 4% ($n=102$), “Misinterpretation” 3% (n = 74), “Retrieving narratives with the tool” 3% ($n=60$), “Ignoring narratives” 1% ($n=33$), and “Collapsing task-based narratives” 1% ($n=30$). Table 2 showed the descriptive statistics.

RQ2: What are the correlations between the use of narrative and students' successful/failed math problem solving in game-based math learning?

We selected “Reading narratives,” “Integrating environmental narratives,” and “Refining solutions” from Table 2 as the predicting variables because these variables were observed as the main narrative-governed actions (i.e., frequency over 100 in Table 2) with all five narrative subtypes listed. We did not include “Revisiting narratives” because, for this study, we focused on the outcomes related to what learners do *after* revisiting the narratives for meaningful learning. We chose “Successful problem solving” and “Failed problem solving” as the outcome variables. The results of the analysis showed that the overall model explained 74% of the variance ($R^2=.74$), and significantly predicted “Successful problem solving” (F (3, 538) = 491.61, $p<.001$). In other words, the usage of narrative is effective in predicting successful math problem-solving performance.

Particularly, two predictors, “Reading narratives” (β = .64, $t=22.44$, $p<.001$) and “Refining solutions” (β = .06, $t=1.97$, $p=.049$), were positively correlated with “Successful math problem solving.” “Integrating environmental narratives” had nonsignificant correlation statistically (β = .07, $t=1.93$, $p=.055$), but a clinical medium effect size ($r=.47$, 95% C.I. [.40, .53]). There were no significant correlations found between the three predicting variables and the “Failed problem solving” (F (3, 142) = 1.48, $p>.05$). Table 3 summarized the results of the two models.

The results above showed that interacting with both symbolic representations (i.e., “Reading narratives”) and iconic representations (“Integrating environmental narratives”) were useful for successful math problem solving. Interview results indicated how *environmental narratives* helped learners: “it's *learning through association*, I was actually seeing it, I understood that concept through visualizing instead of someone explaining it to me,” or “sometimes visual representations can help some people, *maybe trying to combine both* (i.e., plot-based narratives and environmental narratives).”

Moreover, narrative-supported refinement (i.e., “Refining solutions”) is also a significant predictor for successful math problem solving. Qualitative thematic analysis further supported that solution refinement processes were framed by multiple types of game

Table 3 Results of the regression models

Dependent variables	Predictors	β	SE	t	p
Successful problem solving	Reading narratives	0.64	0.03	22.44	< .01*
	Integrating environmental narratives	0.07	0.04	1.93	.055
	Refining solutions	0.06	0.03	1.97	.049*
Failed problem solving	Reading narratives	0.09	0.06	1.61	.109
	Integrating environmental narratives	0.05	0.06	0.93	.353
	Refining solutions	0.06	0.05	1.18	.240

*$p<.05$

Table 4 Frequencies of narratives using behaviors by gender and chi-square test results

Behaviors	Female[a]	Male[a]	χ^2 test
Reading plot-based narratives	93	51	$\chi^2(3) = 6.70$ ($p = .82$)
Reading object-oriented narratives	127	96	
Reading environmental cues	57	56	
Reading environmental landscape	15	17	
Revisiting plot-based narratives	38	56	$\chi^2(3) = 5.40$ ($p = .15$)
Revisiting object-oriented narratives	109	102	
Revisiting tool-retrieved narratives	0	1	
Revisiting environmental landscape	17	12	
Integrating environmental narratives (Integration of environmental objects)	20	48	$\chi^2(1) = 1.53$ ($p = .22$)
Integrating environmental narratives (Evaluation of environmental objects)	56	91	
Successful problem solving with plot-based narratives	52	133	$\chi^2(4) = 17.43$ ($p = .002$*)
Successful problem solving with object-oriented narratives	160	85	
Successful problem solving with tool-retrieved narratives	8	10	
Successful problem solving with environmental landscape	36	40	
Successful problem solving with environmental cues	9	6	
Refine solutions with plot-based narratives	16	12	$\chi^2(4) = 13.33$ ($p = .01$*)
Refine solutions with object-oriented narratives	37	12	
Refine solutions with tool-retrieved narratives	2	0	
Refine solutions with environmental landscape	4	11	
Refine solutions with environmental cues	5	3	

*$p \leq .01$

[a]Frequencies of the observed behaviors by gender

narratives. The following example illustrated how "Object-oriented narratives," "Tool-retrieved narratives," "Environmental landscape," and "Environmental cues" coordinately prompted students to perform purposeful math problem solving and solution refinement:

> Carson's math problem-solving behaviors have undergone three phases: initial phase, mindless trial-and-error phase, and purposeful math problem solving phase. By interacting with different types of narratives in the game, he was prompted to consciously and meticulously engage in math thinking from unplanned gaming behaviors.

In the following observations, Carson's three phases of mathematical thinking and problem-solving practices were detailed:

> In the initial phase, he started from reading the plot-based narratives and navigating the game world. While exploring the game world, he tried to practice the game action (assigning families to a temporary shelter) but failed. He got environmental cues from the game world, then adjusted his game action and got familiar with it.

In this beginning phase, Carson only used plot-based narratives, but plot-based narratives alone did not help him solve the problem. Plot-based narratives, together with the environmental cues for his failed attempts, oriented him to the math task-related game inquiry.

> In the second phase, he started to mindlessly assign families. He tried to complete the entire task without thinking or a strategy. He spent 9 minutes and 44 seconds in this phase. After multiple trials and *being iteratively prompted by environmental cues*, he asserted to himself: "*I'll do math, I'll do math!*"

Although Carson got familiar with the math task and game action, he did not engage in purposeful math thinking and problem solving. After a long period of trial and error and prompted by the environmental cues (a narrative in the form of consequential feedback——the families can't be assigned successfully), he adapted his mindset and started to thoughtfully use other forms of narrative for math problem solving.

> He then carefully revisited the object-oriented narratives (the size of the families) and tool-retrieved narratives (the size of the shelter), compared the information from two narratives and adjusted his math reasoning: "*It (the space) was not sufficiently used!*" Now, he started to engage in math thinking and problem solving with the given task. He strategically completed the tasks, laughing jubilantly and stretching his arms and body.

In the final stage, Carson coordinated different types of narrative, including "Object-oriented narratives," "Tool-retrieved narratives," "Environmental landscape," and "Environmental cues," which collectively activated his math reasoning and problem solving. His realization was prompted by the failure to play the story based on the consequential feedback (Gresalfi & Barnes, 2016). These types of game narratives have propelled him to engage in purposeful mathematical thinking, by framing and refining his mathematical solutions.

Data from interviews suggested that the storyline and the environmental narratives assisted him in the math problem-solving processes: "I measured, but I knew it was 18 m^2 because it was in the previous level (in the storyline) as well;" "I felt engaged because I was actually doing it in the story. *I was a part of it*…if someone is more interested in the story they are more likely to do the work in order to *play the story*."

RQ3: Is there a gender difference on the use of narratives in game-based math learning for problem solving?

To address RQ3, we performed Chi-square test of independence to examine if there are gender differences in the usage of different types of narrative (see Table 4). The results showed that there was no statistically difference between male and female students' interactions with "Reading narratives" ($n=512$), "Revisiting narratives" ($n=335$), and "Integrating environmental narratives" ($n=215$).

It is not surprising to find a nonsignificant difference between girls and boys on "Reading narratives" since almost all participants began the gameplay by reading plot-based narratives as indicated in "RQ1: What and how are the different types of narrative used in game-based math learning for problem solving?" section. Nonetheless, we observed an interesting trend that male students portrayed more behaviors of attending to environmental narratives.

We found a significant difference between male and female students in terms of narrative-supported successful math problem solving ($n=539$). We found that plot-based narratives contributed to male students' ($n=133$) successful math problem solving 2.56 times higher than female students ($n=52$). But object-oriented narratives contributed to female students' ($n=160$) successful math problem solving 1.88 times higher than male students ($n=85$).

Finally, there was a significant difference in the observed behaviors of refining solutions with narratives between male and female students ($n=102$). Female students were found to refine solutions using plot-based narratives and object-oriented narratives more frequently than male students. In particular, female students used object-oriented narratives to refine solutions 3.08 times higher than male students. However, male students refined solutions with environmental landscapes more (2.75 times more frequent) than female students.

Discussion

Narrative usage in DGBL for math problem solving

In this study, we found that students used plot-based narratives, property-based narratives, and environmental narratives during game-based math problem solving. These narratives coordinate three modes of meaning representations——symbolic, iconic, and enactive (Bruner, 1964). Written plot-based narratives, a type of symbolic representation, played a role of connecting learners' prior experience and active exploration in environmental storytelling. Specifically, the learners' immersion and exploration in the environmental storytelling were mediated by *reading* the written plot-based narratives. This finding supports the argument that the semantic connections between the written narratives and learners' experience strengthened the symbolic immersion (Dede, 2009), as well as framed the necessary cognitive processes (i.e., encoding information) for solving and making sense of the given math task. Reading plot-based narrative is an essential part of solving contextualized math problems. The narrative presents a set of task goals or sub-goals to guide player's subsequent behaviors in the DGBL environment, including planning, exploring, investigating, and coordinating task-relevant information distributed in the game world.

Furthermore, we found that students used multiple types of narratives, including *both* linear and open-ended narratives. This finding extends the understanding of static narratives, and is aligned with the argument of integrating *non-linear* (Dickey, 2020; Ferguson et al., 2020; Jenkins, 2004) and *emergent environmental narrative*s (Salen & Zimmerman, 2003). It also supports the proposition that *multi-layer narratives* and *inscriptions* could support students' inquiry (Barab et al., 2007).

Narrative usage and successful math problem solving in DGBL

We found narrative-governed actions (i.e., reading narratives, refining solutions, and integrating environmental narratives) positively predict successful math problem solving. Qualitative analysis has confirmed this finding. The significant results of "reading narratives" point to the importance of text comprehension of reality-based tasks (Leiss et al., 2019; Wisittanawat & Gresalfi, 2021). The result is consistent with Bennett et al.'s (2019) suggestion that using symbolic representations (i.e., text-based narratives without iconic representations) is effective for math learning. Nonetheless, the medium effect size of "integrating environmental narratives" for refining solutions and qualitative interviewing indicate that iconic-based narratives are also valuable. Indeed, students need to perform transformations of iconic representations (Ainsworth, 2014; Moyer-Packenham et al., 2021). Specifically, when students use iconic-based narratives, they will actively interpret meaning between iconic representations and the contextualized math problem through dynamic interactions with the game narrative system to explore and refine the problem solutions. Thus, the game narrative design should strengthen the meaningful connections between narratives and the domain-specific content to provide more opportunities for representation transformations. This finding supports the importance of *intrinsic narrative design*——the narrative features should be intrinsically integrated into the game environment (Habgood & Ainsworth, 2011).

The study findings provide preliminary evidence speaking to the concerns of cognitive load in using game narratives in DGBL. Actually, the intrinsic integration coupled with a coherent design of the narrative system plays a role in reducing extraneous cognitive load when students interact with a DGBL environment. Another identified design heuristic in this study is aligned with Ferguson et al.'s (2020) recommendation in that narratives should be non-linear to allow freedom of exploration and learner control. This recommendation is also consistent with the concept of *emergent narratives* proposed by Salen and Zimmerman (2003). By interacting with dynamic game narratives, learners are able to actively process the input and use it to alter solutions and mental schema (Sweller et al., 2011).

The study findings also provide conditional evidence supporting the perspectives of productive failure (Kapur & Bielaczyc, 2012). We found that refining solutions based on the failed attempts is a significant positive predictor of successful math problem solving. The interactive game narrative system has facilitated the experience of productive failure by prompting students to adjust their actions during game-based math problem solving.

In semantically rich domains, solving hard problems requires using memories to keep track of what has been done so that students won't repeat the same failed steps again (Minsky, 1988; Simon, 1969). The game narrative system should be designed to assist learners to recall memories of failed attempts so that the students can use them for solution refinement. We propose that using in-game tracking data could possibly support the narrative design in DGBL. The data can be used for creating an adaptive game narrative system——once the computer detects off-track problem-solving actions by the learners, adaptive game narratives integrating in the environmental storytelling can be activated to prompt or induce students' behaviors of solution monitoring and refinement during gameplay (Liu et al., 2020).

Gender difference in game narrative usage for math problem solving

We found that there is a trend for boys to revisit plot-based narratives and integrate environmental narratives more. Moreover, we found significant gender differences in terms of narrative-supported successful math problem solving and solution refinement. Girls' successful math problem solving is at a higher level with object-oriented narratives, whereas boys benefit more from plot-based narratives. In addition, girls are about three times more frequent than boys in refining solutions with object-oriented narratives whereas boys are almost three times more frequent than girls in refining solutions with environmental narratives.

Consistent with Malone's (1981) finding that girls preferred intrinsic narrative, we also found that girls are supported by intrinsically designed narratives (i.e., object-oriented narratives) for math problem solving more than boys. Our findings partially support Admiraal et al.'s (2014) research that actions of searching and collecting can support girls' performance in DGBL. Situated in the game world, object-oriented narratives are distributed and need to be identified and processed along with the searching or exploring actions. These findings partially explained why girls have benefited more from object-oriented narratives.

On the other hand, boys interacted with the integrated environmental narratives more than girls. Considering environmental narratives require learners' spatial skills to reason and remember the spatial relationships among the game objects and in the environment (referring to Marcus's example in "RQ1: What and how are the different types of narrative used in game-based math learning for problem solving?" section.), this finding may be explained by Yang and Chen's (2010) finding that boys may outperform girls in spatial skills. However, as suggested by Yang and Chen (2010), DGBL can reduce the gap between boys' and girls' spatial abilities. This implies that environmental narratives should entail girls' attention and interest in concert with the narratives that girls found useful (i.e., object-oriented narratives). Further, the overarching storyline of *E-Rebuild* (i.e., *helping* the habitants to rebuild their homes and facilities) may motivate girls' engagement and promote their math-related gameplays. As Diekman et al. (2016) found, *altruism* can motivate girls more than boys, and facilitate girls' math-related pursuits. That said, narratives in games can empower girls' participation in math-related learning activities (Pinkard et al., 2017).

These findings provide heuristics governing gender-inclusive narrative designs (Admiraal et al., 2014). Narrative design in DGBL should incorporate a narrative architecture with diverse types of narrative, as well as an overarching storyline that reflects psychological research (e.g., Diekman et al., 2017) to suit the gameplay and learning needs of both girls and boys.

Implications for narrative system design in DGBL

Taken together, our findings point to the following data-driven game narrative design heuristics that can extend the current literature on DGBL:

(1) DGBL designers should design narratives that integrate and foster application of domain-specific knowledge. The game narrative system should enable the learners to actively interact with multiple external representations of the problem via integrating text-based narratives, narratives inscribed to the game objects, and environmental narratives. Learners should also be guided to exercise transformation between different narratives.

(2) Designing dynamic, adaptive, and meaningful narratives in an open-ended game world is encouraged. Specifically, *emergent narratives* should be considered (Salen & Zimmerman, 2003). Learners can use different sources of events and simulated real-world scenarios to explore and experiment with productive failure.

(3) Game designers and researchers are suggested to connect and integrate different types of narratives as well as design an overarching storyline to create an engaging and effective DGBL experience that is gender-inclusive.

Limitation and future direction

The current study focused on a first-person sandbox game for math learning and problem solving. The narrative heuristics of other game genres, content domains, and how designers craft game narratives (Salen & Zimmerman, 2003) should be further investigated. Moreover, although the participants recruited were justified for the purpose of this study, it is possible that younger learners are more prone to being distracted by the narrative elements. Additionally, although our data collection was iterative and has reached saturation (with 2276 behavioral events coded for the data analysis), future research should consider the usage of a larger sample size. Furthermore, the current study was conducted in a lab-controlled setting for our exploratory purpose. Students' gameplay behaviors may differ in non-controlled settings. Future research should further examine participants' interaction with the game narratives in a more naturalistic setting. Finally, the findings of this study were exploratory by nature. Future study could use multimodal data sources (such as facial emotions detection) as well as an experimental design to further examine DGBL narrative designs on other learning aspects (e.g., motivation to learn and/or engagement).

Conclusion

In this study, we found the positive and supportive role of game narratives in the DGBL environment for math problem solving, as well as the need for gender-inclusive design of a game narrative system. As discussed in the section of implications, we propose a set of evidence-based design heuristics for creating the narrative architecture in DGBL. First, we suggest that the design of game narratives should be a systematic process (Salen & Zimmerman, 2003), which incorporates the design and development of multimodal game narratives in the game world. Second, we maintain that learners' mathematical thinking is cultivated through a series of decision-making during the process of game-based problem solving that is framed and cued by interactive game narratives. In addition, we extend the ideas of pre-scripted and static design of game narratives, arguing for the design of more open-ended, flexible, and emergent game narratives for meaningful and inquiry-based learning. Gender-inclusive design that leverages psychological research on individual differences should also be emphasized. Finally, we want to highlight that the study of narratives and storytelling is critical for DGBL and active learning in general, because narratives and storytelling are central competences unique to human intelligence that can nurture human thinking (Winston, 2011).

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Declarations

Conflict of interest The authors claim no conflict of interest in this work.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the university Institutional Review Board (IRB). The participants were well-informed with the procedures of the study session and their rights before signing the consent form. All participants were pseudonymized.

References

Adams, D. M., Mayer, R. E., McNamara, A., Koenig, A., & Wainess, R. (2012). Narrative games for learning: Testing the discovery and narrative hypotheses. *Journal of Educational Psychology, 104*, 235–249. https://doi.org/10.1037/a0025595

Admiraal, W., Huizenga, J., Heemskerk, I., Kuiper, E., Volman, M., & ten Dam, G. (2014). Gender-inclusive game-based learning in secondary education. *International Journal of Inclusive Education, 18*(11), 1208–1218. https://doi.org/10.1080/13603116.2014.885592

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*(3), 183–198. https://doi.org/10.1016/j.learninstruc.2006.03.001

Ainsworth, S. (2014). The multiple representation principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 464–486). Cambridge University Press.

Barab, S. A., Sadler, T. D., Heiselt, C., Hickey, D., & Zuiker, S. (2007). Relating narrative, inquiry, and inscriptions: Supporting consequential play. *Journal of Science Education and Technology, 16*(1), 59–82. https://doi.org/10.1007/s10956-006-9033-3

Bennett, A., Inglis, M., & Gilmore, C. (2019). The cost of multiple representations: Learning number symbols with abstract and concrete representations. *Journal of Educational Psychology, 111*(5), 847–860. https://doi.org/10.1037/edu0000318

Bruner, J. S. (1960). On learning mathematics. *The Mathematics Teacher, 53*(8), 610–619.

Bruner, J. S. (1964). The course of cognitive growth. *American Psychologist, 19*, 1–15.

Creswell, J., & PlanoClark, V. (2018). *Designing and conducting mixed methods research* (3rd ed.). Sage Publications Inc.

Creswell, J. W., & Poth, C. N. (2017). *Qualitative inquiry and research design: Choosing among five approaches* (4th ed.). Sage Publications Inc.

Dai, C-P., Ke, F., Pan, Y., & Dai, Z. (2020). Work-in-progress—learners' interaction with task narratives for math problem-solving in game-based learning. In Economou, D., Klippel, A., Dodds, H., Peña-Rios, A., Lee, M. J. W., Beck, D., Pirker, J., Dengel, A., Peres, T. M., & Richter, J. (Eds.) *Immersive Learning Research Network. Proceedings of 6th International Conference, iLRN 2020*, Online, June 21–25, 2020. Immersive Learning Research Network. (pp. 299–301) (IEEE). https://doi.org/10.23919/iLRN47897.2020.9155180.

Darejeh, A., Marcus, N., & Sweller, J. (2021). The effect of narrative-based E-learning systems on novice users' cognitive load while learning software applications. *Educational Technology Research and Development, 69*, 2451–2473. https://doi.org/10.1007/s11423-021-10024-5

Dede, C. (2009). Immersive interfaces for engagement and learning. *Science, 323*(5910), 66–69. https://doi.org/10.1126/science.1167311

Denham, A. R. (2015). Supporting conceptual understanding of the associative and distributive properties through digital gameplay. *Journal of Computer Assisted Learning, 31*(6), 706–721. https://doi.org/10.1111/jcal.12113

Dickey, M. D. (2006a). Game design narrative for learning: Appropriating adventure game design narrative devices and techniques for the design of interactive learning environments. *Educational Technology Research and Development, 54*(3), 245–263. https://doi.org/10.1007/s11423-006-8806-y

Dickey, M. D. (2006b). Girl gamers: The controversy of girl games and the relevance of female-oriented game design for instructional design. *British Journal of Educational Technology, 37*(5), 785–793. https://doi.org/10.1111/j.1467-8535.2006.00561.x

Dickey, M. D. (2020). Narrative in game-based learning. In J. L. Plass, R. E. Mayer, & B. D. Homer (Eds.), *Handbook of game-based learning* (pp. 283–306). The MIT Press.

Diekman, A. B., Steinberg, M., Brown, E. R., Belanger, A. L., & Clark, E. K. (2017). A goal congruity model of role entry, engagement, and exit: Understanding communal goal processes in STEM gender gaps. *Personality and Social Psychology Review, 21*(2), 142–175. https://doi.org/10.1177/1088868316642141

Fanfarelli, J. R. (2020). Impact of narrative and badging on learning and engagement in a psychology learning game. *British Journal of Educational Technology, 51*(2), 387–419. https://doi.org/10.1111/bjet.12838

Ferguson, C., van den Broek, E. L., & van Oostendorp, H. (2020). On the role of interaction mode and story structure in virtual reality serious games. *Computers & Education, 143*, 1–10. https://doi.org/10.1016/j.compedu.2019.103671

Gresalfi, M. S., & Barnes, J. (2016). Designing feedback in an immersive videogame: Supporting student mathematical engagement. *Educational Technology Research and Development, 64*(1), 65–86. https://doi.org/10.1007/s11423-015-9411-8

Habgood, M. J., & Ainsworth, S. E. (2011). Motivating children to learn effectively: Exploring the value of intrinsic integration in educational games. *The Journal of the Learning Sciences, 20*(2), 169–206. https://doi.org/10.1080/10508406.2010.508029

Inal, Y., & Cagiltay, K. (2007). Flow experiences of children in an interactive social game environment. *British Journal of Educational Technology, 38*(3), 455–464. https://doi.org/10.1111/j.1467-8535.2007.00709.x

Jenkins, H. (2004). Game design as narrative architecture. In N. Wardrip-Fruin & P. Harrigan (Eds.), *First person: New media as story, performance, game* (pp. 118–130). The MIT Press.

Kapur, M., & Bielaczyc, K. (2012). Designing for productive failure. *Journal of the Learning Sciences, 21*(1), 45–83. https://doi.org/10.1080/10508406.2011.591717

Ke, F. (2016). Designing and integrating purposeful learning in game play: A systematic review. *Educational Technology Research and Development, 64*(2), 219–244. https://doi.org/10.1007/s11423-015-9418-1

Ke, F. (2019). Mathematical problem solving and learning in an architecture-themed epistemic game. *Educational Technology Research and Development, 67*(5), 1085–1104. https://doi.org/10.1007/s11423-018-09643-2

Ke, F., Shute, V., Clark, K., & Erlebacher, G. (2019). *Interdisciplinary design of the game-based learning platform: A phenomenological examination of the integrative design of game, learning, and assessment*. Springer.

Landis, J., & Koch, G. (1977). The measurement of observer agreement for categorical data. *Biometrics, 33*, 159–174. https://doi.org/10.2307/2529310

Leiss, D., Plath, J., & Schwippert, K. (2019). Language and mathematics-key factors influencing the comprehension process in reality-based tasks. *Mathematical Thinking and Learning, 21*(2), 131–153. https://doi.org/10.1080/10986065.2019.1570835

Liljedahl, P., Santos-Trigo, M., Malaspina, U., & Bruder, R. (2016). *Problem solving in mathematics education*. Springer.

Liu, Z., Moon, J., Kim, B., & Dai, C. P. (2020). Integrating adaptivity in educational games: A combined bibliometric analysis and meta-analysis review. *Educational Technology Research and Development, 68*(4), 1931–1959. https://doi.org/10.1007/s11423-020-09791-4

Malone, T. W. (1981). Toward a theory of intrinsically motivating instruction. *Cognitive Science, 5*(4), 333–369. https://doi.org/10.1016/S0364-0213(81)80017-1

Mayer, R. E. (2009). *Multimedia learning* (2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511811678

Miles, M. B., Huberman, A. M., & Saldaña, J. (2020). *Qualitative data analysis: A methods sourcebook* (4th ed.). Sage Publications.

Minsky, M. (1988). *The Society of mind*. Simon and Schuster.

Moyer-Packenham, P. S., Roxburgh, A. L., Litster, K., & Kozlowski, J. S. (2021). Relationships between semiotic representational transformations and performance outcomes in digital math games. *Technology, Knowledge and Learning*. https://doi.org/10.1007/s10758-021-09506-5

Novak, E. (2015). A critical review of digital storyline-enhanced learning. *Educational Technology Research and Development, 63*(3), 431–453. https://doi.org/10.1007/s11423-015-9372-y

Pan, Y., Ke, F., & Dai, C.-P. (2022). Patterns of using multimodal external representations in digital game-based learning. *Journal of Educational Computing Research*. https://doi.org/10.1177/07356331221087771

Pinkard, N., Erete, S., Martin, C. K., & McKinney de Royston, M. (2017). Digital youth divas: Exploring narrative-driven curriculum to spark middle school girls' interest in computational activities. *Journal of the Learning Sciences, 26*(3), 477–516. https://doi.org/10.1080/10508406.2017.1307199

Polkinghorne, D. E. (1988). *Narrative knowing and the human sciences*. State University of New York Press.

Recke, M. P., & Perna, S. (2021). Emergent narratives in remote learning experiences for project based education. *The Electronic Journal of e-Learning (EJEL), 19*(2), 2412. https://doi.org/10.34190/ejel.19.2.2142

Salen, K., & Zimmerman, E. (2003). *Rules of play: Game design fundamentals*. MIT Press.

Schoenfeld, A. H. (2016). Research in mathematics education. *Review of Research in Education, 40*(1), 497–528. https://doi.org/10.3102/0091732X16658650

Simon, H. A. (1969). *The sciences of the artificial*. MIT Press.

Suen, H. K., & Ary, D. (2014). *Analyzing quantitative behavioral observation data*. Psychology Press.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. Springer.

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. https://doi.org/10.1111/jcal.12347

Winston, P. H. (2011). The strong story hypothesis and the directed perception hypothesis. In P. Langley (Ed.). *Proceedings of the AAAI Fall Symposium on Advances in Cognitive Systems* (pp. 345–352). The Association for the Advancement of Artificial Intelligence Press. http://hdl.handle.net/1721.1/67693.

Wisittanawat, P., & Gresalfi, M. S. (2021). The "tricky business" of genre blending: Tensions between frames of school mathematics and video game play. *Journal of the Learning Sciences, 30*(2), 240–278. https://doi.org/10.1080/10508406.2020.1817747

Wouters, P., & van Oostendorp, H. (2017). Overview of instructional techniques to facilitate learning and motivation of serious games. In P. Wouters & H. van Oostendorp (Eds.), *Instructional techniques to facilitate learning and motivation of serious games* (pp. 1–16). Springer International Publishing.

Yang, J. C., & Chen, S. Y. (2010). Effects of gender differences and spatial abilities within a digital pentominoes game. *Computers & Education, 55*(3), 1220–1233.

Yang, J. C., & Quadir, B. (2018). Individual differences in an English learning achievement system: Gaming flow experience, gender differences and learning motivation. *Technology, Pedagogy and Education, 27*(3), 351–366. https://doi.org/10.1080/1475939X.2018.1460618

Zhang, J. (1997). The nature of external representations in problem solving. *Cognitive Science, 21*(2), 179–217. https://doi.org/10.1016/S0364-0213(99)80022-6

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