Education Tech Research Dev
https://doi.org/10.1007/s11423-021-09974-7

DEVELOPMENT ARTICLE

The relationship among prior knowledge, accessing learning supports, learning outcomes, and game performance in educational games

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Accepted: 17 February 2021

Abstract
In-game learning supports aim to help students solve game levels (i.e., game-related supports), and connect to underlying content (i.e., content-related and hybrid supports). Students with different levels of prior knowledge may have different needs for in-game supports. In this study, we designed a 2D physics game with game-related, content-related, and hybrid supports to explore the relationships among students' prior knowledge, their access of learning supports, learning outcomes, and game performance. Our sample included 199 ninth- to eleventh-grade students from a K-12 school in the southeastern US. Our findings indicated that students, regardless of their degree of prior knowledge, tended to access supports that directly addressed the solution of game levels (game-related supports) rather than those which presented content (content-related and hybrid supports). We found that the more frequently students accessed the *hybrid supports*, the greater their knowledge acquisition, and the more game levels they solved. We found no significant relations between the access of game-related and content-related supports and students' learning and game performance. Moreover, students with high prior knowledge tended to use hybrid supports more frequently than those with low prior knowledge. Implications of our findings and suggestions regarding future research are discussed.

Keywords Game-based learning · Educational games · Learning supports · Prior knowledge · Game performance · STEM education

Introduction

Traditional lecture-based science instruction tends to focus on scientific fact memorization (Marino, Israel, Beecher, & Basham, 2013). However, as noted in the Next Generation Science Standards, science education should devote time to science practices such as planning and carrying out investigations towards level solving, hypothesis testing, analyzing and interpreting data, and arguing based on pieces of evidence (National

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Published online: 26 March 2021

Research Council, 2013). Educational games can offer opportunities for such practices by providing engaging and meaningful learning contexts where students enhance their understanding of scientific concepts through solving game levels (Barab et al. 2009; Shute & Ke, 2012; Shute et al., 2019b; Squire & Jan, 2007; Squire & Klopfer, 2007). During gameplay, students experiment with different strategies and ideas, with little fear of failure (Gee, 2005; Squire & Klopfer, 2007).

Kiili (2005) interpreted how learning happens via gameplay by adopting Kolb's (2014) experiential learning theory. That is, when playing educational games, students first generate tentative solutions (i.e., hypotheses) to solve game levels. Then, they test the solutions and reflect on feedback leading to an abstract conceptualization of target knowledge. Afterward, students update their prior hypothesis and refine their prior solution by applying the new knowledge they learned leading to deep learning of the target knowledge. Students continue this hypothesis testing process with new solutions throughout their gaming experience (Kiili, 2005). Along with engaging in scientific practices, science-based video games can help students recognize the value of science concepts as students see their practical utility in solving game levels (Barab et al., 2009).

Well-designed educational games include challenging but doable game levels to keep students engaged in gameplay (Gee, 2005). Gee (2005) and Kiili (2005) have both argued that students' motivation for gameplay lies in game levels which are challenging but within students' competence levels. If game levels are beyond students' capabilities, students tend to get frustrated and lose the flow state (i.e., ultimate engagement on the task at hand, see Csikszentmihalyi, 1975; Gee, 2005; Kiili, 2005). Thus, students may quit playing or lose interest in the content (Schrader & Bastiaens, 2012).

Playing educational games does not necessarily lead to knowledge acquisition (Ke, 2008; Young et al., 2012). Students may solve game levels by guessing or trial-and-error without being cognitively aware of the underlying content knowledge (Ke, 2008; Squire, 2005). Moreover, playing educational games can have negative effects on learning if there is no guidance to remedy misconceptions or incomplete or disorganized knowledge (Kirschner, Sweller, & Clark, 2006; Tüzün, 2007; Weppel, Bishop, & Munoz-Avila, 2012). Consequently, researchers (e.g., Chen, Wong, & Wang, 2014; Ke, 2008; Kirschner et al. 2006; Moreno & Mayer, 2005) have suggested that game designers and teachers consider students' prior knowledge when designing and using educational games. Prior knowledge may affect how students interact with games (Kirschner et al., 2006; Moreno & Mayer, 2005) and their need for supports during gameplay (Ke, 2008). Thus, it is important to investigate the design of in-game learning supports to facilitate in-game level solving and knowledge acquisition.

Educational games with well-designed learning supports (i.e., learning supports that are designed based on learning theories and instructional principles) yield better learning outcomes and game performance than those without them (e.g., Chen & Law, 2016; Shute et al., 2019b; Sun, Wang, & Chan, 2011, Sun, Chen, & Chu, 2018; Young et al. 2012; Zeglen & Rosendale, 2018). Given the role of prior knowledge, it is also necessary to explore the need for supports among students with different levels of prior knowledge. Understanding how students' incoming knowledge is related to their use of in-game supports can provide educational game designers insights into designing learning supports for a variety of learners and experience levels.

Next, we describe the relevant literature on learning supports in educational games designed to facilitate level solving and knowledge acquisition, and the impact of students' prior knowledge on learning via gameplay.

Literature review

Game-related supports

Game-related supports focus on aspects of game levels and range from informing students about what to do next to demonstrating detailed expert solutions (Leemkuil & De Jong, 2012; Schrader & Bastiaens, 2012; Shute et al., 2019b). These supports are designed to enhance students' game performance, in other words, help students solve game levels (Schrader & Bastiaens, 2012; Sun et al., 2011). For instance, Sun et al. (2011) found that, when playing a digital Sudoku game, 7th-grade students solved more game levels when they had access to clues or a demonstration of solutions to game levels than students without such supports.

Game-related supports can additionally reduce the strain on students' cognitive processes during gameplay, clearing more cognitive space for learning content knowledge (Kao, Chiang, & Sun, 2017; Kapoor, Burleson, & Picard, 2007; Kirschner et al. 2006). For instance, Kao et al. (2017) found differing effects of game-related supports on students' learning outcomes between minimal (providing clues of solutions to game levels) and direct guidance (providing a demonstration of expert solutions). The researchers adapted a physics game called *Crayon Physics Deluxe* and compared the effects of minimal and direct guidance on junior high school students' conceptual physics understanding. Results showed that students who received minimal guidance outperformed those receiving direct guidance or no supports on their posttest scores, controlling for the pretest scores. The researchers explained that students who received minimal guidance used the clues to discern the relationships between the physics concepts and, consequently, gained a better understanding of the content. Conversely, students who received direct guidance likely just replicated the solutions without thinking about the underlying relationships.

Game-related supports can help to alleviate some or all of a game levels' difficulty, thus preventing frustration (Kao et al., 2017; Schrader & Bastiaens, 2012; Sun et al., 2011). However, Gee (2005) and Kiili (2005) argued that "pleasant frustration" (i.e., feeling that the game levels are challenging but doable) is essential for students' intrinsic motivation to play. Failure followed by reflection enables students to revise their hypotheses and gain a deep understanding of content knowledge (Squire & Klopfer, 2007). Therefore, although game-related supports can facilitate students' game performance, such supports may have no direct impact on learning (Leemkuil & De Jong, 2012). For example, Leemkuil and De Jong (2012) found no significant difference in posttest scores between undergraduate students who played a knowledge management game—with and without in-game game-related supports.

Further, Sun et al. (2018) noted that when students have unlimited access to game-related supports, they tend to rely heavily on those supports and use them before trying to solve the game levels themselves. This excessive dependence on game-related supports can lead to gameplay without realizing underlying domain-specific knowledge (Kao et al., 2017), which is essential for meaningful learning (Moreno & Mayer, 2005).

We next discuss in-game learning supports that explicitly present content to facilitate knowledge acquisition.

Content-related supports

Content-related supports present content of the subject matter underlying game levels (Koivisto, Niemi, Multisilta, & Eriksson, 2017; Schrader & Bastiaens, 2012; Weppel et al., 2012). Kirschner et al. (2006) have asserted that explicitly presenting organized content is crucial for learning in exploratory environments (e.g., educational games). Moreno and Mayer (2005) similarly note in their multimedia meaningful learning theory that meaningful learning happens when students *select* and *integrate* relevant information into their existing schema of prior knowledge. They argue that presenting subject-based content directs students' attention to relevant information and thus is beneficial to knowledge acquisition.

Tsai, Kinzer, Hung, Chen, and Hsu (2013) and Ke (2008) have also claimed that content-related supports connect gameplay with learning, and thus prevent students from being exclusively focused on just winning the games (e.g., win goal trophies or beat other competitors). For example, Tsai et al. (2013) employed an educational simulation game for teaching projectile motion, in which students had access to reference materials about the targeted content knowledge (e.g., definitions and formulas). Results showed a significant positive correlation ($r = .44$, $p < .05$) between the average time spent viewing content-related supports and students' posttest scores. Ke (2008) conducted a case study to investigate how 4th–5th grade students learn math by playing a series of math game levels *without* content-related supports. The findings showed that students' math test scores did not change significantly after 5 weeks of gameplay. Ke explained that some students adopted "wild guessing" strategies to solve the game levels and rarely reflected on underlying content knowledge, especially when they lacked basic knowledge about the levels. Some students perceived guessing as part of gameplay, while others just avoided cognitively demanding tasks.

Students may also hesitate to access relevant content during gameplay when the content is provided in isolation (i.e., not directly linked to game level solving). In Tsai et al. (2013) study, students spent only seven seconds on average over 100 min of gameplay on content-related supports without external guidance (e.g., teachers' guidance for reading the reference materials before gameplay). The researchers indicated that students were exclusively engaged in solving the game levels and felt distracted when they were required to read the content.

In addition to generally low access of content-related supports, Barab et al. (2009) and Gee (2005) have argued that when the content is given without application contexts, students tend to perceive it as just abstracted facts to be memorized. Schrader and Bastiaens (2012) further noted that content-related supports might detour students from game levels to subject knowledge and require extra cognitive effort to relate the content back to game levels. Therefore, it is important to contextualize domain-specific knowledge within game level solving, i.e., *Hybrid supports*—discussed next.

Hybrid supports

Subject knowledge should be anchored in situational contexts and let students feel that the information is useful to their solving game levels (Barab et al., 2009). Moreover, as Gee (2005) has argued, relevant content should be given "on-demand." He used the game manual as an example. Players rarely read the manual before gameplay. Instead, they use it for reference only when they need extra information to solve game levels or achieve game goals.

Hybrid supports embed content knowledge in gameplay by using focal knowledge to guide game level solving. For example, Van Eck and Dempsey (2002) designed an avatar-based geometry game for middle school students. Researchers added a walkie-talkie icon to the corner of the computer screen. An avatar would show up and help students analyze game levels using the underlying knowledge if students clicked that icon. Similarly, Chen et al. (2014) designed worked examples to provide step-by-step guidance and examples using chemical concepts and formulas to support level solving in a 3D role-play chemistry game. Results showed that middle school students who played the game with such supports outperformed those without such supports on knowledge comprehension but not on knowledge application. Chen and colleagues indicated that such in-game supports helped students focus on learning key scientific concepts. However, in Chen and colleague's study, students had to solve every game level following the worked examples, which might deprive them from the autonomy of figuring out the levels by themselves before accessing any supports.

In addition to prior-gameplay guidance, Delacruz (2010) and Moreno and Mayer (2005) operationalized hybrid supports as elaborated feedback. In these educational games, students were provided with specific explanations of their answers (Delacruz, 2010) or correct answers (Moreno & Mayer, 2005) regarding relevant content knowledge. Delacruz (2010) reported no significant difference in knowledge posttest scores and the maximum level reached between students with and without such supports, controlling for their pretest scores. However, Moreno and Mayer (2005) found that students learned better when they played a botany agent-based multimedia game with elaborated feedback than those without the supports. The contrasting results may be due to whether or not the explanations included correct answers to the specific game level. For instance, in Delacruz's (2010) study, students were told why their solutions were wrong in terms of focal knowledge if they failed to solve the level (e.g., "Denominator violations"). But in Moreno and Mayer's (2005) study, students were provided with an explanation of correct answers regardless of their answers.

Next, we discuss how students' prior knowledge can impact their interaction with educational games and their accessing of in-game learning supports.

Students' prior knowledge

Students with high prior knowledge tend to have more fully developed schemas, making them more capable of integrating and organizing new information than students with low prior knowledge (Kirschner et al., 2006; Moreno & Mayer, 2005). Various studies (e.g., Chen et al., 2014; Yang & Quadir, 2018; Zumbach, Rammerstorfer, & Deibl, 2020) have reported significant positive relations between students' prior knowledge and their cognitive learning outcome when playing educational games. Students with high prior knowledge had higher science learning efficacy and were more ready to apply the new knowledge in solving game levels than their peers with low prior knowledge (Chen et al. 2014). Moreover, students with low prior knowledge experienced more anxiety during gameplay than those with high prior knowledge (Yang & Quadir, 2018). Due to the impact of prior knowledge on learning via gameplay, Chen et al. (2014) and Kiili (2005) have suggested that game designers and teachers consider students' prior knowledge when designing and developing educational games.

Students with differing levels of prior knowledge may also have different needs for in-game learning supports (Sun et al. 2018; Yang & Quadir, 2018). For example, Yang and Quadir (2018) found that, when given free access to various learning supports in educational games, students with low prior knowledge relied on multiple supports to improve their learning, while students with high prior knowledge focused only on direct solutions (i.e., game-related supports). However, Sun et al. (2018) reported that participants with lower pretest scores used more game-related supports and less content-related supports than those with higher pretest scores in a digital reasoning game. They speculated that students with low prior knowledge might already be cognitively overloaded with solving game levels and thus, focus on supports that directly facilitate solutions to the game levels (i.e., game-related supports) than those supports that may “distract” them with content knowledge (i.e., content-related and hybrid supports; Kirschner et al., 2006; Schrader & Bastiaens, 2012; Tüzün, 2007).

To sum up, content-related, game-related, and hybrid supports are designed to facilitate students’ gameplay and learning. However, empirical studies have reported mixed results regarding the effects of these learning supports. On the one hand, some researchers have demonstrated the value of game-related supports (e.g., Kao et al., 2017; Kapoor et al., 2007; Schrader & Bastiaens, 2012; Sun et al., 2011), content-related supports (Ke, 2008; Tsai et al., 2013), and hybrid supports (Chen et al., 2014; Moreno & Mayer, 2005) in facilitating learning and game performance. On the other hand, some studies have reported non-significant or inconclusive effects of game-related supports (Leemkuil & De Jong, 2012; Sun et al., 2018), content-related supports (Schrader & Bastiaens, 2012), and hybrid supports (Delacruz, 2010; Van Eck & Dempsey, 2002). More research studies investigating the relationship between prior knowledge and all three types of learning supports are needed. Therefore, investigating how students with differing levels of prior knowledge interact with various learning supports and how such supports help them learn better via playing educational games is warranted.

Current study

In this study, we designed and developed a physics game called *Physics Playground* (Shute, Almond, & Rahimi, 2019a) with three types of in-game learning supports: (a) game-related supports—providing hints or demonstrations of expert solutions to game levels; (b) content-related supports—explicitly presenting targeted content such as formulas and definitions of physics terms; and (c) hybrid supports—presenting or explaining targeted content, but in the context of the game (e.g., explaining how specific content knowledge guides the solution to the game level). We examined the relationship between students’ prior knowledge and their access of these learning supports. We also tested how the access of various supports related to students’ learning outcomes and game performance. Towards that end, we addressed the following research questions:

1. What is the relationship between students’ prior knowledge and their accessing game-related, content-related, and hybrid supports?
2. What is the relationship between students’ accessing game-related, content-related, and hybrid supports and their learning outcomes?
3. What is the relationship between students’ accessing game-related, content-related, and hybrid supports and their game performance?

Method

The current study was a part of a large project by Shute et al. (2020a) to evaluate the effects of three different conditions of the physics game (i.e., adaptive, linear, and free choice) on students' learning. In the main study, students were randomly assigned into four groups that differed in how game levels were delivered: (1) *adaptive* group ($n = 64$)—where the next level was delivered based on students' performance in the game; (2) *linear* group ($n = 68$)—where the next level was delivered based on a predefined order of levels; (3) *free choice* group ($n = 67$)—where students could freely choose any level to play; and (4) *control* group ($n = 64$)—where students simply completed the pretest and the posttest. Students in the three game groups had free access to content-related, game-related, and hybrid supports throughout gameplay. We excluded the control group from the current analysis because they did not play the game and thus had no learning support data.

Participants

Our sample included 199 ninth- to eleventh-grade students (104 males, 91 females, and four self-identified as "other" or selected the option "prefer not to answer") from a K-12 school in the Southeastern US. Regarding ethnicity, 41% of the students identified their race as White, 31% as Black or African American, 8% as Hispanic, and 19% as other races. All students completed both the pretest and posttest and received a $30 gift card for participation.

Educational game

In this study, we used a physics game named *Physics Playground*, a 2D computer-based educational game about Newtonian physics (e.g., the laws of force and motion, linear momentum, and torque). The goal is to direct a green ball to hit a red balloon. There are two game-level types: *sketching* and *manipulation*. In sketching levels, students draw simple physics machines (i.e., ramps, levers, pendulums, and springboards) to guide the ball to the balloon (Fig. 1). To solve manipulation levels, students adjust various sliders

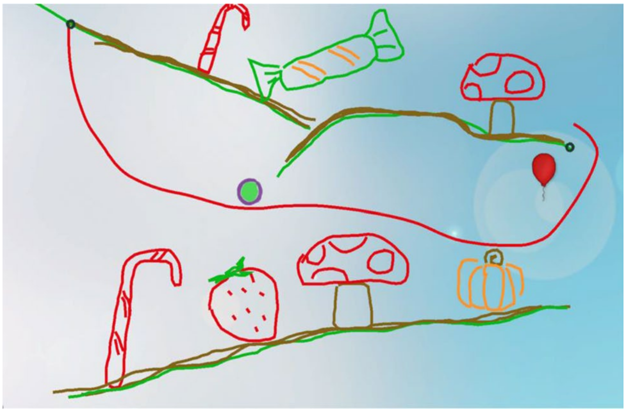

Fig. 1 *Chocolate factory*—an example of a sketching level

to change physics parameters (i.e., gravity, air resistance, and mass and bounciness of the ball), and also manipulate external forces such as puffers and blowers (Fig. 2).

The game consisted of 10 tutorial levels (i.e., levels to introduce basic game mechanics such as how to draw a springboard), and 81 game levels (34 sketching levels and 47 manipulation levels). The game contained game-related, content-related, and hybrid supports. Students could access all supports by clicking on an ever-present button presenting three options: (a) *Show me the Physics*, which linked to content-related and hybrid supports; (b) *Show me a Hint or Solution*, which linked to game-related supports; and (c) *Show me Game Tips* (short descriptions of the game mechanics). The specific learning supports under each type (i.e., game-related, content-related, and hybrid supports) are presented in Table 1.

In this study, we designed our hybrid supports as animation-based explanations of major game mechanisms using targeted physics concepts. First, the specific content was presented in the context of the game environment so that students could see the connection(s) between gameplay and physics content. Second, the supports could not be used to solve a particular game level directly. Students had to comprehend the knowledge and transfer it to solve game levels.

Moreover, according to the literature (e.g., Sun et al., 2018; Tsai et al., 2013), students may abuse supports that can directly help them win the game and neglect supports that may distract them from gameplay. Therefore, we included a monetary incentive system to avoid abuse of the game-related supports (*Solutions*) and encourage the use of content-related and hybrid supports. Students could earn \$5 or \$10 (of game money) the first time they access a content-related or hybrid support at a game level. For example, the game provided \$10 for the first use of a *Physics Animation* and \$5 for the first use of the *Glossary*. However, students had to pay \$60 for each use of *Solutions* at a level. Student level solutions were also incentivized. Students could earn a silver (\$10) or a gold coin (\$20) based on the quality of the solution for a level. See Rahimi et al. (2021) for more details on the incentive system's effects on students' learning support access and content learning outcome.

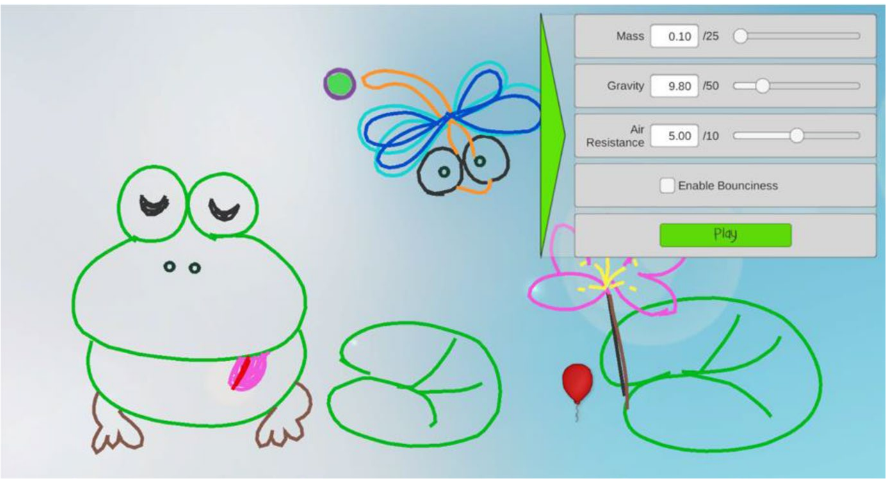

Fig. 2 *Frog*—an example of a manipulation level

Table 1 List of learning supports under game-related, content-related, and hybrid supports

Type of learning support	Learning support	Description
Game-related supports	*Solutions*	Direct guidance that shows videos presenting the full expert solution for a game level (click https://bit.ly/3dceuXt for a solution in the *Frog* level.)
	Hints	Minimal guidance that directs students to the correct path without revealing the full solution (e.g., "Try drawing a lever")
Content-related supports	*Glossary*	Brief explanations of 29 physics terms (Fig. 3)
	Definitions	Composed of a short animation about a physics term, e.g., "energy," and a drag-and-drop quiz-like activity to increase interactivity, in which students drag phrases to fill in the blanks within the definition of the physics term
	Formulas	Formula or equations corresponding to physics concepts along with a description of each formula component
	Hewitt videos	Cartoon animations developed by Paul Hewitt explaining various physics concepts (click https://bit.ly/2KV2PAd for a physics animation about the property of torque.)
Hybrid supports	*Physics animations*	Short narrated animations explaining the relevant physics concepts in the context of game levels (Fig. 4)

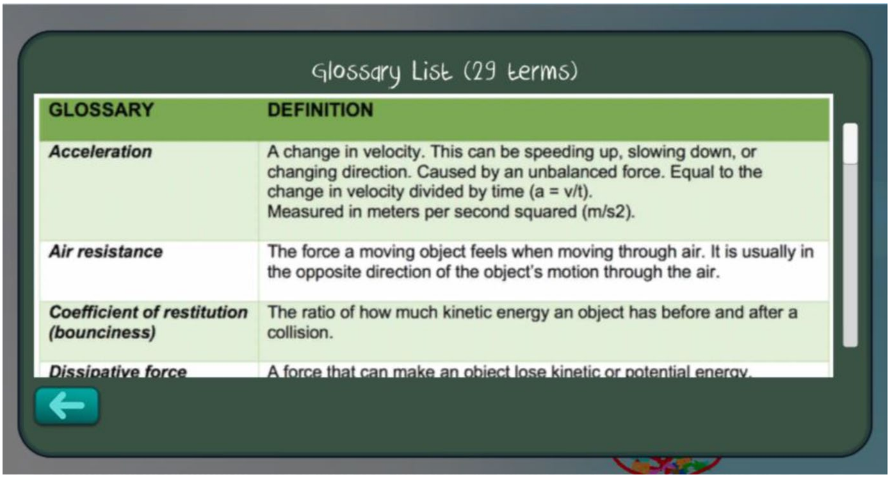

Fig. 3 Glossary—an example of content-related supports

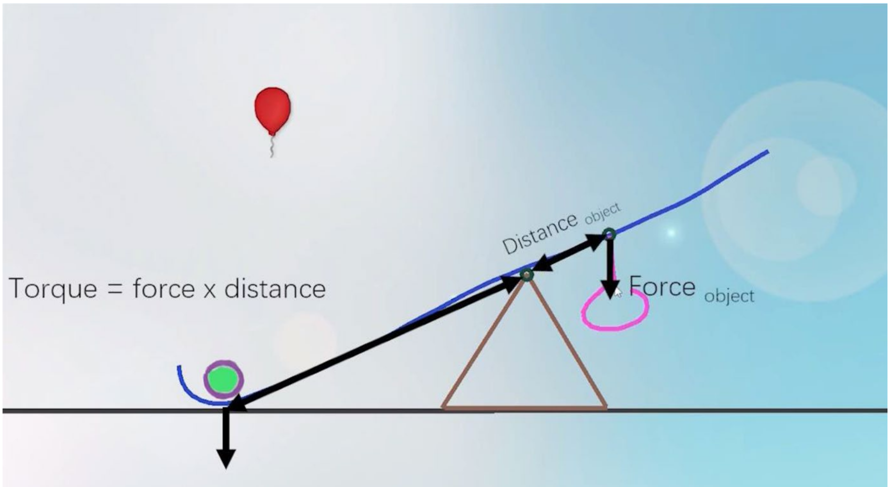

Fig. 4 A screenshot of a physics animation about the properties of torque. Click https://bit.ly/3i1mv4J for the full video

Procedures

All students played the game in 50-min sessions across six days, in classroom settings. On the first day, participants completed a demographic survey and an online pretest of physics knowledge (18 items), followed by an introduction to the game. Students played the game individually during sessions two through five and were monitored by research team members. The final session consisted of gameplay followed by the online posttest and receipt of the gift cards for students who completed the study.

Measures

Accessing game-related, content-related, and hybrid supports

The game automatically records students' game actions during gameplay. For example, entering a game level, drawing objects (e.g., a line, a pendulum, a ramp), accessing supports, winning a game level, and quitting a game level are all recorded in the log files with the time stamp related to each event. To measure students' access of game-related, content-related, and hybrid supports, we parsed the log data to extract and compute the frequency of use of each learning support described above. To compute game-related supports access, we summed the frequencies across students' use of *Solutions* and *Hints*. To compute content-related supports access, we summed the frequencies across students' use of *Glossary, Definitions, Formulas*, and *Hewitt Videos*. We used the frequency of *Physics Animations* to measure hybrid supports access.

Physics understanding test

To assess students' change in physics understanding (i.e., content learning outcome), we created two isomorphic tests with multiple-choice items (pretest = 18 items, $\alpha = .77$; posttest = 18 items, $\alpha = .82$). The test items were (a) designed in the context of the game (i.e., including a video or an image from the game environment), (b) developed with the help of two physics experts, and (c) subjected to two pilot tests before being administered (Fig. 5).

Game performance

Like accessing learning supports, students' actions of completing levels were also recorded in the log file. The game performance data focused on in this study was measured by the total number of completed levels, per student.

Results

Students were randomly divided into three treatment conditions (i.e., adaptive, linear, and free control). To determine if we could combine the participants across these conditions in addressing the research questions of this study, we tested the equivalence of learning outcome and game performance across these three groups. Three one-way ANCOVAs were conducted to examine the differences among adaptive, linear, and free choice conditions on students' posttest scores and the number of completed levels, controlling for pretest scores. Results showed no significant effect of treatment conditions on posttest scores (F (2, 195) = .34, $p = .71$, partial $\eta^2 = .25$) or the number of completed levels (F (2, 195) = 2.21, $p = .11$, partial $\eta^2 = .69$), holding pretest scores constant. Therefore, we combined the data of students from all three groups for the following analyses.

Descriptive statistics

Before testing the research questions, we first computed descriptive statistics of focal variables: students' prior knowledge of relevant physics concepts, access of learning supports, learning outcome, and game performance—presented in Table 2.

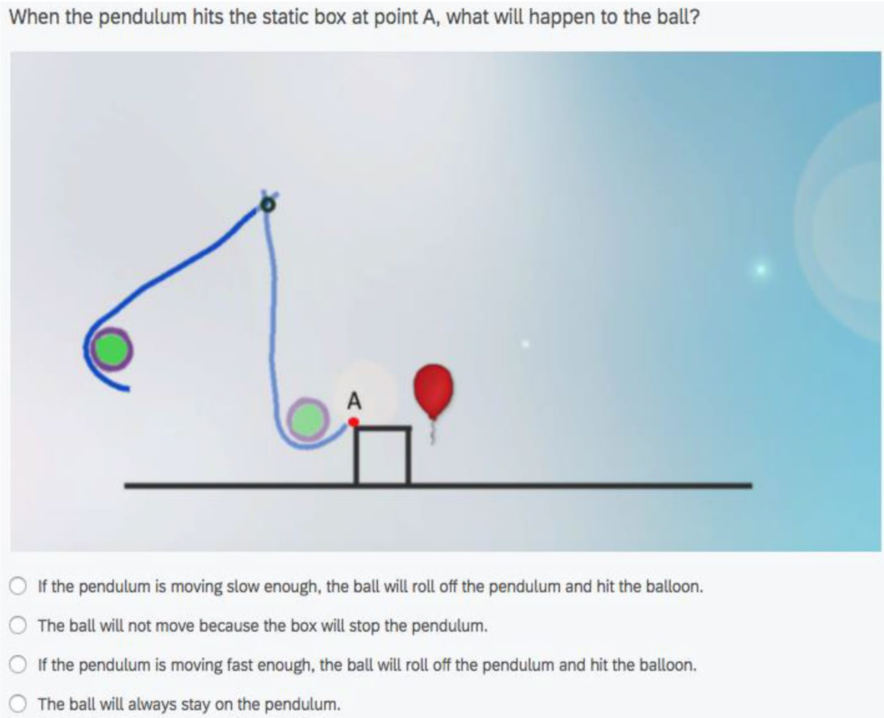

Fig. 5 Example of an item from the physics understanding test

Table 2 Descriptive statistics of pretest score, access of learning supports, posttest score, and number of completed levels ($n = 199$)

Variable	M	SD	Skewness	Kurtosis
Pretest score	11.82	3.53	− .47	− .29
Game-related support frequency	9.16	7.67	1.15	.95
Content-related support frequency	2.18	10.63	8.35	75.06
Hybrid support frequency	5.43	5.71	1.42	2.21
Posttest score	12.46	3.88	− .75	− .22
Number of completed levels	45.94	16.18	.48	− .01

Table 2 shows that the data for content-related support frequency was highly skewed. Around 75% of the students ($n = 148$) did not access content-related supports at all despite the monetary incentive (i.e., students got \$5 to \$10 game currency for the first access to a content-related support). Therefore, we conducted a non-parametric test to compare frequencies across the three types of learning supports. A Kruskal–Wallis H test showed a statistically significant difference in frequencies across the three types of learning supports, $H(2) = 218.04$, $p < .001$. Overall, students accessed more game-related supports, followed by hybrid supports, and content-related supports.

RQ1—prior knowledge and accessing learning supports

Regarding RQ1 (i.e., the relationship between students' prior knowledge and their accessing game-related, content-related, and hybrid supports), we hypothesized that students with low prior knowledge would access the game-related supports more frequently than the content-related and hybrid supports compared to those with high incoming knowledge.

Considering that the frequencies of game-related, content-related, and hybrid supports were tallies, we first planned to conduct three Poisson regression analyses (Hutchinson & Holtman, 2005) to predict the usage patterns using students' pretest scores. However, the equal dispersion assumption for the Poisson regression analysis was not met. The Chi-squared goodness-of-fit tests for the Poisson regression models were all significant: (a) game-related support frequency ($X^2(197) = 1261.34$, $p < .001$), (b) content-related support frequency ($X^2(197) = 2121.35$, $p < .001$), and (c) hybrid support frequency ($X^2(197) = 1041.74$, $p < .001$). Therefore, we adopted the Negative Binomial regression, which is a generalization of the Poisson regression without making the equal dispersion assumption (Hilbe, 2011). We computed three Negative Binomial regression analyses to predict game-related, content-related, and hybrid support frequency using students' pretest scores. The Omnibus test results showed that students' pretest scores did *not* significantly predict game-related support frequency (Likelihood Ratio (1) = .14, $p = .71$) or content-related support frequency (Likelihood Ratio $X^2(1) = 3.03$, $p = .08$). However, hybrid support frequency was significantly predicted by students' prior knowledge. The higher the students' pretest scores, the more frequently they accessed the hybrid supports. Therefore, our hypothesis that students with low prior knowledge would access game-related supports more frequently and content-related and hybrid supports less frequently than those with high prior knowledge was not supported.

RQ2—relationship between accessing learning supports and physics learning

To test if accessing learning supports predicts students' learning and game performance outcomes, accounting for their pretest scores, we first computed a Pearson correlation for the focal variables (see Table 3). The results showed that students' pretest scores and hybrid support frequency significantly correlated to their posttest scores. Students' pretest score, content-related support frequency, hybrid support frequency, and posttest score were significantly correlated to the total number of completed levels that students solved.

Table 3 Pearson correlation matrix for pretest score, access of learning supports, posttest score, and number of completed levels ($n = 199$)

Variable	1	2	3	4	5	6
1. Pretest score	–					
2. Game-related support frequency	.03	–				
3. Content-related support frequency	.08	.08	–			
4. Hybrid support frequency	.30*	.05	.44*	–		
5. Posttest score	.70*	.02	.06	.32*	–	
6. Number of completed levels	.44*	.09	.22*	.44*	.56*	–

*$p < .05$

Regarding RQ2 (i.e., the relationship between students' access of learning supports and their content learning), we hypothesized that students accessing game-related, content-related, and hybrid supports more frequently would score higher on the posttest than those with less frequent access, controlling for their pretest score. To test this hypothesis, we computed a multiple linear regression analysis of posttest scores using the frequencies of game-related, content-related, and hybrid supports as predictors, holding pretest scores constant (Model 1). The multicollinearity issue and the homoscedasticity assumption were checked. Results are shown in Table 4.

Results indicated that Model 1 was significant, F (4, 194) = 49.38, $p < .001$. However, among all three types of learning supports, only hybrid support frequency was significant in predicting posttest scores, controlling for other predictors. Therefore, we removed the non-significant predictors and built Model 2. Results regarding Model 2, also shown in Table 4, was also significant, F (2, 196) = 98.45, $p < .001$, with an R^2 of .50. Specifically, the result indicated that posttest scores would increase by .12 standard deviations when the frequency of hybrid supports increased by one standard deviation, controlling for pretest score. We adopted Model 2 since it had more predictive power (i.e., larger adjusted R^2) and fewer predictors than Model 1.

In short, among the three types of learning supports, only hybrid support frequency predicted students' posttest score after controlling for their pretest score, thus our hypothesis that students' accessing game-related, content-related, and hybrid supports would predict their learning outcome was partially accepted.

RQ3—relationship between accessing learning supports and game performance

Regarding RQ3 (i.e., the relationship between students' accessing supports and their game performance), we hypothesized that students who accessed game-related, content-related, and hybrid supports more frequently would solve more game levels than those with less frequent access, controlling for their prior knowledge. To test this hypothesis, we computed a multiple linear regression analysis to predict the number of completed levels using the frequencies of game-related, content-related, and hybrid supports as predictors, and pretest scores as covariate (Model 1)—presented in Table 5. The multicollinearity issue and the homoscedasticity assumption were checked.

Table 4 Two multiple regression results predicting posttest scores based on the frequencies of learning supports controlling for pretest scores

Predictor	t	β	F	df	R^2	Adjusted R^2
Model 1			49.38*	4, 194	.51	.49
Game-related support frequency	.04	.00				
Content-related support frequency	− 1.15	− .07				
Hybrid support frequency	2.60*	.15				
Pretest score	12.41*	.66				
Model 2			98.45*	2, 196	.50	.50
Hybrid support frequency	2.34*	.12				
Pretest score	12.52*	.66				

*$p < .05$

Table 5 Two multiple regression results predicting game performance based on frequencies of learning supports controlling for pretest scores

Predictor	t	β	F	df	R^2	Adjusted R^2
Model 1			21.49*	4, 194	.31	.29
Game-related support frequency	1.04	.06				
Content-related support frequency	.82	.06				
Hybrid support frequency	4.53*	.32				
Pretest score	5.43*	.34				
Model 2			42.07*	2, 196	.30	.29
Hybrid support frequency	5.47*	.34				
Pretest score	5.41*	.34				

*$p < .01$

Results showed that Model 1 was significant, F (4, 194) = 21.49, $p < .001$. However, among all three types of learning supports, again only hybrid support frequency was a significant predictor of the number of completed levels, controlling for other predictors. Therefore, we conducted another linear regression after removing the non-significant predictors (Model 2), shown in Table 5. Model 2 was also significant, F (2, 196) = 42.07, $p < .001$, $R^2 = .30$. Specifically, the number of completed levels would increase by .34 standard deviation when the frequency of hybrid supports increased by one standard deviation controlling for the pretest score. We adopted Model 2 since it had the same predictive power (i.e., same adjusted R^2) and fewer predictors than Model 1.

In summary, among the three types of learning supports, only the usage of hybrid supports predicted students' number of levels completed after controlling for incoming knowledge. Our hypothesis that students' accessing game-related, content-related, and hybrid supports would predict their game performance controlling for students' prior knowledge was partially accepted.

Discussion

Well-designed educational games provide engaging learning environments where students can learn targeted content through using it to solve game levels (Barab et al., 2009; Shute & Ke, 2012; Shute et al., 2019b; Squire & Jan, 2007; Squire & Klopfer, 2007). But students may get overwhelmed by really difficult game levels (Schrader & Bastiaens, 2012) or play the games without connecting the underlying content knowledge to gameplay (Ke, 2008; Kirschner et al., 2006; Squire, 2005). The current study focused on three types of in-game learning supports designed to help students solve game levels (i.e., game-related supports) and facilitate targeted knowledge acquisition (i.e., content-related supports and hybrid supports). We designed a physics game with these learning supports embedded therein to investigate the relationship between students' prior knowledge and their access of these three supports. We also explored if accessing different types of learning supports related to students' learning and game performance.

Accessing learning supports and prior knowledge

Game-related supports may directly help students improve game performance, while content-related and hybrid supports present targeted content—in isolation and in the context of the game, respectively. We found that all students accessed game-related supports more frequently than hybrid and content-related supports, even though we designed a monetary incentive system to demotivate the use of *Solutions* and encourage hybrid and content-related supports use. We further found that 75% of the students did not access content-related supports at all across the whole intervention. These findings align with Tsai and colleagues' study (2013), which reported that students rarely used content-related supports without instructors' guidance.

Challenging but doable game levels are crucial to keeping students engaged in gameplay (Gee, 2005). Ke (2008) observed that students tend to focus exclusively on solving game levels to win the game rather than learning content. This may explain why students in the current study preferred game-related to content-related supports since the latter presented isolated knowledge having no intuitive connection to the game levels. Students were supposed to apply relevant knowledge (in our case—related to Newtonian physics) to solve game levels, but, as Schrader and Bastiaens (2012) argued, students might find it difficult to relate the content back to game environments.

We found no significant difference in students' access of game-related and content-related supports relative to prior knowledge levels. This result contradicts the findings by Sun et al. (2018), who reported that students with low pretest scores accessed game-related supports more frequently than content-related supports compared to students with high pretest scores. We speculate that students, regardless of their prior knowledge, prefer learning supports that provide direct help with solving game levels to those that might help tangentially.

Although both content-related and hybrid supports present content, students accessed hybrid supports twice as often as content-related supports, indicating that embedding content in the context of the game environment can increase students' access. We also found that students with high prior knowledge accessed more hybrid supports than those with low prior knowledge. One possible explanation is that students with high prior knowledge found such supports could effectively help them understand physics knowledge more deeply, and thus allow them to apply that knowledge to solve game levels, discussed below.

The effect of hybrid supports on learning and performance

Our findings showed that the hybrid supports were the only useful predictor among the three types of learning supports in predicting students' physics learning and game performance, controlling for their prior knowledge. Barab et al. (2009) and Gee (2005) have argued that explicitly explaining how relevant knowledge guides decision making during the solution of game levels (i.e., hybrid supports) can promote knowledge acquisition. Our findings support this argument by revealing that the more frequently students accessed hybrid supports, the higher their posttest scores. We also found a positive correlation between students' hybrid support frequency and their game performance, although unlike the hybrid supports designed by Chen et al. (2014), hybrid supports in the current study cannot be used to solve any specific game levels directly. Our findings also contradict the results of studies reported by Van Eck and Dempsey (2002) and Delacruz (2010), which reported a non-significant correlation between students' use of hybrid supports and their knowledge acquisition and the total number of completed game levels. One possible reason for these inconsistent results is the design of our hybrid supports. In this study, we designed hybrid supports based on empirically validated multimedia learning principles (e.g., the coherence principle) with the guidance of physics experts (see Shute et al., 2020b).

Regression analysis alone cannot be used to establish causality. However, after controlling for students' prior knowledge and their access of other supports, we posit that hybrid supports may help students learn content when playing educational games. Moreover, considering the positive relationship between hybrid supports access and students' game performance, we speculate that such supports could help students learn the content knowledge by building a connection between content knowledge and game levels. Students, in turn, learn to apply the knowledge to solve more game levels, which further enhances their conceptual understanding of the subject knowledge.

The effect of game-related supports on learning and performance

Game-related supports, which are designed to directly facilitate the solution of game levels, can reduce the strain on cognitive processes, thus creating more opportunities to acquire focal knowledge (Kapoor et al., 2007; Kirschner et al., 2006). However, we did not find any significant relation between game-related support frequency and students' learning. This result supports findings from Leemkuil and De Jong's work (2012), who similarly reported a non-significant correlation between game-related supports use and students' posttest scores.

Our finding of the non-significant relation between accessing game-related supports and learning outcomes indicates that focusing on supporting game solutions may *not* benefit knowledge acquisition. As suggested by Sun et al. (2018), students might access expert solutions before trying to solve game levels by themselves, regardless of the monetary cost for accessing *Solutions*. Failure and subsequent reflection are necessary for learning via playing educational games (Squire & Klopfer, 2007).

Moreover, and in contrast with the findings of Sun et al. (2011), the current study reported no significant relationship between accessing game-related supports and game performance. One possible reason for this finding is that *Hints*, making up 66% of the total frequency of game-related supports accessed in this study, may not guarantee success in solving game levels. For instance, a hint "Try drawing a lever" did not tell students where to draw the fulcrum or how long the lever arms should be.

The effect of content-related supports on learning and performance

Explicitly presenting targeted knowledge is crucial to meaningful learning in educational games (e.g., Kirschner et al., 2006; Moreno & Mayer, 2005). However, we did not find a significant relationship between accessing content-related supports and students' learning. This finding differs from Tsai and colleague's work (2013), who reported a significant correlation between students' access of content-related supports and their posttest scores.

We note that only around 25% of the students in the current study chose to view content-related supports even with an incentive system in place to motivate its use. Thus, the non-significant impact of content-related supports may be due to low access. Moreover, as suggested by Barab et al. (2009) and Gee (2005), students might find it hard to connect the content to the game levels they were solving. Therefore, they might just neglect the content after accessing such supports.

Conclusion and future research

We aimed to explore the effects of in-game supports on students' learning and game performance outcomes via playing educational games. We also examined if students with different levels of prior knowledge had different preferences for game-related, content-related, and hybrid supports. The findings of this study further illuminate students' need of various in-game learning supports and shed light on the design of in-game supports which can connect gameplay with content learning. We found that students, regardless of their prior knowledge levels, preferred learning supports that could directly help them solve game levels rather than those focusing more on the targeted content.

Solving game levels using only trial-and-error without cognitive awareness of the underlying reasoning does not elicit learning (Barab et al., 2009; Chen et al., 2014; Delacruz, 2010; Gee, 2005; Moreno & Mayer, 2005; Van Eck & Dempsey, 2002). Our findings suggest that embedding content knowledge within the guidance on solving game levels (i.e., hybrid supports) is a promising way to help students build the connections between content knowledge and gameplay. When presented within the context of the game environment, students find targeted content useful, rather than distracting. Moreover, such supports may increase students' learning of content through application in gameplay solutions. The current study used an educational physics game with hybrid supports explaining game mechanisms with physics content designed for high school students. Caution is needed before generalizing the findings to educational games in other subjects (e.g., language learning) and at other educational levels.

Exploratory learning environments are especially challenging for students with low prior knowledge (Kirschner et al., 2006; Moreno & Mayer, 2005). We further assert that such students are also less likely to access potentially effective in-game supports. Therefore, future studies are needed to explore how to motivate students, especially those with low prior knowledge, to access more hybrid supports. One example is to make in-game supports mandatory to view, or provide outside-the-game guidance (e.g., have instructors guide students in building a connection between the underlying knowledge and game levels in debriefing sessions after gameplay). Moreover, further experimental studies are needed to verify the effects of hybrid supports on learning. In addition, to better understand the impact of hybrid supports, we need to qualitatively explore the process of how such supports help students learn content from gameplay. For example, future researchers can conduct post-gameplay interviews for students to elaborate on their internal thoughts when accessing hybrid supports.

Game-based supports are designed to alleviate potential frustration when game levels are beyond students' competency levels to avoid frustration or quitting. But this study, similar to the findings reported by Kao et al. (2017) and Sun et al. (2018), implies that some students might access such supports before trying a solution on their own. Therefore, we suggest that researchers investigate ways to provide game-related supports, only when they are necessary. For example, researchers can monitor students' frustration levels and present game-related supports as needed. Individualized adaptivity based on students' affective states can offer the opportunity for just-in-time support that can encourage learning and further exploration.

Acknowledgements This work was supported by the US National Science Foundation [Award Number #037988] and the US Department of Education [Award Number #039019]. We also would like to acknowledge Russell Almond, Fengfeng Ke, Zhichun Liu, Jiawei Li, Chen Sun, Xi Lu, and Chi-Pu Dai for helping in different phases of this project.

Declarations

Conflict of interest We confirm that there are no known conflicts of interest associated with this manuscript.

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