Learning from Errors in Game-Based versus Formal Mathematics Contexts

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Abstract

Research suggests that educational games may be particularly useful for helping children learn STEM concepts; however, the mechanisms involved in game-based learning are not well understood. The present study tested the hypothesis that games are effective because they provide a supportive learning context that allows children to react adaptively to errors. Children (*M* age – 7 yrs, 6 mo) were given two half-hour learning sessions in which they solved nontraditional arithmetic problems (e.g., __ = 3 + 4) in game and formal contexts. In a third session, children were given a transfer test in which they solved mathematical equivalence problems (e.g., 1 + 5 = __ + 2). Children who committed more of their learning errors in the game context solved a greater number of problems correctly on the transfer test than did children who made more of their errors in the formal context. Moreover, children reacted less negatively to errors made in the game context than in the formal context. These findings suggest that educational games may be an effective learning tool because they provide a supportive context that allows children to learn from errors.

Parents and teachers often use educational games (e.g., computer games, card games, board games, etc.) to help children learn important academic skills. This strategy is intuitively appealing because educational games are widely available, and they seem to make learning fun. The use of educational games is also backed by research in psychology and education. Indeed, many prominent researchers throughout history have suggested that games and other "play" activities facilitate children's learning and cognitive development (Hirsh-Pasek & Golinkoff, 2003; Piaget, 1962; Ramani & Siegler, 2008; Schultz & Bonawitz, 2007; Vygotsky, 1967).

Research suggests that educational games may be particularly useful for helping children learn science, technology, engineering, and mathematics (STEM) concepts (Annetta, Minogue, Holmes, & Cheng, 2009; Barab, Thomas, Dodge, Carteaux, & Tuzun, 2005; Ke, 2008; Ramani & Siegler, 2008; Siegler & Ramani, 2008; Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). For example, in a series of recent experiments, Siegler and Ramani (2008, 2009; Ramani & Siegler, 2008) demonstrated that the numerical knowledge of children from low-income backgrounds could be improved substantially by playing numerical board games with equal-sized spaces that are linearly arranged and consecutively numbered. Other studies have demonstrated that children who learn STEM concepts via computer games show more motivation, more engagement, and more positive attitudes toward learning than children who learn STEM concepts via formal instruction (Annetta et al., 2009; Coller & Scott, 2009; Ota & DuPaul, 2002). Taken together, the evidence suggests that educational games have the potential to promote learning and engagement in STEM domains.

Although it is widely acknowledged that educational games can be a useful tool for learning STEM concepts, the mechanisms involved in the benefits of game-based learning are not well understood. In the present study, we focused on one potential mechanism involved in the benefits of game-based learning. Specifically, we hypothesized that games promote learning, in part, because they provide a supportive learning context that allows children to react adaptively to and to learn from errors.

All children inevitably make errors when they are learning something new, and the way that they react to these errors has the potential to affect the learning process (Baker, D'Mello, Rodrigo, & Graesser, in press; Elliot & Dweck, 1988; Dweck, 2000). Specifically, negative reactions to errors such as frustration, anxiety, or helplessness are likely to hinder learning (Ashcraft & Kirk, 2001; Baker et al., in press; Dweck, 2000).

Importantly, research suggests that the nature of the learning context can influence how children react to their errors (Mueller & Dweck, 1998; Okolo, 1992). Some learning contexts are more supportive than others. Supportive learning contexts are non-evaluative and deemphasize the association between errors and intelligence (Burhans & Dweck, 1995; Elliot & Dweck, 1988; Dweck, 2000). Such contexts buffer children from reacting negatively to errors and encourage children to persist longer in the face of errors (Okolo, 1992).

We propose that the benefits of games may derive, at least in part, from the supportive learning context they provide. Games are less evaluative than formal learning contexts. Children's performance is typically not graded during games, and failure during games can often be attributed to luck. Thus, games may help deemphasize the association between errors and intelligence. For these reasons, games should help children learn because they remove the evaluative factors that often cause children to lose motivation for learning. If children do not feel like they are being evaluated, then they may react more adaptively to their errors.

In contrast, formal contexts may make children feel more evaluated. When children err in a formal context, their sense of intelligence may be threatened, and they may respond with helpless behaviors. For example, children might stop trying to solve the problems correctly so that poor performance can be attributed to lack of effort rather than to low intelligence. If children's focus is on being evaluated instead of on learning, then they may react more negatively to their errors.

In the present study, we tested these ideas by studying a group of children who were learning to solve mathematics problems in the context of both games and formal flashcards. If games provide a supportive learning context for making errors, then children should be less likely to react negatively to the errors they make in a game context versus a formal context. Thus, we hypothesized that the proportion of errors that children reacted to negatively during the games would be lower than the proportion of errors that children reacted to negatively during the flashcards. Moreover, if games facilitate learning *because* they provide a supportive context for making errors, then children's learning should benefit from erring more in a game context relative to a formal context. Thus, we hypothesized that children who committed more of their errors during the games would learn more than children who committed more of their errors during the flashcards.

Method

Participants

This study used existing data from a larger study that tested how various ways of solving addition problems affect children's understanding of mathematical equivalence. The participants of interest were 37 children who participated in two sessions in which they learned to solve addition problems that were presented in a nontraditional format (e.g., __ = 3 + 4; 10 = 6 + __). Children were recruited from a diverse range of public and private elementary schools in a mid-sized city in the midwestern United States. One child was excluded because he did not make any errors over the course of the learning sessions. Thus, the sample contained 36 children (*M* age = 7 years, 6 months; 19 boys, 17 girls; 3% Asian, 3% Hispanic or Latino; 11% African-American or black; 83% white).

Procedure

Children participated individually in three half-hour sessions. During the first two sessions, children learned to solve nontraditional addition problems (e.g., __ = 3 + 4; 10 = 6 + __) by playing games one-on-one with a tutor (i.e., game context) and by answering flashcards (i.e., formal context). All children participated in both the game and formal contexts in alternating order during both sessions. Each session started with games, continued onto flashcards, and then ended with more games. During a third session, children were introduced to a new experimenter who assessed their learning by giving them a transfer test. All three sessions were video recorded.

Learning sessions The learning sessions were designed to help children solve single-digit addition facts with two addends (e.g., 17 = 9 + 8, 14 = 8 + 6). All problems were presented in a nontraditional format with the operation on the right side of the equal sign. This format is considered to be "nontraditional" because arithmetic problems are traditionally presented with the operations on the left side of the equal sign. Children learned via two main types of activities: (a) two-player games involving cards, dice, or the computer, and (b) flashcards. Children received feedback about correctness throughout the sessions in both the game and formal contexts, and any errors were corrected.

Game context. Children played several two-player games over the course of the learning sessions with the experimenter. One game was a modified version of "Snakey Math" by Curry K. Software. In this computer game, an addition problem was presented at the bottom of the computer screen (e.g., __ = 3 + 4), and several possible numbers (e.g., 7, 1, 12, 8) were scattered in random locations on the screen. The child and the tutor each controlled an animated snake, and the goal was to be the first snake to "eat" the number that correctly solved the addition problem.

Another game was called "Smack it!" In this card game, the child and tutor each used a swatter with a suction cup at the end. At the beginning of the game, four addition problems were placed face-up on the table, and a pile of number cards were placed face down. To start each round, the tutor turned over one of the number cards to serve as the target number. The goal was to be the first player to "smack" the addition problem that should have the target number in the blank. Children also played other two-player games that were similar in content and scope. Most of the games were rigged so the child would win; however, some games involved luck, so the tutor occasionally won. Overall, children solved an average of 46.03 problems in the game context across the two learning sessions.

Formal context. The formal context consisted of flashcards presented in succession. Before completing the flashcards, children received a brief demonstration on how to solve the flashcards. Children solved an average of 45.11 flashcards in total across the two learning sessions. Thus, there was not a significant difference in the number of problems that children solved in the game and formal contexts, $F(1, 35) = 0.21$, $p = 0.65$.

Transfer test Children solved four mathematical equivalence problems (1 + 5 = __ + 2, 7 + 2 + 4 = __ + 4, 2 + 7 = 6 + __, 3 + 5 + 6 = 3 + __). Similar to the addition problems solved during the learning sessions, these problems do not correspond to the traditional "operations on left side" format, so they drew on the knowledge that children had gained from the learning sessions. However, they were much more difficult than the problems solved in the learning sessions because they have operations on both sides of the equal sign. Children never saw problems with operations on both sides of the equal sign during the learning sessions. Previous research has shown that most children in this age range in the U.S. have trouble solving mathematical equivalence problems correctly in the absence of special instruction (Alibali, 1999; Falkner, Levi, & Carpenter, 1999; McNeil & Alibali, 2005; Perry, Church, & Goldin-Meadow, 1988). We limited the transfer test to four problems for the sake of efficiency because previous research has shown similar performance on mathematical equivalence problems regardless of whether children solve three, four, or more than four problems (e.g., Alibali, 1999; Perry, 1991; Rittle-Johnson & Alibali, 1999; Siegler, 2002).

When each problem was presented, the tutor told the child to figure out what number to put in the blank to make the right side of the equal sign the same amount as the left side of the equal sign. If the child provided the correct number, the tutor gave positive feedback, such as "good job" and then moved on to the next problem. However, if the child provided an incorrect number, the tutor provided the feedback as follows: "No, that's not the number that goes in the blank. The correct number is *x* because *a* plus *b* is equal to *x* plus *y*" (the actual numbers in the problem were used in the place of *a*, *b*, *x*, and *y*).

Coding

Errors during the learning sessions Children's errors during the learning sessions were tallied, and the total number of errors made in the game context was compared to the total number of errors made in the formal context.

Reactions to errors Children's immediate reactions to hearing that they had made an error were coded as "negative" or "not negative." Reactions were coded as "negative" if children said something negative (e.g., "this is hard," "I'm getting really messed up," "no fair") or exhibited negative behaviors (e.g., whining, growling, huffing, rolling their eyes, or withdrawing). Reliability was established by having a second coder code the reactions of 20% of the children. Agreement between coders was 81.5%.

Transfer performance Children's solutions on the transfer test were coded as correct or incorrect based on a system used in prior work (e.g., Alibali, 1999; Perry et al., 1988; McNeil & Alibali, 2004; Rittle-Johnson, 2006). Children were given a point for every correct solution. Scores ranged from 0-4.

Results

Performance during the learning sessions was highly variable across children. Collapsing across the game and formal contexts, children made an average of 13.70 (SD = 11.01) errors. To test if children made more errors in the game or formal context, we performed a repeated measures analysis of variance (ANOVA) with context (game or formal) as the independent variable and number of errors as the dependent variable. There was no statistical difference in the number of errors that children made in the game context ($M = 6.53$, $SD = 4.73$) versus the formal context ($M = 7.19$, $SD = 7.95$), $F(1, 35) = 0.32$, $p = .58$.

Although there were not general patterns in terms of which context elicited more errors, there were individual differences in which context elicited more errors. Some children made more of their errors in the game context (n = 20), whereas some children made more of their errors in the formal context (n = 16). We predicted that children who made more of their errors in the game context would learn more than and perform better on the transfer test than children who made more of their errors in the formal context.

To test our hypothesis, we performed a between-subjects ANOVA with error group (more errors in game context or more errors in formal context) as the independent variable and number correct on the transfer test (out of 4) as the dependent variable. Consistent with our predictions, there was a significant main effect of error group, $F(1, 34) = 5.99$, $p = .02$, $\eta^2 = .15$. Children who made more of their errors in the game context performed better on the transfer test (M = 2.70, SD = 1.75) than did children who made more of their errors in the formal context ($M = 1.13$, $SD = 1.62$). These results held even when controlling for the total number of errors made across contexts (total number of errors was not a statistically significant predictor of transfer performance, $F < 1$).

Results also held when the independent variable was treated as a continuous predictor and a regression analysis was performed. For the regression analysis, we calculated a difference score by subtracting the total number of errors each child made in the formal context from the total number of errors that child made in the game context. Thus, a positive difference score reflects more errors made in the game context relative to the formal context. This difference score was then used to predict number correct on the transfer test (out of 4). As predicted, the difference score was positively associated with performance on the transfer test, $b = 0.12$, $t(34) = 3.00$, $p = 0.005$. The greater the difference between the errors made in the game versus formal context, the greater the number of transfer problems solved correctly. More specifically, for every additional error made in the game context versus the formal context, the number correct on the transfer test increased by 0.12 (out of 4). The effect was moderate, with the difference score accounting for 21% of the variance in transfer performance.

Finally, we hypothesized that it would be more beneficial for children to make their errors in the game context versus the formal context because games provide children with a more supportive context for making errors. According to this account, children should be less likely to react negatively after making an error in the game context than after making an error in the formal context. To test this prediction, we calculated the proportion of errors that children reacted to negatively in the game context and the proportion of errors that children reacted to negatively in the formal context. Five children were excluded from this analysis because they did not make at least one error in both contexts. We then performed a repeated measures ANOVA with context (game or formal) as the independent variable and proportion of errors that children reacted to negatively as the dependent variable. Consistent with predictions, there was a significant main effect of context, $F(1, 30) = 5.47$, $p = .03$, $\eta^2 = .15$. The proportion of errors that children reacted to negatively was lower in the game context ($M = .14$, $SD = .18$) than it was in the formal context ($M = .28$, $SD = .30$).

Discussion

Games are widely used to teach children STEM concepts because they are intuitively appealing, and they promote learning and motivation. The results of the present study suggest that games may be an effective instructional tool for learning mathematics concepts because they provide a supportive context for making errors. Children who made more of their errors in the game context learned more than did children who made more of their errors in the formal context. This was confirmed by superior performance on the transfer test. Moreover, children had fewer negative reactions to the errors they made in the game context than they did to the errors they made in the formal context. This suggests that games may provide children with a supportive context that allows children to react adaptively to errors, which promotes learning.

Errors are inevitable during the learning process, and how children react to these errors may have important implications for learning. When children react negatively to errors, they may exhibit frustration, anxiety, or helplessness. Such behaviors reduce the probability of learning (Baker et al., in press; Elliot & Dweck, 1988; Dweck, 2000). In contrast, when children do not react negatively to errors, they may be more likely to persist in the face of challenge and regard errors as an opportunity to learn (Dweck, 2000; Okolo, 1992). Such behaviors increase the probability of learning. The present results suggest that games may facilitate learning, in part, because they buffer children from reacting negatively to errors.

Although the results of this study supported our hypotheses, it is important to note that this study was not designed specifically to test the mechanisms by which game contexts outperform formal contexts. The data were collected as part of a larger study that was designed for a different purpose, so future studies will be needed to corroborate the results and rule out alternative explanations. For example, it is possible that the difference between game and formal contexts could be due to an individual difference variable that leads children to perform worse in both the formal context and the transfer test. Specifically, children who have mathematics anxiety may have made more errors in the formal context and on the transfer test because both of these contexts resemble traditional school contexts, and thus, might have been viewed as an evaluative, anxiety-provoking situation.

Alternatively, it is possible that children who committed more errors in the game context (versus the formal context) performed better on the transfer test not because they were buffered from negative reactions in the game context, but because the specific act of playing a game made them more engaged in learning. If children learn to solve the problems correctly in the game context, then they will be more likely to win the game. Thus, it is possible that learning is more instrumental in the game context than in the formal context. Future research should control for this potential confound.

Future research should also examine whether the present results generalize to the classroom setting. In the present study, children learned in game and formal contexts while working one-on-one with a “tutor” who stuck to a meticulous script. More typical learning environments are often less structured and less conducive to one-on-one instruction. In order to determine the practical effectiveness of the game context on learning, future studies should investigate whether the results generalize to the types of game and formal contexts that are used in classroom environments.

Overall, the present results are consistent with prior research suggesting that educational games can be helpful for learning STEM concepts. Results suggest that games are helpful not just because they are fun and engaging, but also because they provide a supportive context for making errors. Future work should continue to investigate the benefits of educational games and other innovative contexts that facilitate children’s learning.

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