Digital Game based Learning for Undergraduate Calculus Education: Immersion, Calculation, and Conceptual Understanding

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ABSTRACT

This study has two goals: First, to investigate the effectiveness of using a digital game to teach undergraduate-level calculus in terms of improving task immersion, sense of control, calculation skills, and conceptual understanding. Second, to investigate how feedback and visual manipulation can facilitate conceptual understanding of calculus. 132 undergraduate students participated in a controlled lab experiment and were randomly assigned to either a game-playing condition, a practice quiz condition, or a no-treatment control condition. The authors collected survey data and behavioral-tracking data recorded by the server during gameplay. The results showed that students who played the digital game reported highest task immersion but not sense of control. Students in the game condition also performed significantly better in conceptual understanding compared to students who solved a practice quiz and the control group. Gameplay behavioral-tracking data was used to examine the effects of visual manipulation and feedback on conceptual understanding.

KEYWORDS
Calculus, Digital Game Based Learning, Higher Education, Math, Visual

INTRODUCTION

Calculus is the foundation for higher-level mathematics in disciplines such as physics, engineering, and economics. Calculus is not only important for understanding more advanced courses in school, it is also a significant predictor of one’s earnings at work beyond school (Rose & Betts, 2004). However, several studies have reported a disconnect between the calculus that students learned in classrooms and students’ ability to apply calculus concepts to other disciplines and to utilize calculus outside of schools (Lesh & Zawojewski, 2007). Students often fail to transfer their calculus knowledge because...
they lack hands-on experiences of applying their understanding to solving authentic problems; in fact, around 70% of problems in one calculus textbook are solved by mimicking the examples shown in the textbook (Lithner, 2004). This might cause students to be less motivated to learn because they do not understand the value of calculus in application. Studies have shown that students who experienced problem-solving scenarios in pre-calculus classes have better conceptual understanding of calculus applications, can identify and use appropriate resources, and are more motivated to take an active role in learning calculus (Stanley, 2002). Learning across multiple contexts (e.g., different media or different problem context) can also promote transfer because students can compare their experiences to abstract general concepts and construct a flexible understanding that can be applied to different contexts (Bransford, Brown, & Cocking, 1999).

Digital games have been proposed as an effective way to promote students’ conceptual understanding of abstract knowledge and problem-solving transfer (Boyle, Connolly, & Hainey, 2011; Garris, Ahlers, & Driskell, 2002; Gee, 2007). Modern digital games can facilitate meaningful problem-solving experiences for students, allowing them to visualize abstract concepts and situate the concepts in different contexts to gain a better understanding (Squire, 2003). They can provide immediate, or just-in-time feedback for students to assess and adjust their process (C.-Y. Lee & Chen, 2009). Games encourage players to form initial hypotheses, test them, observe the outcome, and revise their hypotheses. This process is similar to the process of experiential learning (Kolb & Kolb, 2005). In other words, digital game can simulate authentic problems for students to apply their calculus knowledge. They also allow students to visualize and actively manipulating factors to construct a flexible mental model which improves transfer across contexts.

While many studies have examined the use of digital games to enhance mathematics education, most of them focus on primary to secondary school mathematics or drill-and-practice for mathematical calculations (e.g., Ke, 2008a, 2008b; Mayo, 2009). Few studies have investigated using digital games to facilitate undergraduate-level mathematics, especially calculus, which is a complex foundational concept that affects student performance in more advanced courses. A major challenge of designing a calculus game is balancing the complex concepts and skills while keeping students immersed in the game. In this study we developed a game to teach undergraduate-level calculus called Mission Prime which is based on mathematical education principles.

The main goal of this study is to compare the effects of a digital game to teach university-level calculus to a traditional method of solving practice questions and a no-treatment control group. A secondary goal is to investigate (if any) what affordances of the game promote students’ conceptual understanding. We used behavioral-tracking data of player actions during gameplay to investigate whether the affordances of digital games to provide feedback and visual manipulation improved students’ conceptual understanding of calculus. The study design is a controlled lab experiment with random assignment that employs both pre- and post-test questionnaires paired with server-based player behavioral data to examine the following general research questions:

1. Is playing a calculus video game more effective in promoting conceptual understanding than traditional practice questions or no-treatment?
2. Is playing a calculus video game more effective in promoting calculation skills than traditional practice questions or no-treatment?
3. Is the experience of playing a calculus game more immersive than traditional practice questions or no-treatment?
4. Do the number of feedback provided by the video game and the ability to manipulate visual representations improve students’ conceptual understanding of the content mathematics?
THEORETICAL BACKGROUND

Promoting Calculus Transfer

Traditional mathematics courses are designed to guide students through a sequence of modules that makes up complex mathematical concepts. Students are introduced to one small module at a time and are expected to be able to piece together the modules and understand how the modules fit together to form a bigger picture. However, student may fail to realize the bigger picture and are left with isolated, incomplete understanding of the concepts (Tall, 1991). Even students who do well in mathematics classes may understand equations as symbol manipulation and fail to realize its relation to real-life problems and applications (Siegler, 2009). This may be a reason that can explain why many STEM educators feel that students are under-prepared in their calculus training and fail to understand its application in other disciplines (Lesh & Zawojewski, 2007).

The major goal in the calculus education reform since the 80s is to shift from the traditional focus on memorization and calculation techniques to promote conceptual understanding and focus on calculus applications. Many mathematics educators argue that in order to reach this goal, mathematics course should be designed the opposite way around (Kaput, 1994; Tall, 1991), meaning that students are first exposed to authentic application problems so that they can develop a need for learning the concepts. Then the complex systems are broken down into smaller modules facilitated by visual aids for students to manipulate and observe (Disessa & Sherin, 2000; Kaput, 1994). This type of design situates the mathematic concepts within authentic problems, allowing students to take on a more active role in knowledge construction (Oehrtman, 2009). This may facilitate better appreciation of concepts and promote transfer between contexts.

Several studies have tested the effects of teaching mathematics through authentic problems and visual manipulations. For example, Stanley (2002) provided students with real-life problems such as designing drug dosage or developing a saving plan. She then asked them to work in groups to solve these problems using calculus. The study found that although the students did not perform better in quizzes than students who were not exposed to real-life problems, but the students who solved real-life problems were more motivated, were better at identifying appropriate resources, and had a better understanding of calculus applications. Another study by Kidron and Zehavi (2002) found that using software to display dynamic graphics helped students visualize the mathematical processes and gave meaning to the abstract concepts.

Using Digital Games to Promote Calculus Education

Digital games have been proposed as effective means for teaching mathematics because of several unique affordances. Digital games can (a) provide meaningful problems in situated contexts for players to solve (Gee, 2007; Steinkuehler & Duncan, 2008), (b) allow players to visualize complex systems and manipulate dynamic factors (Shaffer, 2006), (c) present multiple representations to demonstrate the underlying concepts (Betz, 1995), (d) give immediate performance or formative feedback for players to track the progress or adjust their hypotheses (Delacruz, 2012), and (e) promote sense of immersion and motivations (Squire et al., 2003).

Educators have been experimenting with using digital games for education for quite some time. “Edutainment,” or the combination of education with entertainment was a concept that was thought as the future of education in the 80s. However, poor design that simply masks practice-and-drill with animations has earned edutainment a sour reputation for being neither effective education nor entertaining (Van Eck, 2006). As digital games progressed from simple games to games that can simulate complex systems and engage players in dynamic relations, so has research on the affordances of digital games and how to utilize them for education (Charsky, 2010). A recent study found that when used appropriately, even a practice-and-drill game can be designed to motivate students to learn mathematics (Ke, 2008a).
Many studies have empirically examined the use of digital games to enhance mathematics education, but most of those studies focused on primary or secondary school education with mixed results. Meta-analyses and systematic reviews of games for education generally attribute the mixed results to small sample sizes and the lack of control groups in many studies (Connolly, Boyle, MacArthur, Hainey, & Boyle, 2012). Cordova and Lepper (1996) found that students who learned through a game in mathematics classes outperformed students in classes that did not incorporate games. They also found that the sense of control, challenge, curiosity and the ability to situate knowledge into context increased students’ intrinsic motivation. Another study compared classrooms that used a game to teach ninth-grade algebra and those that did not, the findings showed that students who used the games outscored students that did not in the ETS algebra assessments (Morgan & Ritter, 2002). Spotnitz (2001) examined the effect of a mathematics game on forth to sixth-grade students’ intrinsic motivation, self-efficacy, task involvement, and performance. After four weeks of 30-minute sessions, students answered a questionnaire along with a mathematics quiz. The study found that students who learned through the game reported higher intrinsic motivation, self-efficacy, and task involvement. Although there was significant improvement between the pre and post-test, students who played the game did not perform significantly better than students who received traditional education. Similarly, Ke (2008a) also found that student were more motivated and engaged when using digital games, yet they did not perform significantly better when assessed with traditional paper-and-pencil tests. We hypothesize that students in the game condition would report higher immersion and sense of control, but we believe the effects on improving calculation skills can go either way, and thus pose it as a research question.

**H1:** Participants in the game condition report higher immersion than (a) the practice quiz condition and (b) the no-treatment control condition.

**H2:** Participants in the game condition report higher perceived control than (a) the practice quiz condition and (b) the no-treatment control condition.

**RQ1:** Will participants in the game condition perform better in calculation skills than (a) the practice quiz condition and (b) the no-treatment control condition?

While there are mixed evidence on digital games’ ability to improve mathematics calculation skills, studies have shown that it may be effective in promoting higher-order metacognition and deep conceptual understanding. For example, Liang and Zhou (2009) conducted a qualitative assessment of students’ experience with a mathematics game and their academic performance. They found that students who used the game reported more positive attitudes towards mathematics. The students also felt that the feedback provided by the games helped them develop a sense of responsibility for their own learning and correct their mistakes without fear of embarrassment. More importantly, the students felt that they have a better understanding of how mathematics is connected to their everyday life when learning through the games. Another study by Lopez-Morteo and López (2007) used a game-like computer supported system to engage students in mathematics. They found that students who used the game-like system gained a positive attitude towards mathematics, which is a significant predictor of mathematics performance. Students in the experiment also appreciated the system for presenting theorems and problems from multiple perspectives, allowing them to understand that “mathematics are more than counting numbers” (p.636). Because problem-solving experiences and multiple representations were argued to promote deep conceptual understanding of mathematics (Kaput, 1994; Tall, 1991), we hypothesize that students who played the calculus game would have better conceptual understanding than students who received a traditional practice quiz or received no treatment.

**H3:** Participants in the game condition perform better in conceptual understanding than (a) the practice quiz condition and (b) the no-treatment control condition.
In addition to comparing the effectiveness of a calculus game to traditional methods of education, we are also interested in examining which features of the game would facilitate students’ conceptual understanding. As suggested by Anderson, Greeno, Reder, and Simon (2000), in order to promote effective learning, it is crucial to examine the students’ learning activities and cognitive procedures to gain a deeper understanding of how students are learning from our educational design. We use in-game behavioral tracking data to observe student activities in the game and test the hypotheses that games promote conceptual understanding through providing feedback and allowing students to manipulate visual representations.

**H4:** Visual manipulation positively predicts conceptual understanding among participants in the game condition.

**H5:** Number of feedback positively predicts conceptual understanding among participants in the game condition.

**METHOD**

**Experiment Design**

A between-subject experiment design was used to test the hypotheses and research questions. 132 students were recruited from Calculus II classes at a large Midwestern university using extra credits as incentives. When participants arrived at the lab, after giving informed consent, they were administered a short online survey measuring their attitude towards mathematics, the number of calculus classes that they have taken, and basic demographics including age, gender, and department majors. Next, the participants were randomly assigned to one of the three conditions (game, practice quiz, control). Of the three conditions, the digital game group was asked to play a calculus game until they finished all the scenarios or until one hour had elapsed; the practice quiz group received a calculus practice quiz for them to solve in one hour; the third group control group did not receive any treatment before the measurements and played the game after they completed all the questionnaires. An hour was used because the game was designed to be used as support material in an undergraduate Calculus classroom, therefore it had to fit within a class period. After the stimulus, the participants’ calculation skills and conceptual understanding were measured using a paper-and-pencil calculus test designed by members of the research team from the Mathematics department. The participants’ perceived immersion and sense of control were measured with a subset of the cognitive absorption scale developed by Agarwal and Karahanna (2000). While the game group played the game, we tracked their behaviors in the game including the frequency of different actions, the number of feedback they received, the duration of time on each action and scenario, whether they used the visual manipulation function, and how long they spent manipulating the visual representations.

After removing seven participants who did not complete the study, a total of 125 participants were included in the analyses with 50 in the game condition, 38 in the practice quiz condition, and 37 in the control condition. The average age of the participants was 19.39 years old (SD=2.57). There were more male participants (n=77, 65.8%) than female (n=40, 34.2%), and the majority were university freshman (n=97, 82.9%), perhaps due to recruitment from calculus courses which are often required foundational courses in many STEM departments.

**The Game: Mission Prime**

The game used in this study is a game developed by the research team to enhance the learning experience of undergraduate calculus to freshmen and sophomores. The project is part of a university-wide initiative to incorporate technology into foundational STEM courses to enhance student learning. For calculus, we designed a game called *Mission Prime*. In the game, the players’ goal is to help set up a space colony using their knowledge of optimization, one of the key concepts in calculus.
each scenario, players are given a problem such as maximizing the interior of a fence with limited resources. The player will be able to select objects, adjust viable parameters, view the problem space from multiple perspectives, and ultimately select the mathematical ‘tools’ necessary to solve the given problem.

The goal of the game is to train students to: (a) Identify the type of problem, (b) model the problem, (c) select the appropriate resources to solve the problem, (d) set up a function to solve the problem, and (e) find a correct answer to the problem. The game instruction focuses on the identifying, modeling, selecting tools, and setting up a function to solve the problems. Calculations were not emphasized in favor of deeper, perhaps more conceptual understanding of the problem.

The players were asked to assemble a function to solve the problem out of a set of formulae provided. For example, in a scenario the players were asked to construct a hydraulic generator and the player must figure out the dimensions (see Figure 1). Once the function is built out of these various components the player will be able to perform various operations on it and observe the final output. If the function yields the correct answer, the player will complete the scenario. If the function yields an incorrect answer, the player will be given feedback and will be asked to modify the function until the right answer is found. This design allowed players to focus on learning the conceptual framework of the problem without having to memorizing formulae and perform calculations. During the problem-solving process, players can manipulate the visual representation of the objects, rotate their view of the problem space, and switch between two-dimensional and three-dimensional perspectives to help them come up with a solution to the problem (see Figure 2).

Each scenario in the game represents a new problem that is built on previous learning. This design allows players to learn the concepts through multiple representations and allow the players to incorporate new mathematical concepts with their existing mental representations as they progress.

The game Mission Prime was designed with mathematical educational theories in mind. Students were given an application problem to facilitate purposeful engagement, and each scenario is a different representation of the basic concept of optimization. Visual aides were given that allow students to move around and observe. Both performance and formative feedback was given to help students keep track of their progress and adjust their actions.

MEASUREMENTS

Conceptual Understanding: Calculus conceptual understanding was measured by two open-ended questions developed by members of the research team from the Mathematics department. The first question asked participants to describe “What do you think are the important concepts in optimization?” and the second question asked participants to explain “how and why we use the derivative to solve optimization problems?” The open-ended questions were scored by the researchers according to a scoring rubric while blind to the experiment conditions. The scores ranged from 0 to 4 on each question and were averaged to gain a general calculus concept score. The average score across the conditions was 1.66 (SD=1.15).

Calculation Skills: Calculus calculation skills were measured using two quiz questions to test the students’ ability to solve an optimization problem. Each of the two questions requires two answers for width and height, which result in four answers. Each of the answers were scored 0 for incorrect answers and 1 for correct answers, the scores were aggregated to create a calculation score that ranged from 0 to 4. The average score across the conditions was 1.30 (SD=1.37).

Immersion: Perceived immersion was measured by a subset of the cognitive absorption scale developed by Agarwal and Karahanna (2000). The subscale consisted of five Likert-type items that asked participants to rate how much they agree with the statements (e.g., “While I was engaged with the training tool, I was able to block out most other distractions.”). The items were reliable with Cronbach’s α=.91.
Figure 1. Players must figure out the dimensions before constructing a hydraulic generator.

In order to power the facilities, you will need to set up the hydraulic generator unit. The unit has a conical protective casing with a radius of 6 meters and a height of 10 meters. Before installing the casing, we need to build a generator unit that will fit inside of it. The generator unit is cylindrical, but its dimensions can vary, based on your specification. The larger the generator is, the more power it can produce, so try to maximize the volume while remaining within the dimensions of the protective cone.

Figure 2. Players must visually manipulate the objects in order to solve the problem.
Sense of Control: Sense of control was measured by another subset of the cognitive absorption scale which consisted of three Likert-types items (e.g., “When I was engaged with the training tool, I felt in control.”). The items were reliable with Cronbach’s α=.85.

Game Behavioral-Tracking Data: Feedback and Visual Manipulation: We measured number of feedback and duration of visual manipulation in each scenarios using unobtrusive behavioral-tracking from the game server. A major advantages of using behavioral data is that the measurement is unobtrusive, thus the player will not feel threatened when making mistakes and spending large amount of time on manipulating the visual representations (Y.-H. Lee, Heeter, Magerko, & Medler, 2012). Behavioral-tracking also allowed us to gain exact frequency and duration of actions without the potential problem of having human observer errors (Heeter, Lee, Medler, & Magerko, 2013). These behavioral data also gave the game development team insights into parts of the game that players were having trouble in and improve the game in future iterations. Players received both performance and formative feedback when they submit a decision in the game, the performance feedback tells the players if they are correct or not. The formative feedback tells players how they can improve. Duration of visual manipulation tracks how much time each player spends on manipulating the visual representation in each scenario.

RESULTS

Equivalence between Groups

The current experiment used random assignment at the subject level to establish equivalence between groups. Until recently, many education studies have used group-level assignment to compare different treatments. A problem with group-based assignment is that the different natural groups (i.e. classes or schools) may have different instructors, use different materials, and consists of students from different departments which can confound the effect. Another potential threat of group-level assignment is selection bias. That is, researchers may intentionally assign their preferred treatment to classes with better performances in the first place. Because of the potential biases in group-based assignments, the Institute for Education Sciences advocates expanding research on practical programs using experiments with random assignments (Simpson, Lacava, & Graner, 2004).

Random assignment at the subject level, if implemented correctly, can ensure that the third variables which may cause difference in the effects are evenly distributed between the experiment groups. A random assignment also ensures that the researcher cannot manipulate the results by intentionally assigning certain subjects to specific groups.

While random assignment at the subject level is assumed to establish equivalence between groups, we conducted Chi square tests on the sex, age, and number of Calculus courses taken to establish equivalence between groups. Chi square results showed that there was no significant difference in terms of sex (χ² =.03, p=.987), age (χ² =17.21, p=.372), and number of Calculus courses taken (χ² =10.26, p=.114), suggesting that the three experiment groups are equivalent and the difference in results can be attributed to the different experimental treatments.

Immersion

Hypothesis 1 posited that participants in the game condition report higher perceived immersion in the task than the practice quiz condition and the control condition. We conducted one-way Analysis of Variance (ANOVA) to test the hypothesis. Experiment conditions were used as the independent variable, and perceived immersion was the dependent variable.

The result showed that there was significant difference between the three conditions, F(2, 122)=4.77, p=.010, eta squared=.07 in perceived immersion. Post-hoc comparison with Tukey HSD showed that the game condition (M=5.67, SD=1.05) reported significantly more immersed in the task than the practice quiz condition (M=4.90, SD=1.26) and the control condition (M=5.04, SD=1.50).
The practice quiz condition was not significantly different from the control condition \((p=.873)\). The result was consistent with hypothesis 1. The findings indicate that participants felt more immersed in playing the game than doing practice quiz.

### Sense of Control

Since digital games can facilitate self-paced learning that may increase students’ sense of control in their own learning progress and results, hypothesis 2 posited that participants in the game condition would report higher sense of control than participants in the other two experiment conditions. We conducted a similar ANOVA to test the hypothesis, this time with sense of control as the dependent variable. The results showed that unlike what we hypothesized, there was no significant difference between the conditions in their sense of control, \(F(2, 122)=1.22, p=.300\). Participants in the game condition \((M=4.60, SD=1.47)\) did not report higher sense of control than the practice quiz condition \((M=4.85, SD=1.16)\), nor the control condition \((M=4.33, SD=1.55)\). The result was not consistent with hypothesis 2.

### CALCIUS CALCULATION SKILLS

Research question 1 asked whether the game will improve students’ calculation skills over the traditional practice quiz or no treatment. In order to test this research question, we conducted an Analysis of Covariance (ANCOVA). Experiment condition was entered as the independent variable, and the calculation skill score was used as the dependent variable. Since number of calculus classes taken would potentially affect one’s calculation skills, we controlled for the number of calculus classes taken as a covariate.

The result showed that there were no significant difference between the three conditions, \(F(2, 113)=.20, p=.818\). This suggests that the game condition \((M=1.30, SD=1.57)\) did not perform significantly better than the homework condition \((M=1.39, SD=1.28)\) or the control condition \((M=1.18, SD=1.17)\) in terms of calculation skills. The findings indicate that playing an hour of the game was not more effective in improving the students’ calculation skills than doing practice quiz or no treatment at all. A surprising finding was that the practice quiz did not outperform the control group in terms of calculation skills, perhaps because the practice quiz did not help students retrieve relevant knowledge and improve their calculation skills.

### Conceptual Understanding

One of the key arguments for using digital games for mathematics education is that it has the potential to facilitate conceptual understanding. Hypothesis 3 posited that participants in the game condition would perform better than the homework and control condition in their understanding of calculus concepts. We conducted another ANCOVA similar to the one for calculation skills, this time with conceptual understanding as the dependent variable. The result showed that there was a significant difference between the three conditions, \(F(2, 113)=5.22, p=.007\), eta squared=.08. Post-hoc comparison showed that the game condition \((M=2.10, SD=1.26)\) was significantly higher than the practice quiz condition \((M=1.57, SD=1.04)\) and the control condition \((M=1.32, SD=1.01)\). Again, the practice quiz condition was not significantly different from the control condition \((p=.747)\). The data was consistent with hypotheses H3a and H3b. The findings indicate that the game was more effective in improving students’ understanding of calculus concepts than doing one hour of practice quiz or no treatment at all.

### Feedback, Visual Manipulation and Conceptual Understanding

Literature suggests that games promote conceptual understanding through giving players feedback and the affordance of visual manipulations (e.g., Delacruz, 2012; Tall, 1991). Hypotheses 4 and 5 focused on the game condition to investigate whether number of feedback and visual manipulations
predicts conceptual understanding. After removing seven participants who were either idling during the gameplay or did not play for the required duration, a total of 44 participants were included in the analyses. Because not all the participants were able to complete all the scenarios within the one hour experiment time, we focused on analyzing player behavioral data in the first scenario, which is where players learn the mechanics of the game and the basic concepts. On average, players received 37.72 feedback ($SD=45.43$, ranging from zero to 195) about their performance and how to correct their mistakes. On average, the students in the game condition spent an average of 18.57 ($SD=19.57$) seconds on active visual manipulation in scenario 1. We define “actively used” as usage beyond the required usage in the tutorial phase of scenario 1.

In order to test hypotheses 4 and 5, we conducted a hierarchical regression. Total time spent on scenario 1 was controlled in the first block because total time in the scenario is positively correlated with number of feedback and duration in visual manipulation. The independent variables were number of feedback and duration of active visual manipulations. Conceptual understanding was entered as the dependent variable. The overall model was significant, $F(3, 29)= 2.67$, $p=.031$, $adj R^2 =.11$.

Visual manipulation was not a significant predictor of conceptual understanding, $\beta=-.09$, $t=-.52$, $p=.607$. Which suggest that increased time spent in visual manipulation did not significantly predict better conceptual understanding. The result was not consistent with hypothesis 4. Further examining the distribution of scores indicated an inverse u-curve between the duration of visual manipulation and conceptual understanding. Students who did not spent time (i.e. duration = 0) in visual manipulation had the largest variance in terms of conceptual understanding, $M=3.11$, $SD=1.02$. Perhaps because this subgroup consists of students who had better conceptual understanding to begin with and did not need the visual aide and also consists of students who simply did not pay attention to the game and did not improve their conceptual understanding. For the students who did use the visual manipulation function, there was a positive correlation between visual manipulation and conceptual understanding between 1 to 12.94 seconds, this positive trend reversed after 12.94 seconds, in which increased time spent on visual manipulation beyond 12.94 seconds reduced conceptual understanding.

Number of feedback was a significant predictor of conceptual understanding, but in the opposite direction, $\beta=-.40$, $t=-2.36$, $p=.023$. The result was not consistent with hypothesis 5. The finding suggests that students who were exposed to more feedback actually performed worse in the conceptual understanding. This maybe because players only received feedback when they make a mistake, therefore the number of feedback may also be an indication of the players’ performance. When we eliminated students with extremely high number of feedback (i.e. outliers with more than 50 feedback) in the first scenario ($n=8$) from the analysis, number of feedback did not negatively predict conceptual understanding, suggesting that the students with extremely high number of feedback may have skewed the analyses.

**GENERAL DISCUSSION**

This study was designed with two main goals in mind. The first goal was to compare the effectiveness of a digital game approach to a traditional approach in promoting calculus conceptual understanding, calculation skills, and sense of immersion and control among undergraduate students. The second goal was to examine actual behavioral data to test whether the affordances digital games to support visual manipulation and feedback improved students’ conceptual understanding of calculus.

In line with previous literature (e.g., Ke, 2008a, 2008b; Kebritchi, Hirumi, & Bai, 2010; Kim & Chang, 2010; Liang & Zhou, 2009; Ota & DuPaul, 2002), we found that students felt more immersed in the task when learning through the game in comparison to doing practice quizzes or no treatment. Digital games communicate through designed problems that invite players to solve with limited resources (Gee, 2007). In other words, digital games can facilitate what Siegler (2009) calls **purposeful engagement**. When students understand the purpose for learning, they are more likely to allocate
attention to the task and cognitively process the information because they are motivated to solve the problems. Previous literature also suggest that students felt more ownership and responsibility for their own learning (Liang & Zhou, 2009). However, in our study, the students who played the game did not report higher sense of control than the students who solved the practice quiz.

Previous studies on using digital games for mathematics education have shown mixed results in its effectiveness to promote calculation skills (see Connolly et al., 2012 for review). Our result showed that students who played the game did not perform better than students who solved a practice quiz or received no treatment at all. This may be because the game Mission Prime was designed to promote conceptual understanding and intentionally deemphasized calculation and formula memorization in the game. However, had the game required more calculation, the calculation could potentially decrease players’ sense of immersion because the gameplay flow would be constantly interrupted by calculations. What was surprising was that the paper-and-pencil practice quiz did not improve calculation skills than no treatment. The most common instructional goal of practice quizzes in education is to let students practice and refresh their memory of materials that they learned in class (Cooper, Robinson, & Patall, 2006). A practice quiz can also act as a self-assessment for student to understand how well they understand. However, students may not benefit from practice quiz alone. Without guidance or feedback to help students understand how well they are doing, and how to correct their mistakes and improve, students cannot learn from doing quizzes. Instead, students may feel demotivated because they do not see the purpose of the practice quiz.

In terms of promoting conceptual understanding, our results found that undergraduate students who played the game had deeper conceptual understanding than students who solved a practice quiz or no treatment. Mathematics educators have argued that in order to promote conceptual understanding of calculus, it is suggested that calculus could be taught by providing students with a general understanding of its application, and then supporting self-paced learning through feedback and visual representations (e.g., Disessa & Sherin, 2000; Kaput, 1994; Tall, 1991). Digital games can afford this type of educational design by providing meaningful problem for students to solve, constant feedback on the students’ process, and allow students to manipulate multiple visual representations that explain the underlying concepts.

Next, we focused on the game condition to investigate whether the number of feedback messages received and duration of visual manipulations predicted better conceptual understanding. Our analyses using behavioral-tracking data of the students’ behavior during gameplay found that duration of visual representation manipulation was not a significant predictor of conceptual understanding. When we further examined the data, we found an inverse u-curve among students who actively used the visual manipulation function. Duration spent on visual manipulation was positively correlated with better conceptual understanding to a point (around 12.94 seconds), beyond that point, more time spent on visual manipulation decreased conceptual understanding. There are several potential explanations for this outcome. First, perhaps a moderate amount of visual aide helps students understand the underlying concepts and how it is applied, but excessive time spent on visual manipulation may distract students and impede their understanding. Another potential explanation is that the students who spent a large amount of time on visual manipulation were the ones who could not figure out how to play the game and spent large amount of time exploring all the different functions.

The results also showed that number of feedback predicted conceptual understanding, but in the opposite direction. That is, students who received large numbers of feedback performed worse in conceptual understanding. One possible explanation of this finding is that in the game, feedback appears after the player has made an incorrect attempt. Therefore, a large number of feedback may also indicate that the player is performing poorly and that the feedback were not effective in improving the player’s understanding. Another possible explanation is that some students were simply trying random combinations without putting much thought into reading the feedback. For example, one student received as much as 195 feedback in first scenario alone. Because these students were not cognitively processing the feedback message, their understanding may not have improved.
Overall, we found that students reported the gameplay experience as more immersive than traditional practice quiz, and students who played the game also gained a deeper understanding of the underlying concepts that were used to solve the problems in the game. There was no significant difference in terms of improving calculation skills. When examining what caused students in the game condition to have better conceptual understanding, behavioral-tracking data revealed that the students who actively manipulated the visual representation performed better when asked to explicate their understanding of the concepts, but only to a certain point. This finding partially supports theories that argued for the game affordances of manipulating visual representations and that presenting abstract mathematical concepts through multiple representations may promote deeper understanding of the concepts and its applications.

**Limitations**

This study was conducted in a controlled laboratory setting with random assignment. Therefore, external factors such as teachers’ ability, classroom environment, duration of class, etc. were controlled in the experiment. As previous researchers have argued, the effectiveness of digital games in classroom education largely depend on the dynamics between the learners, the instructors, curriculum design, and the game design (Ke, 2008a). The findings from this study are the results of comparing the digital game approach to practice quiz and no treatment approach in isolation and should be generalized with caution. In a classroom setting, students may be able to seek additional support from their instructors or fellow students, which may supplement the game or practice quiz to improve learning effect. Other students in the classroom may distract players of the game or students may feel fatigued because of the long duration of classes, which may decrease the effect of the game or the practice quiz. By eliminating these external factors that can influence the students’ performance, we are able to focus on comparing the two different approaches and its affordances.

Due to resource and time constraints, students in this study only played the game once for an hour in the laboratory. Longer gameplay time and repeated play may increase the effectiveness of digital game based learning.

The participants in this study were recruited from calculus classes; they have already learned the materials covered in the game and the practice quiz in the previous semester. Therefore the results should be interpreted as the effect of using digital game or practice quiz to rehearse and enhance calculus classroom education, not the effect of using digital games or practice quiz as an initial learning approaches.

**CONCLUSION**

Few studies have examined the application of digital game based learning in undergraduate-level mathematics education; fewer studies have examined the actual gameplay processes to identify affordances of digital games that promote deep cognitive understanding of mathematics. Findings from this study suggest that a well-designed digital game can be used to promote student motivation and conceptual understanding in undergraduate-level calculus education. Some mathematics educators have argued that a problem-based learning approach and visual manipulations can motivate learners to take on an active role in learning, and through manipulating and experimenting with visual representations, construct a deep understanding of the underlying concepts (C.-Y. Lee & Chen, 2009; Stanley, 2002; Tall, 1991). This study shows that digital games may provide meaningful problems that immerse students in mathematical problems. The findings marginally support that manipulation of visual representations may predict better conceptual understanding of the mathematics and its application, but only to a certain extent, excessive visual representation may distract learners and disrupt conceptual understanding.

Does this imply that digital games will always improve conceptual understanding over traditional approaches? Not necessarily. The effect of any educational design is ultimately determined by the
interaction between the instructor, learner, content, and context. While some instructors can effectively incorporate digital game based learning into their course design, others may be able to motivate authentic learning and conceptual understanding without using digital games. Future studies should test the effects of digital games in conjunction with traditional approaches, and replicate the study in classroom setting to observe how students and instructors interact with the new medium, especially if the digital games are designed to target persistent problem areas in undergraduate calculus education.

Future instructional game designers also need to put more efforts into making sure students understand the affordances and feature of the game that support learning. For example, while the game Mission Prime provided the function of visual manipulation, not all the students actively used the function. Findings suggest that students who actively used the function performed better in conceptual understanding to a point. A challenge for instructional games at more advanced mathematical levels is the balance between maintaining engagement in the game and attaining complex learning goals. Mission Prime intentionally emphasized conceptual understanding of optimization over computations, in part to maintain game engagement. If learning goals are more computational in nature, a game would necessarily require creative design solutions so that performing computations does not disrupt gameplay.
REFERENCES


