How the Balance of Gaming and Mathematics Elements Effects Student Learning in Digital Math Games

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Abstract: Digital math apps on touch-screen devices have become popular as effective tools to support mathematics learning. Many apps incorporate gaming elements such as points, stars, coins, or storylines to increase student interest and motivation. However, there is limited research regarding the balance of gaming and mathematics elements and how it affects student learning. The purpose of this paper was to understand how 51 fifth-graders’ interactions with gaming and mathematics elements in three game-based mathematics iPad apps were associated with student learning. Findings highlight the importance of a balanced focus and connections between gaming and mathematics affordances to support student learning.

Purpose

Digital mathematics iPad apps (hereafter referred to as digital math games) have become popular as effective tools to support mathematics learning. In a national survey, 75% of teachers reported using technology daily, with 65% using iPads in their classrooms to support learning (Sharp, 2016). Although there are thousands of different digital math games available for download (Gröger et al., 2013), not all games are created equal, which can impact their effectiveness as learning tools (Boyer-Thurgood, 2016; Van Eck, 2015). Additionally, educational games are designed with different levels of integration between learning (i.e., mathematics) and entertainment (i.e., gaming) goals (Clark et al., 2016; Ito, 2008). In this study, when we describe balancing gaming and mathematics, we are suggesting that it is important that the gaming elements and the mathematics elements are represented equally so that one does not dominate the other. Thus, the purpose of this paper was to understand how students’ interactions with gaming and mathematics elements were associated with learning.

Research Perspective

Digital math games whose mathematics and gaming objects are well-integrated can effectively support students’ learning (Boyce, 2014; Clark et al., 2016; Habgood, 2011, Ito, 2008). However, the design of many digital math games often separates the mathematics and gaming objectives (Ito, 2008). Students’ actions during gameplay can potentially re-connect these two domains to enhance learning (Garofalo et al., 2000; Falloon, 2013).

Each student constructs their own personalized gameplay experience based on their own behavioral and cultural experiences before, during, and after interacting with digital math games (Berger & Luckmann, 1966; Van Eck, 2015). These experiences inform not only their experience in the game, but also the transfer and application of learning from in-game to out-of-game situations (Paek et al.). This is important because educators want students to be able to applying knowledge learned in a digital math game to paper/pencil math tests and real-world problems.

Students’ gameplay is a balance of two elements: exploring the affordances or boundaries of the game and making progress towards in-game goals (Lindley, 2002). Affordances are defined as “cues of the potential uses of an artefact by an agent in a given environment” (Burlamaqui & Dong, 2014, p. 13) whereas boundaries are the limits of

Five categories of affordances that promote learning are “focused constraint, creative variation, simultaneous linking, efficient precision, and motivation” (Moyer-Packenham & Westenskow, 2013, p. 35). Focused constraint affordances are those that focus students on specific processes or procedures. Creative variation affordances allow freedom of student interaction and response. This affordance category “encourages creativity and novelty, and prompts experimentation” (p. 43). Simultaneous linking affordances are present when multiple representations are available to the user at the same time. Representations may be auditory, visual, or haptic. Visual representations may be written words, numbers, or pictorial images. Efficient precision affordances are designed to help increase student accuracy and efficiency. Motivation allows student immersion to maintain attention as well as persistence. Features that promote this are defined as motivational affordances. All of these affordances come to the user in the form of feedback from the digital math game. These built-in features offered by the game help students to identify whether they have correctly accomplished a task, made an error, as well as providing hints or help guides.

As seen in the Mathematics Gaming Framework (Fig. 1), five factors may potentially influence students’ construction of in-game experiences and transfer to out-of-game learning. Out-of-game learning is important in this study as we sought to explore factors that influences changes in students’ understanding after playing the games. These five factors are numbers in Figure 1.

![Figure 1. Mathematics Gaming Framework](image)

When students interact with the digital math game, they are introduced to both mathematical and gaming affordances and goals. The balance of these two elements can be influenced by the game design and students’ experiences. Clark et al.’s (2016) meta-analysis categorized games into four categories, based on the level of integration between educational and gaming goals and affordances. These categories range from fully integrated (simplistically intrinsic) to completely separate (extrinsic). Clark et al.’s categories are important to this research because they offer insight into the balance of mathematics and gaming affordances within the game designs in this study.

Students bring prior mathematical and gaming understanding with them to their gameplay. Prior knowledge is important in this study because it can influence students’ focus and awareness of in-game affordances (Riconscente, 2013; Van Eck, 2015), which may influence learning. During gameplay, students employ various strategies to test the boundaries and affordances to successfully complete in-game tasks and goals. As students explore the game, they adopt more efficient and accurate strategies (Egenfeldt-Nelsen, 2005; Garris et al., 2002; Siegler and Svetina, 2006). Gaming strategy is important in this study because it can influence students’ access to...
learning opportunities as well as in-game success. In-game success is important because it shows whether students can successfully complete the tasks which were designed to support the intended mathematical learning goals.

Students may also have varying awareness of the mathematics goals, depending on the level of integration. This is important in this study because conscious awareness of mathematical ideas in digital math games can help focus students’ mathematical thinking to support learning (Sarama and Clements, 2009). Gaming elements designed to motive students can potentially distract students from the mathematics (Garfalo et al., 2000); however, connections between gaming and mathematics may help students refocus, develop a deeper understanding of the mathematics, and support transfer of learning to other contexts (Falloon, 2013; Garofalo et al., 2000; Gros, 2015). Students’ connections are important in this study because they provide contexts for student perceptions of in-game balances between gaming and mathematical elements.

This study sought to explore the relationship of factors in the Mathematics Gaming Framework (i.e., prior knowledge, gaming strategy, mathematics awareness, success with in-game tasks, connections between gaming and mathematics, out-of-game transfer of knowledge). Therefore, the mixed method research question in this study was: How are students’ interactions with elements of gameplay and in-game affordances associated with in-game success and changes in performance on pre- and post-tests?

Methods

To answer the research questions, this study used a mixed methods design (Tashakkori & Teddlie, 2010). Researchers quantitatively tested significance factors of in-game success and post-test performance (Cohen, 2013) and qualitatively explored students’ interactions with in-game affordances (Saldaña, 2015).

Fifty-one students, ages 9-10, in the inter-mountain west of the United States were recruited for this study. Students participated in individual clinical interviews in a research building equipped with two-way mirrors, audio-observer booths, and built-in cameras. During interviews, students completed a pretest, interacted with three randomly ordered digital math games (see Table 1), answered semi-structured interview questions, and completed a posttest.

There were two data sources: pre- and post-test of mathematics accuracy and video data (i.e., wearable GoPro and wall-mounted cameras) of students’ gameplay interactions and interview responses. The pre-test contained six multiple choice questions related to mathematics objectives in each of the digital games (total of 18 questions), as well as six control questions on a non-related topic. Pre-test questions were randomized for the post-test.

Digital Math Games

Table 1 provides a brief overview of the three digital math games in this study. The first two columns provide the name and screenshot of the games. The last two columns describe the gaming and mathematics elements in each game.

<table>
<thead>
<tr>
<th>Name</th>
<th>Screen Shot</th>
<th>Gaming Elements</th>
<th>Mathematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Game 1 – Drag on Box Elements</td>
<td><img src="image" alt="Screenshot" /></td>
<td>● Storyline&lt;br&gt;● Progressive Levels&lt;br&gt;● Student trace/tap lines to find “warriors”&lt;br&gt;● Student fight bosses with created warriors&lt;br&gt;● Music/Background</td>
<td>Mathematics Domain:&lt;br&gt;● Geometry&lt;br&gt;Intended learning outcomes:&lt;br&gt;● Identify equilateral triangles&lt;br&gt;● Identify isosceles triangles</td>
</tr>
</tbody>
</table>
Based on Clark et al.’s (2016) categories, Dragon Box Elements is *primarily intrinsic* as the mathematic goals are implicitly integrated within more complex gaming mechanics. Math Planet Place Value is *simplistically intrinsic* as there is only a single mechanic for both the gameplay and explicit mathematics (i.e., answer questions). Coordinates Map Maker is *not fully intrinsic* as it is a mix of intrinsic and extrinsic mechanics. The first part of the game starts with extrinsic gaming mechanics as there is no explicit connection to mathematics the first time students place icons on the map. The second part of the game has questions generated by student placement choices, which means that they are not extrinsically separated from the first part of the game.

**Data Analysis**

**Quantitative**

Paired sample T-tests tested difference in students’ performance from pre- to post-test. Linear regression models, using SPSS software, tested factors and interactions relating to in-game success and post-test performance for each digital math game (Cohen, 2013).

Researchers defined In-game success as the number of mathematics tasks successfully completed without errors or multiple attempts. We quantitized (Saldaña, 2015) Mathematics awareness from interview responses on a scale of 1-4: 1) No awareness (e.g., “I don’t know”); 2) General domains (e.g., shapes, map, place value); 3) General topics (e.g., triangles, decimals, grids); 4) Specific vocabulary (e.g., isosceles triangles, rounding to tenths, coordinates). We defined Gaming strategy using a dichotomous coding based on evidence of student use of one pre-identified common gaming strategy for each digital math game. In Dragon Box, gaming strategy was color; in Math Planet, gaming strategy was starting position; in Map Makes, gaming strategy was placing items on intersections. We defined Connecting gaming and mathematics using a dichotomous coding of evidence of students’ verbalization of a relational connection between gaming and mathematics (e.g., “when they are the same color, the lines are the same length,” is a relational connection between the gaming feature (color) and mathematics (length of shape sides)).

**Qualitative**

Researchers structurally coded video data for students’ interactions and interview responses relating to in-game affordances that helped with in-game success, hindered progress, enhanced gameplay experiences, promoted mathematics awareness, or facilitated connections between gaming and mathematics (Saldaña, 2015). We revisited video data multiple times to refine patterns related to the three emergent themes discussed in the results section.
Results and Discussion
Quantitative Results

Paired sample T-test results indicated significant differences in students’ performance from pre- to post-assessment (Tab. 2) on questions related to all three games and no significant difference in performance on control questions.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Mean Pre</th>
<th>Mean Post</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Game 1: Dragon Box Elements</td>
<td>1.52</td>
<td>2.48</td>
<td>.001***</td>
</tr>
<tr>
<td>Game 2: Math Planet Place Value</td>
<td>1.79</td>
<td>2.88</td>
<td>.001***</td>
</tr>
<tr>
<td>Game 3: Map Maker Co-ordinates</td>
<td>2.20</td>
<td>5.03</td>
<td>.001***</td>
</tr>
<tr>
<td>Control Questions</td>
<td>0.90</td>
<td>1.08</td>
<td>.268</td>
</tr>
</tbody>
</table>

***significant a p < .001

Table 2. Summary of Learning Gains from Pre- to Post- Test

Linear regression results indicated no significant relationship between students’ in-game success and performance on post-test (Fig. 2).

![Diagram of in-game success and post-test performance](image)

*significant at p < .05, **significant a p< .01, ***significant a p < .001
Game1 – Dragon Box; Game2-Math Planet; Game3 – Map Maker

Figure 2. Linear Regression Results for In-Game Success and Post-Test Performance

In-Game Success

Each game had a unique combination of significant factors associated with in-game success, which accounted for 29-41% of the variance. Pre-test, mathematics awareness, and dominant gaming strategy were each significant positive factors of in-game success for two of the three games. This means that as these factors increased, in-game success also increased for the associated games. However, connections between gaming and mathematics was not significantly associated with in-game success for any of the games.

Post-Test Performance

Pre-test and Connecting Gaming and Mathematics were significant factors of post-test performance for all three games (Fig. 2). This means that as these in-game factors increased, performance on the associated post-test questions also increased. Strategy was negatively associated with post-test performance for Math Planet, which means that students who used the pre-identified strategy had decreased performance on this post-test. An interaction
between pretest and connections was negatively associated with post-test performance for Map Maker. This means that as students’ pre-test scores increased, the difference in post-test gains between students who made connections and students who did not make connections decreased (i.e., students with low pre-test scores who made connections had the highest gains). These factors explained 59-61% of the variance in post-test performance.

Qualitative Results

Qualitative results identified three themes relating to students’ interactions with in-game affordances that may help explain and contextualize the quantitative results: a) students’ prior experiences, b) students’ gameplay focus, and c) students’ in-game connections.

Students’ Prior Experiences

During the interview, many students, especially in Math Planet and Map Maker, explained that their prior experiences either helped (e.g., “I already learning this in class.”) or hindered (e.g., “I haven't learn these things yet.”) their gameplay. This may help explain why pre-test was a significant factor for success in these two games. Prior experiences also had the potential to influence students’ strategies. For example, in Math Planet, some students explained that their prior experiences helped determine whether to press the arrow up or down (e.g., “What I learned in class, if the numbers were higher than 5, the numbers would round up, and if lower than 5, it would round down.”) whereas other students who indicated the math was new were more likely to guess (e.g., “I just like tapping things in the same area.”).

Students’ prior experiences influenced the preconceptions students brought to their gameplay, which sometimes promoted misconceptions regarding in-game mathematics. For example, when rounding in Math Planet Place Value, the game’s efficient precision feature limits place values on the screen to those needed to complete the task (Fig. 3).

This may have inadvertently supported two place value misconception based on prior experiences with the whole number place value system (ones, tens, hundreds from right to left). The first misconception was that “tenths place kept moving.” As seen in figure 3, the tenths place is in a different position for tasks A-C. This confused some students, who complained that the tenths place kept “moving.” In task D, the names of places are mixed up to allow students to match places to names. This may have supported the misconception that decimals “moving” in task A-C was a game feature rather than recognizing place values relations. An imbalance between students’ prior mathematics preconceptions and the gaming elements, resulted in misconceptions regarding both the intended mathematics and the games efficient precision feature.

Students’ Gameplay Focus

Students who made no post-test gains or regressed from pre- to post were more likely to focus on gaming, rather than mathematical, aspects of the games which may have compromised their potential to learn from the game. For example, after playing Dragon Box Elements, some students said, “It is like a real game.” or “It's kind of not really a learning game. It kind of is but it's not pure because when you are done with the monsters you get to battle.” Students who focused on one or more of the motivation gaming features in Math Planet (Fig. 4) often focused on
completing tasks quickly to increase their score, rather than mathematics (e.g., “Being timed also helps you because you try to get them faster and faster.”; “The timer could rush you because you are like I wanna get as much coins as possible.”; “You can beat your high score. Like you could get 104 and then you could get 106 or something and beat your score”).

Figure 4. Math Planet Motivation Affordances

A focus on speed may have also promoted a misconception for some students in Dragon Box Elements. In this game, finding an equilateral triangle creates three dragons (regular, isosceles, & equilateral), which if created first, can help students quickly complete the required level tasks. Students who regressed from pre to post utilized this gaming aspect before quickly tracing the remaining shapes, which caused an unexpected timing issue with the simultaneous linking affordance which names created shapes (Fig. 5).

Figure 5. Disconnect in simultaneous linking affordance.

The left screenshot shows a completed equilateral triangle with the words “isosceles triangle” above it. On the right side, the student has already moved on to build a new isosceles triangle. At this point, the words for “Equilateral triangle” are displayed. A review of post-test answers shows these students inverted their understanding of isosceles and equilateral triangles (i.e., for every equilateral posttest question, they chose the answer that corresponded to isosceles triangles and vice versa). The mismatch in timing in the game may have contributed to an inaccurate linking, which negatively affected students’ learning outcomes.

In Map Maker, students who regressed were also more likely to place icons in locations that would increase their speed to find items while playing the game. For example, one student placed every icon on row 2 and explained, “Lining up in a line makes it easier because they always start with 2.” Another student placed icons in a diagonal on intersections of the same number (i.e., (2,2);(3,3);(4,4) etc.), and explained, “Like you got to put them where you wanted to so it would be easier for you to know where they were.” These students took advantage of the creative variation affordance to simplify the demand, which may have limited their opportunities for mathematical learning. These results support Garofalo et al.’s (2000) warning that interactions with technology have the potential to disrupt the balance between gaming and mathematics, which can compromise mathematics learning by limiting student’s awareness of learning opportunities. The results also indicate that balanced connections between game interactions and formal aspects of math could prevent these problems.
Students’ In-Game Connections

Students’ in-game connections may have helped them re-organize their conceptual understanding of the mathematics, which may explain connections as a significant factor of post-test performance. For example, during the interview, students with gains often said linked representation affordances helped them (Fig. 6).

Figure 6. Examples of Linked Representations

Two linked affordances in the left screenshot in Figure 6 mentioned by students as helpful were, “The white words, they would tell me the shape” and “All the shapes that we get have same number sides [points to dragons in bubbles, seen in the center of the left screenshot].” Students also noted that matching the task in the right screenshot helped connect place name and location representations. As two students explained, “I looked at where it said the real number was I saw that how it said tens place with a th at the end because after the point is with the th at the end and before the dot is without the th,” and “I thought the ones place was where the tenths place is, but after I realized that the tens place is after the decimal and I didn’t know that before.”

Students with gains also noted connections from efficient precision affordances. In Dragon Box Elements, students often mentioned the game “already had lines drawn” which helped some students make connections between length, color, and triangle type. For example, several students explained, “It [equilateral] is all the same size and color. The different colors don't make upgraded.”; “I usually eyeball it. The lines help. In general the lines connect together are different lengths”; and “This one was equilateral because all the sides were same. This one has two sides that are same length.” Efficient precision provided by the grid lines in Map Maker Co-ordinates also helped students make connections between numbers and coordinate locations (e.g., “You weren't just guessing the number, you would figure it out and come to the object that was meeting on those two lines”; “I would just count the lines until the next line intersects it.”)

Feedback affordances also helped students identify problems in their strategy to make connections and refocus on the mathematics. After playing Math Planet one student explained, “It would tell me it was wrong so I knew it was wrong so I learned from it.” In Map Maker Co-ordinates, getting it “wrong” helped student make connections with the procedure for identifying coordinates. Although they were not able to use specific terminology, they were able to describe the procedure (e.g., “You find that [point to x-axis] first and that [y-axis] second.”). All students with perfect post-test scores mentioned some variation of this procedure example. These examples show how students’ connections may have helped them focus on a balance of gaming and mathematics elements.

Conclusions

Game design features and affordances such as efficient precision (e.g., number of visible place values), simultaneous linking (e.g., name of triangle displayed), focused constraint (e.g., limiting answers to four choices), motivation (e.g., coins), and creative variation (e.g., allowing students to place icons anywhere on grid) both positively and negatively affected students’ mathematical connections and understandings from the games. Game design effects the affordances offered to students in order to make connections between the gameplay and the mathematics. However, students’ interactions with the affordances is an even greater indicator on whether the affordance was helping or hindering for the transfer between in-game experience and out-of-game performance.
These results show the importance of balanced interactions with gaming and mathematics affordances in digital math games. Educators should consider students' prior experiences, affordances that promote connections and the balance between mathematical and gaming elements in the selection of digital math games.

References


