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How Design Features in Digital Math Games Support Learning and Mathematics

Connections

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Abstract

Current research shows that digital games can significantly enhance children's learning. The purpose of this study was to examine how design features in 12 digital math games influenced children's learning. The participants in this study were 193 children in Grades 2 through 6 (ages 8-12). During clinical interviews, children in the study completed pre-tests, interacted with digital math games, responded to questions about the digital math games, and completed post-tests. We recorded the interactions using two video perspectives that recorded children's gameplay and responses to interviewers. We employed mixed methods to analyze the data and identify salient patterns in children's experiences with the digital math games. The analysis revealed significant gains for 9 of the 12 digital games and most children were aware of the design features in the games. There were eight prominent categories of design features in the video data that supported learning and mathematics connections. Six categories focused on how the design features supported learning in the digital games. These categories included: accuracy feedback, unlimited/multiple attempts, information tutorials and hints, focused constraint, progressive levels, and game efficiency. Two categories were more specific to embodied cognition and action with the mathematics, and focused on how design features promoted mathematics connections. These categories included: linked representations and linked physical actions. The digital games in this study that did not include linked representations and opportunities for linked physical actions as design features did not produce significant gains. These results suggest the key role of mathematics-specific design features in the design of digital math games.

How Design Features in Digital Math Games Support Learning and Mathematics

Connections

Children's early mathematics experiences have a long term effect on their mathematics performance and success in middle school and high school (Geary, 2011; Geary, Hoard, Nugent, & Bailey, 2012, 2013). Digital math games provide one instructional tool to enhance positive mathematics experiences for elementary-aged children. A meta-analysis by Clark, Tanner-Smith, and Killingsworth (2016) concluded that digital games significantly enhance learning when compared with non-game conditions. Their meta-analysis reported that there were features in the games that promoted higher learning outcomes, such as progressive hints that provided scaffolding and visual and audio feedback that provided information on performance accuracy.

National surveys of digital game use in classrooms reveal a significant increase in the use of digital games, with 55% of teachers reporting digital game use every week, and 23% of teachers reporting digital game use every day (Jhee, 2014). The increased use of digital games for instruction has prompted research on the effectiveness of individual games and the design features in games that enhance learning. *Design features*, also referred to as game attributes (Bedwell, Pavlas, Heyne, Lazzara, & Salas, 2012), are programmed elements of a digital game, which may determine the function or behavior of the game (e.g., rewards, feedback, transitions between levels, and challenging tasks; Boyer-Thurgood, 2017). Prior research on design features shows their importance for learning. For example, Falloon (2013) reported three broad categories of design features that impacted learning. These included: 1) design features that supported learning (e.g., scaffolds, some types of feedback, and some types of instructions), 2) design features that impeded learning (e.g., some types of feedback, game/learning imbalance, restricted content, and some types of instructions), and 3) design features that placed parameters around

learning (or not). In other research on design features, Berkling, Faller, and Piertzik (2017) reported three design features that promoted enjoyment, including graphics, ability to improve oneself, and increasing difficulty of tasks.

With research on digital games touting them as powerful learning tools (Herodotou, 2018; VanEck, 2015), there is still much to be learned about how game design features influence children's learning. The purpose of this research project was to examine how design features in 12 commercially-available digital math games influenced children's learning.

Theoretical Perspective

The dynamic objects in digital math games are sometimes referred to as *virtual manipulatives*. Moyer-Packenham and Bolyard (2016) define a virtual manipulative as: “an interactive, technology-enabled visual representation of a dynamic mathematical object, including all of the programmable features that allow it to be manipulated, that presents opportunities for constructing mathematical knowledge” (p. 13). Research on virtual manipulatives has consistently shown positive learning outcomes for children (Moyer-Packenham & Westenskow, 2013, 2016). The success of these tools depends, in a large part, on the programmable design features in the games.

Boyer-Thurgood's (2017) dissertation examined over 100 mathematics apps and identified eight categories of design features in the apps: task, transition, interaction, mathematical, constraint, timing, reward, and feedback. These design features (or game attributes) are integral to how the learner interacts with the mathematics in the digital game. For example, Byers and Hadley's (2013) study of children, aged 3 to 8, reported that design features could obscure children's interactions with the intended mathematics. The attributes of a digital game demarcate the possible activities a child may engage in while playing the game. However,

while an activity may be possible within a game environment, it is probable that children will not attend to every attribute or design feature within a game or may not attend to them in the way intended by the designer (Falloon, 2013).

Digital Games and Artifact-Centric Activity Theory

Children's activities are framed by how they interact with the technological tool they are using and with the design features in the tool. Ladel and Kortenkamp's (2016) Artifact-Centric Activity Theory (ACAT) provides a useful lens for exploring how this interaction occurs. ACAT considers the relationships among the subject (a child), the artifact (a digital math game), the object (mathematics), the rules (e.g., mathematics didactics and design principles), and the group (a child's peers and teacher). Figure 1 depicts these relationships.

Figure 1. Ladel and Kortenkamp's (2016) Artifact-Centric Activity Theory (ACAT).

The main focus of our inquiry in this study occurs along the main axis, the subject-artifact-object center line, where the child is interacting with the mathematics (the object) through the use of the digital math game (the artifact); and, in the upper right triangle, which

includes “the rules and principles that help to design the artifact according to the object” (Ladel & Kortenkamp, 2016, p. 31). The activities of ACAT are classified in terms of internalizations and externalizations:

The subject externalizes mental representation through the artifact and in turn internalizes specific knowledge that is represented by the artifact as feedback to the subject’s actions. The artifact (i.e., the digital game) itself externalizes the object (i.e., the mathematics) as a psychological reflection of the programmer’s (or designer’s) knowledge. The programmer in turn designs the artifact according to the programmer’s knowledge about the object (Ladel & Kortenkamp, 2016, p. 31).

A key question to ask in this relationship is: How do the design features in the digital game help the child interact with the mathematics? In using ACAT as a lens for our inquiry, we focus on how the design features of the artifact (the digital math game) broker the internalization and externalization of the mathematics the children learn while playing the game. Through the use of video analysis, we can view children’s behaviors and examine patterns in children’s verbalizations as a way to provide insights on how the design features in the games promote children’s mathematics learning. This helps us to better understand how children abstract the mathematics from the digital games as they interact with the design features, and how children’s internalizations during their interactions support or impede mathematics learning.

Digital games, and consequently their design features, “always contain and reflect the experience and the knowledge of the programmer or designer” (Ladel & Kortenkamp, 2016, p. 28). This is due, in part, to the externalization activity the designers of games participate in when creating the digital math games, based on their own internalizations of the mathematics. For the

child, this means that they may be limited in how they are able to interact with the game (i.e., their externalizations with the artifact and the object), based on what the programmer created in the design features of the game. For example, when using an array model for division, a digital game may restrict the model to having the divisor represented by the number of rows only, rather than allowing the child to place the divisor in either the rows or the columns. Nemirovsky, Kelton and Rhodehamel (2013) describe this type of interaction with externalized representations as thought and abstraction, because children's interactions with the representations simultaneously generate thought.

Digital Games and Embodied Cognition

Another useful lens for interpreting children's interactions with digital math games is embodied cognition. In Lakoff and Núñez's (2000) conception, mathematics develops through bodily experiences into conceptual domains connected by conceptual metaphors. Conceptual metaphors are cognitive mechanisms, used automatically and unconsciously, having abstracted patterns of inferences from physical experiences. The meanings of signs (e.g., words, actions, objects, symbols, texts) are contextualized and situated in embodied experiences (Gee, 2007). Lakoff and Núñez (2000) described embodied experiences as including "those used for the following ordinary ideas: basic spatial relations, groupings, small quantities, motion, distributions of things in space, changes, bodily orientations, basic manipulations of objects (e.g., rotating and stretching), iterated actions, and so on" (p. 28). Thus, embodied cognition involves movement of the physical body, movement of thought within the brain, and the linking of the two. The abstraction of mathematics comes from physical actions such as "forming collections, putting objects together, using measuring sticks, and moving through space" (Lakoff & Núñez, 2000, p. 102). In this study we refer to this abstraction as *mathematical connections*.

Mathematical connections are made when a physical action is connected to an abstract mathematical concept, when a visual image is related to a numeric representation, and when action and abstraction are intertwined. This network of conceptual metaphors is the basis of mathematical knowledge. When children play a digital math game, their perception and action with the game, and with the mathematics in the game, develops mental images that become a conceptual object (Presmeg, Radford, Roth, & Kadunz, 2016). Therefore, the development of children's conceptual knowledge about mathematics is being mapped within the sensory-motor system through the physical activity while playing a digital math game (Gallese & Lakoff, 2005).

Research shows that when children use direct touch devices (such as an iPad), in comparison with indirect touch devices (such as a computer mouse), this direct action encourages higher level strategies, less guessing, better accuracy, and faster completion times. (Segal, 2011). Congruent mapping (i.e., the degree of closeness of the mapping between the abstract mathematics and the physical representation; the connection between one's embodied actions and the mathematical actions) has been reported to be more effective for learning, regardless of the interface or device (Segal, 2011). This finding was supported by Tucker and Johnson (2018) who reported that the direct mapping of children's interactions with touchscreen devices influences their number sense with subitizing. Kindergarten children using touch-based interactions scored significantly higher than children using a mouse (Jong, Hong, & Yen, 2013). Riconsente's (2012) research with fifth graders also describes the embodied nature of the Motion Math Bounce game and how children's physical activity with the game contributed to the game's effectiveness for increasing fraction understanding. Alibali and Nathan's (2012) research supports this assertion, claiming that physical gestures reflect the grounding of a person's understanding of the physical environment. In their study, using videos of middle school

mathematics classroom teachers and students, there was evidence of representational gestures, which manifest a person's mental simulations of their actions and perceptions, and metaphoric gestures, which were used to create embodied ideas of the abstract mathematical ideas. During this process of physical activity, children are making sense of the representations and making mathematical connections among them and between them and their physical activity.

In the present study, children used a touch-screen tablet device during gameplay. Some of the games selected in this study required the children to move or tilt the tablet, to pinch or swipe the screen, and to trace objects on the screen. Each of these motions required a certain embodied action by the child (Botzer & Yerushalmy, 2008). This means that the physical motion or activity required by the artifact has the potential to link the physicality with the mathematics, based on the design. Martin and Schwartz (2005) describe this as embodied concrete action integrated with semiotic activity because it is grounded in the physical activity with the artifact. This linking of representations, in an embodied way, can promote mathematical learning. In fact, some authors suggest that the perceptuomotor integration that occurs when children interact with mathematical objects on touch screen devices is the intertwining of action and thought (Nemirovsky et al., 2013), which is consistent with the theory of embodied cognition as conceptualized by Lakoff and Núñez (2000). These results highlight the important connection between the design features and what the features afford for the learner.

Research Questions

To better understand the role of design features on children's learning with digital math games, this study focused on the following overarching research question and sub-questions: How do design features in digital math games influence children's learning?

RQ 1: How do interactions with digital math games impact children's proficiency?

RQ 2: How do design features in digital math games support learning and promote mathematics connections?

We answered RQ 1 by collecting and analyzing pre- and post-test data using quantitative data analysis techniques. We answered RQ 2 by collecting and analyzing video data using qualitative techniques to identify patterns in the data. Finally, we developed meta-inferences (Tashakkori & Teddlie, 2010) to answer our overarching research question.

Methods

Research Design

The research design used in this study was a convergent parallel mixed method design (Creswell & Plano Clark, 2011). For this design, we gathered quantitative and qualitative data concurrently and merged the results using complementary techniques (Teddlie & Tashakkori, 2006). The quantitative data analysis provided information on changes in children's mathematics proficiency. The qualitative data analysis provided information on children's interactions with the digital math games and children's responses to the interviewer through examination of videos. This design enabled us to better understand the research phenomenon through a complementary interpretation of the data.

Participants

The participants in this study were 193 children in Grades 2-6, ages 8-12. The children participated in four concurrent experiments, with each experiment having its own participants and its own set of digital math games (Experiment 1: N = 46; Experiment 2: N = 44; Experiment 3: N = 52; Experiment 4: N = 51). The children were recruited from public schools, charter schools, and home-schooling groups. Those interested in participating in the study called or e-mailed a member of our team to schedule an interview. Participants were screened to ensure that

they could perform basic technology gestures with a touch-screen device (e.g., tap, swipe, pinch). Children were assigned to one of the four experiments, based on a pre-test of their knowledge of grade-specific CCSSM standards (National Governors Association Center for Best Practices, 2010).

Digital Math Games

The first criteria in the selection of the 12 digital math games for this study was to identify three games at each grade level (Grades 3 to 6) that focused on mathematics topics aligned with national standards. The second criteria was to select games that included dynamic interactive mathematics objects, which aligned with Moyer-Packenham and Bolyard's (2016) definition of a virtual manipulative. A third criteria was to select games that promoted engagement and provided scaffolding, based on McLeod, Vasinda, and Dondlinger's (2012) criteria. McLeod et al. use the term *scaffold* to mean that there are successive levels of temporary support (e.g., hints, directions, demonstrations, or examples) that help children to progress to higher levels of mathematics skill within the digital games that they may not be able to achieve without assistance. In game design, the supportive features may be removed as the child achieves greater proficiency on their own. The 12 digital math games selected for the study are presented in Table 1.

Table 1

Screenshots of the 12 Digital Math Games Selected for the Study

Experiment 1: Grade 3 Math Topics		
Dragon Box Elements Shapes (Level 1)	Motion Math Bounce	Montessori Division Board

Experiment 2: Grade 4 Math Topics		
<p>Angle Asteroids</p>	<p>Motion Math Zoom</p>	<p>Chicken Coop Painter</p>
Experiment 3: Grade 5 Math Topics		
<p>Dragon Box Elements Triangles (Level 2)</p>	<p>Math Planet Place Value</p>	<p>Co-Ordinates Map Maker</p>
Experiment 4: Grade 6 Math Topics		
<p>Grid Lines: Ordered Pairs</p>	<p>Motion Math Hungry Fish</p>	<p>Smart Pirate Percent</p>

The researchers selected three apps for each experiment. The goal of the *Dragon Box Elements Shapes* game is to find and build geometric shapes based on the number of sides of each shape. Children build triangles (3 sides) and quadrilaterals (4 sides) using their fingers to trace shapes on the tablet. In *Motion Math Bounce*, the goal is to tilt the tablet to place a falling

fraction ball correctly on a 0 to 1 number line in the least amount of tries. The goal of the *Montessori Division Board* game is to create an array to represent a specific mathematical problem. This goal is not graded, scored, or given feedback but is used to support the second goal of the game, which is to solve the division problem by selecting the correct answer. In *Angle Asteroid*, the goal is to create angles of n degrees around a 360-degree rotational center that correspond to asteroid locations, and shoot a designated number of asteroids to collect coins using a movable lever to rotate the angle of the ship. In *Motion Math Zoom*, the goal is to place numbers on a number line, by zooming in and out, and find decimal numbers in the tenths and hundredths. In *Chicken Coop Painter*, the goal is to paint a chicken coop using equivalent models of the fractions on the paint cans, and all fractions add up to 1 (which is the total chicken coop).

The goal of the *Dragon Box Elements Triangles* game is to find and build triangle shapes, based on properties of equal sides, equal angles, and right angles. Users identify and trace triangle types, including scalene, isosceles, and equilateral. In *Math Planet Place Value* the goal is to match numeral representations to their place value names, and round numbers to the next place value by tapping on the correct place value to round to tens, tenths and hundredths. In *Co-Ordinates Map Maker*, the goal is to identify and locate items on a player-created, map-themed, coordinate plane. The goal of *Grid Lines Ordered Pairs* is to form lines with two coordinate pairs that intersect polygons on a coordinate plane. In *Motion Math Hungry Fish*, the goal is to combine integers to form a target negative number to feed to a fish. In the *Smart Pirate Percent* game, the goal is to select a fraction equivalent to the target percent or decimal (level 1), and then select a fraction greater than the target percent or decimal (level 2).

Data Sources

There were two primary sources of data used to answer the research questions: pre- and post-tests and video/audio of children playing the digital math games and responding to interview questions.

Pre- and post-tests. We created pre- and post-tests, administered before and after gameplay, to assess children's knowledge of the mathematics topics in the digital games. The pre- and post-tests for the four experiments each aligned with the CCSSM standards for Grades 3, 4, 5, and 6. The items on each test included game-specific questions that focused on the mathematics topics learned in the digital game. The topics of the games for each grade level were distinct with as little mathematical overlap as possible. There were also 6 test items that did not align with the mathematics topics learned in the games. Therefore, the pre- and post-test for each experiment contained 24 questions: 18 questions aligned with mathematics topics learned in the digital games and 6 questions on a mathematics topic not aligned with the games (to act as a control).

Video/audio of children playing the games and responding to questions. The second data source was videos of children playing the digital games from two different video perspectives. A wall-mounted video camera captured game play from six feet away and a GoPro camera (worn by the child) captured a view of the child's hands interacting with the digital games on the iPad screen from six inches away. Figure 2 shows both camera views. Both cameras captured video and audio of all interactions during the interview. The videos were downloaded onto external hard drives for security immediately following the interviews.

Figure 2. Camera views from the wall-mounted camera (left) and the GoPro camera (right).

After interacting with each digital game, we asked children questions about the game they had just played. Some typical questions included: 1) Were there any features in this game that you noticed while you were playing the game? 2) Were there features in the game that were helpful to your learning? 3) What mathematics did you learn from this game? These questions provided insight into children's awareness of the design features, how they viewed the role of the design features in their learning and gameplay.

Procedures

Children in the study participated in one 60-minute structured clinical interview. Parents or guardians observed the interview process. We described the study process to the child and their guardian and allowed time for both to read through the informed consent and assent information for the study. Each child's guardian completed a demographic survey and received an information sheet describing the study.

Each interview began with children completing a written pre-test. Children were initially given pre-tests that contained mathematics topics that were above their current achievement level. However, if a child answered five (or six) of the first six questions correctly, the child was

moved up to the next highest grade level experiment. For example, a child who demonstrated 100% knowledge of Grade 3 mathematics standards would be moved to the experiment that contained Grade 4 mathematics standards.

Once assigned to the experiments, children played three digital math games on an iPad. After playing each digital game, interviewers asked the children questions about the features they noticed in their interactions with each game. All of the gameplay and the question-response between the interviewer and the child was captured on the video and audio recordings. The interview concluded with children completing a written post-test. At the close of the interview experience, children were given a small toy for their participation.

Data Analysis

We conducted separate analyses for each of the four experiments. To answer RQ 1, we initially created line graphs for a visual inspection of the data. Next we computed paired-samples *t*-tests to identify significant changes in children's proficiency between the pre- and post-tests. To answer RQ 2, we transcribed and used descriptive and process coding to describe the actions and verbalizations of the children (Saldaña, 2015). We coded behaviors and verbal responses made by children while they played the digital games and when they responded to the interviewer's questions after gameplay. In this part of the analysis, we selected gerunds "to connote observable and conceptual action in the data" (Saldaña, 2015, p. 296). Next, we used pattern coding to label similarly coded data and organize the coded data into eight prominent categories of design features that appeared in at least four of the digital math games. In this part of the analysis, we assigned "a category label (meta code) that identifies similarly coded data" and is "appropriate for second cycle coding" (Saldaña, 2015, p. 296). After second cycle coding, the research team examined how the categories aligned with design features reported in prior

research. Four coders were trained to code the data and enter the transcriptions of behaviors and verbalizations into pivot tables as a way of organizing the data. After coding eight videos in each experiment, the team met to clarify and make adjustments to the coding parameters. Coders next coded half of the video data, and then met to discuss patterns in the data. After coding all of the data, coders met again to discuss patterns across the digital games. Finally, an additional four coders were trained to code 10% of the data to ensure reliability. This double-coding process resulted in a high level of agreement (95% or more) among the coders (Corbin & Strauss, 2014; Schubert, 2009).

Results

The results are organized to address the two main research questions. First, we discuss the quantitative analysis of pre- and post-tests for each experiment. Next, we present evidence from the video data of design features that supported children's learning and math connections.

Changes in Children's Proficiency between the Pre- and Post-tests

RQ 1 focused on changes in children's proficiency on each mathematics topic before and after playing the digital games. The line graphs for the four experiments in Figure 3 show the average pre- and post-test scores for each experiment. Each line graph shows the results for the three digital games and the control questions in each experiment.

Figure 3. Line graphs of pre- and post-test results for digital games and control items in four experiments; * indicates significant results at $p < 0.05$.

This analysis showed that children's pre- to post-test scores for all 12 digital games improved, with 9 of 12 games showing statistically significant improvement on the paired-samples t -tests (7 of 12 were significant at $p < 0.01$). The control test items in each experiment were not statistically significant. Appendix A includes a table with the results of the t -tests.

Examination of Design Features through the Video Data Sources

Through descriptive coding of the video data, we determined that over 95% of children in the study articulated their awareness of design features in the digital games. This high level of awareness of game design features contributed to children's improved scores between the pre- and post-tests. In an effort to abstract and distill insights and generalizations across the 12 games, we organized the data from behavioral descriptions, examined the transcribed quotes, and identified salient patterns. During the qualitative analysis we identified and labeled eight

prominent categories of design features present across the 12 digital math games. Six of these categories focused on how the design features provided learning support in the digital game. Two of these categories focused on how the design features prompted mathematics connections. The eight major categories were present in at least 4 of the 12 digital math games. The eight categories could be divided into two main categories: Learning Support and Math Connections. We labeled the six categories that focused on how the design features provided learning support as: accuracy feedback (A), unlimited/multiple attempts (U), information tutorials and hints (I), focused constraint (F), progressive levels (P), and game efficiency (E). We labeled these six categories the “Learning Support” categories because these were design features that provided general support for learning in the digital math games. This main category aligns with one of Falloon’s (2013) three broad categories of design features that support learning. These design features are not specific to a mathematics game. For example, a digital game on any topic (e.g., identifying historical figures or matching words with their abbreviations) could include feedback on the accuracy of the child’s response, unlimited attempts to find the answer, information tutorials and hints that help the player during the game, and levels that get more and more difficult as the game progresses.

We labeled the two categories that focused on how the design features prompted mathematics connections as: linked representations (LR) and linked physical actions (PA). We labeled these two categories the “Math Connections” categories because the video data showed linking behaviors (described in the results below) related specifically to mathematics connections. These design features were mathematics specific and included simultaneously linked mathematical representations in visual images, words, and symbols, and embodied actions that connected the mathematical ideas with the children’s activity. Table 2 provides a summary

of the eight categories and their presence (or absence) in each of the 12 digital math games.

Table 2 is organized with the nine games that produced significant pre- to post-test gains at the top of the table, and the three games that produced non-significant gains at the bottom of the table.

Table 2

Summary of Design Feature Categories across the 12 Digital Math Games

Games	Learning Support						Math Connections	
	A	U	I	F	P	E	LR	PA
Significant Gains								
Dragon Box (Shapes)	A	U	I		P	E	LR	PA
Motion Math Zoom	A		I	F		E	LR	PA
Math Planet Place Value	A	U		F			LR	PA
Dragon Box (Triangles)	A	U	I		P	E	LR	PA
Division Board	A	U				E	LR	
Angle Asteroids	A	U	I	F	P		LR	
Co-Ordinates Map Maker	A	U		F			LR	
Smart Pirate Percent	A		I					PA
Grid Lines	A	U		F		E	LR	
Non-Significant Gains								
Motion Math Bounce	A		I		P			
Chicken Coop Painter	A		I					
Hungry Fish	A	U	I	F				

Note. Learning Support design features: A = accuracy feedback; U = unlimited/multiple attempts; I = information tutorials and hints; F = focused constraint; P = progressive levels; E = game efficiency. Math Connections design features: LR = linked representations; PA = linked physical actions.

The six sub-categories under the main category of Learning Support are presented in the six columns at the center of the table. The right side of the table shows the two sub-categories under the main category of Math Connections. It is important to note that, while there was video evidence of many of the Learning Support categories in all of the games, the Math Connections categories were only observed in the games that produced significant gains. In the sections below, we provide detailed examples for each of these categories.

Design features that provide learning support. After children played the digital math games, we asked: *Is there anything in this game that helped you?* Table 3 shows the percentage of children (for each game) who reported and described design features that supported their learning. The sections below the table highlight specific examples of the six categories of design features that provided learning support.

Table 3

Percentage of Children Who Identified Design Features that Provided Learning Support in the Digital Math Games

Experiment	Game 1	Game 2	Game 3
#1	Dragon Box Elements Shapes 93%	Motion Math Bounce 91	Montessori Division Board 83
#2	Angle Asteroids 89	Motion Math Zoom 82	Chicken Coop Painter 59
#3	Dragon Box Elements Triangles 79	Math Planet Place Value 71	Co-ordinates Map Maker 90
#4	Grid Lines Ordered Pairs 84	Motion Math Hungry Fish 65	Smart Pirate Percent 65

Accuracy feedback. All 12 games included video evidence of the children interacting with design features in the *accuracy feedback* category. Feedback on the child's accuracy in the digital game was provided in one of three ways: visual (i.e., animations and pictures), auditory (i.e., sounds and oral praise), and numerical (accumulating score or coins). Several apps used multiple forms of feedback. Figure 4 shows an example of all three types of accuracy feedback in Motion Math Bounce.

Figure 4. Three types of accuracy feedback in Motion Math Bounce.

The stars across the top of the gameboard in Figure 4 are visual feedback of accuracy and progress. One student noted, “And I know, when you have to complete, um, ten stars... I mean you have to complete ten things before you can bounce to another level.” These stars reset for each new level. The score on the top right is numerical feedback of accuracy that accumulates throughout the game. At the bottom of the screenshot, the speech bubble (i.e., “precise”) represents the auditory feedback.

Feedback on accuracy, regardless of form, supported children's learning. For example, in Hungry Fish, one child said, "Whenever he ate a right bubble, he gained some score and also made a little noise and grew." In Chicken Coop Painter, one child said, "So if there's a cracked egg, then that's wrong, and if there's a hatched egg, that one's right." In Smart Pirate Percent, one child said "it has sounds like whenever you get it right like a pirate shouts and whenever you get wrong, the thing explodes or you fall off the balance." These examples illustrate how accuracy feedback helped children know when their responses were correct.

While playing Math Planet Place Value, one student observed, "They put the scores that will make people feel confident. You can beat your high score, like you could get 104 and then you could get 106 or something and beat your score." While playing Co-ordinate Map Maker, another child said, "Oh come on, give me the stars," then, when the round was completed, he pointed at the numerical score and said "I scored 7 out of 8. Can I try again?" In Montessori Division Board, one child entered an incorrect response and said, "It doesn't say if I got it right or not. It usually has a checkmark." She then looked back at her array and said, "Oh. Whoops!" fixed her error and smiled when she was rewarded with a checkmark. These examples illustrate how the accuracy feedback helped motivate students to increase their accuracy.

Accuracy feedback is commonly reported as a design feature in digital games. For example, feedback is one example of Falloon's (2013) broad categories of design features that support learning, and Boyer-Thurgood's (2017) research identified six types of feedback features (e.g., auditory, visual, text, immediate, delayed, and requested). Prior researchers have reported that when games offer no corrective feedback, student mistakes are often repeated, which limits learning (Benton, Saunders, Kalas, Hoyles, & Noss, 2018; Falloon, 2014).

Unlimited/multiple attempts. Eight games included video evidence of the children engaged in *unlimited/multiple attempts* to reach game goals. This design feature allowed children to experiment and to attempt their responses multiple times during the games. For example, in Dragon Box Elements Shapes, one child described multiple attempts to find the shapes by saying, “There wasn’t a way to die. It was like, just keep on trying, you’ll get it eventually.” In the Grid Lines Ordered Pairs game, children liked the design feature that allowed them to have multiple attempts at finding the coordinate pairs. One child remarked, “It’s kinda hard, but at least you get many tries.” Another child stated, “I liked how I can take those back,” meaning that the child could put the rocks back multiple times and try different coordinate combinations without being penalized. In Motion Math Hungry Fish, this design feature allowed children to experiment with multiple responses. As one child said, “I, kinda like, had to experiment with them.” This experimentation led children to develop strategies that supported their success.

Prior research has reported the importance of unlimited or multiple attempts in digital mathematics games. For example, Gee’s (2007) 12th principle notes that virtual environments entice students to spend more time on the tasks, which increases opportunities to practice skills in order to automatize their learning. One drawback of automatized learning from drill practice is that it often creates an inflexible understanding of procedures which are difficult to transfer to new situations or contexts. In contrast, the design of digital mathematics games help create flexible understanding as they “build in many opportunities for learners to operate at the outer edge of their regime of competence, thereby causing them to rethink their routinized mastery and move, within the game and within themselves, to a new level” (Gee, 2007, p. 67-68). Benton et al.’s (2018) research with Year 5 and Year 6 students in London showed that the class which allowed for multiple attempts had higher success than the class without. Similarly, Berkling et al.

(2017) found that students were more likely to quit games and disliked games with no replay of level opportunities, which did not allow them the chance to improve.

Information tutorials and hints. Eight games included video evidence of the children using *information tutorials and hints* that explained the game, the game features, or provided information on what to do next. Figure 5 illustrates two examples from Dragon Box Elements Shapes and Dragon Box Elements Triangles.

The screenshot on the left in Figure 5 shows an example of a tutorial from Dragon Box Elements Shapes that introduced a “new power,” which provided guidance on how to interact with the game to create a quadrilateral. Many children described this design feature stating: “It showed me new powers;” “It had the instructions what to do before you played it;” and, “It taught you how to do it.” The Motion Math Zoom game included a similar information tutorial that demonstrated how to perform the zooming in and out motion on the number line. One child explained this design feature: “When it said ‘when you need help’ and you, like, pressed it, and it shows you how to do it.” The screenshot on the right in Figure 5 shows the guidebook that children referenced when they had difficulty remembering the information from the tutorials.

The Chicken Coop Painter game also included a guidebook in the form of a magnifying glass. One child explained how the guidebook helped him: “There was sometimes two of the bowls [of paint], so if you done one hint of one thing you could do the other of the other hint.” These types of instructions provided children with scaffolded support.

Some games included progressive informational hints during gameplay. Figure 6 shows an example of progressive hints in Motion Math Bounce. The first time children missed placing the bouncing ball in the correct location on the number line, an arrow below the line hinted at the correct direction. The next hint was lines that segmented the number line. Benchmark numbers below the number line provided a third hint, and a vertical arrow pointing to the number line provided a final hint, if needed.

The effectiveness of information tutorials and hints has been reported in some prior studies. For example, *instructions* is one example of Falloon’s (2013) broad categories of design features that support learning. Other researchers (Lim, Lee, & Richards, 2006) have noted that “there is a need to integrate cues, hints or guide notes to scaffold their learning process” (p. 234). Herodotou (2018) also noted the importance of hints in a study where many children, who would have benefited from the hint feature in the app, were not aware of it or did not access it.

Focused constraint. Six games included video evidence of *focused constraint*, where the design features focused and constrained the range of mathematical information available to children during gameplay. Figure 7 shows an example of the design features in Math Planet Place Value that constrain the number of decimal places shown to only those needed to solve the problem. In the first screen shot, the values are constrained to the tens, ones, and tenths place that match the corresponding digits. In the second and third screenshots, children see only the decimals needed to round to the requested place value. This built-in design constraint helped children increase their efficiency when completing the tasks because, as one child noted, “I could just tap the last arrow up or down.”

Figure 7. Design feature that focused and constrained the mathematics regarding the number of decimal places.

Similarly, the Grid Lines game provided only four possible numbers (grey rocks) to create two sets of coordinate pairs. While working through one problem involving the number set $\{0, -8, -8, 10\}$, one child shared his thinking: “So let's try eight and eight together and zero and ten. All the way up there! Hmmm. How about switch that.. hmmm.. still no.. What if I did ten there and eight there. That would be all the way up there. So if I switch it, it will be at that line and ten so at the very end.” The design constraint in this game allowed children to use trial and error in order to learn how the order of coordinates, and the positives and negatives of the numbers, affected their positions on the coordinate plane.

Other constraint features helped children focus on benchmark numbers. For example, Angle Asteroids constrains the selection of angle measures on the slide bar and the asteroid location to increments of five or ten degrees, thereby focusing on benchmarks. Motion Math Zoom constrains the number line to only the range of place values shown. For example, if children were placing the number 4.7, they would be allowed to zoom out to single numbers and zoom into tenths. Whereas, if children were placing the number 13.27, they would be allowed to zoom out to double digit numbers and zoom in to hundredths. This helped children focus on the benchmark whole numbers and decimals that came before and after the target number.

Focused constraint is one of the categories of affordances identified by Moyer-Packenham and Westenskow's (2013/2016) meta-analyses of virtual manipulative affordances that impact mathematics learning. Falloon's (2013) categorization calls this *design features that place parameters around learning*. Boyer-Thurgood's (2017) research names the main category *constraint features*, and names five sub-categories which she calls *object*, *movement*, *numerical*, *order*, and *snapping constraints*. Zhang, Trussell, Gallegos and Asam (2015) found that fourth-grade students using an iPad app to learn decimals and multiplication exhibited higher performance when the content was broken into small constrained chunks.

Progressive levels. Four games contained video evidence of *progressive levels* that moved from less to more difficult. The progression of difficulty sometimes included increases in computational or conceptual complexity.

Figure 8 shows one example of progressive levels in Angle Asteroids. The first screen shot in Figure 8 shows that, in Level 1, asteroids are only located in the first quadrant. The second screenshot shows that, in Level 3, asteroids are located in the first and second quadrants. One child said, “The last level that I did it went all the way around,” indicating awareness that, by Level 10, asteroids were appearing in all four quadrants, as seen in the third screenshot in Figure 8. The third screenshot also illustrates that there were many more objects on the screen on this level. One child explained, “Level one, like, had five and level two had, like, thirty or something.”

Children enjoyed the progressive difficulty of the games. Figure 9 shows two different levels of difficulty in the Dragon Box Elements Triangles game. In the left screen shot in Figure 9, there are individual triangles; in the right screen shot, there were more triangles at the higher levels in the game and the triangles were often embedded in other shapes. This progression of difficulty provided scaffolded support, from simple to complex shapes. In the Dragon Box Elements Triangles game, one child noted that, “The clutter [in higher levels] makes it harder to find the triangles.” One child explained that the game, “is good for any age because [it has] easy levels and hard levels.” Another child added that, “Different levels made it into a game.” After playing Dragon Box Elements Shapes, one child said, “It does, um, like, give you more things that you can do. Like, as you get higher.” Each of these comments shows that children recognized the progression of simple to complex tasks within the games.

Progressive levels have recently been reported as a design feature that impacts learning. For example, Berkling et al. (2017) uses the terminology *increasing difficulty of tasks* to describe design features that promote enjoyment. Boyer-Thurgood’s (2017) categorization uses the term *tasks* for the main category, which includes *multiple progressive tasks* and *multiple adaptive tasks* as two sub-categories of important design features in digital math apps. Recent research shows that children are more likely to persist at mathematical games when there are increasing levels of difficulty (Berkling et al., 2017).

Game efficiency. Five games contained video evidence of design elements that supported *game efficiency* during children’s interactions with the games. For example, the Montessori Division Board includes an efficient auto-placement feature that moves the beads into the array. When one child discovered this feature, she explained the efficient process saying, “You can just throw them at it,” which made placing the beads much faster. Another design feature tracked the

amount of beads in the bowl and on the array board (see Figure 10). Children's comments, such as: "I don't have to count! It counts for me," showed that children recognized this design feature and how it supported efficient gameplay.

Figure 10. Efficiency of auto counting in the Montessori Division Board.

In the Motion Math Zoom game, the zooming feature allowed children to efficiently move from one place value to another (e.g., from hundredths to hundreds) with the quick zooming action of the number line. In the Grid Lines game, the reset feature allowed children to clear their placement of the four coordinates and start again. Similarly, the two Dragon Box Elements games (Shapes and Triangles) included design features to reset the selected shapes, starting the level again. These design features allowed children to focus on their next attempts in the learning tasks more efficiently, without losing the flow of the game.

Efficient precision is one of the five affordance categories shown to have a positive impact on learning identified by Moyer-Packenham and Westenskow (2013/2016). Kosko's

(2017) research on the CandyDepot game showed that children who accessed game features, meant to increase their efficiency, exhibited higher gains than students who did not. When a digital game includes design features that support user efficiency, this promotes mathematical *flow*, a state of completely focused motivation, which impacts learning by mediating enjoyment and performance (Pavlas, 2010).

Design features that prompt mathematics connections. Falloon (2014) found that students who made connections between their gaming activities and the mathematics were more likely to have a deeper understanding of the intended learning outcomes. Two patterns emerged from the video analysis that focused on children's internalizations and externalizations of the mathematics and were exhibited as *linked representations* and *linked physical actions*. Table 4 shows the percentage of children for each game who reported and described design features that prompted these linked mathematical connections.

Table 4

Percentage of Children Who Identified Design Features that Prompted Mathematics Connections in the Digital Math Games

Experiment	Game 1	Game 2	Game 3
#1	Dragon Box Elements Shapes 98%	Motion Math Bounce 85	Montessori Division Board 89
#2	Angle Asteroids 70	Motion Math Zoom 59	Chicken Coop Painter 84
#3	Dragon Box Elements Triangles 96	Math Planet Place Value 92	Co-ordinates Map Maker 94
#4	Grid Lines Ordered Pairs 84	Motion Math Hungry Fish 88	Smart Pirate Percent 90

As Table 4 shows, a high percentage of children recognized the mathematics in the games and understood the games' mathematical goals. For example, one child described the goal of Motion Math Bounce: "There was a number line and you had to put the fraction on the number line." Another child told an interviewer the goal of Chicken Coop Painter: "It was asking me to use the right amount of fractions to paint the coop." Their descriptions showed that children knew the intended mathematics in the games. Children's comments also showed that they, themselves, recognized that they were learning mathematics in the games. For example, describing her experience with Math Planet Place Value, one child reported, "At first, I thought the ones place was where the tenths place is. But after [matching ones and tenths places], I realized that the tenths place is after the decimal, and I didn't know that before." The sections below highlight specific examples of how design features prompted mathematics connections.

Linked representations. Eight games included video evidence of the children's interactions with *linked representations*, which included multiple and simultaneously linked mathematics representations in the games. These games include visual representations of the mathematics linked with other visual representations, auditory words linked with visual representations, and number symbols or number words linked with visual representations. Figure 11 shows an example of the linked representations in the Montessori Division Board game. Children recognized that the objects they dragged onto the division board created an array, which helped them solve the division equation presented in the game. When children moved the beads, this resulted in an array formation which assisted them in identifying the two factors of the array region. As one child explained how she learned from the game, she said, "That [pointing to the array] shows the array and examples."

Figure 11. Simultaneously linked representations in Montessori Division Board.

Another child describing the Montessori Division Board game was confident in her responses for each equation because she explained that the game showed her the answers: “It made arrays and used an example and so that I had the correct amount of groups. It sort of gave me the answer there [pointing to the vertical number and the division equation].” It was also evident in children’s comments that they recognized different parts of the equation (e.g., divisor, dividend, and quotient) while interacting with the game. As one child explained his solution process: “I know what it is. It tells you to make arrays. So the circle parts are the parts you put in here [pointing to the divisor in the equation] and then you put the diamond parts at the top for how many there are [pointing to the dividend in the equation].” This shows the child recognizing the link between the visual array display of beads and the numeric parts of the equation.

Motion Math Zoom contained an implicit magnitude link between the size of the creatures on the number line and the size of the numbers on the line. By zooming (pinching motion) in and out on the number line, children would see creatures of different magnitudes (e.g., rhinoceros or bees) and numbers of different magnitudes (e.g., millions, thousands, or tenths). Figure 12 illustrates the link between the size of the creatures and size of the numbers.

Figure 12. Design feature that simultaneously links the magnitude of creatures and numbers in Motion Math Zoom.

Many children recognized the link in Motion Math Zoom between the size of the animals and the numbers. One child explained that the tiny bugs would align with the tiny numbers (pointing to the hundredths place) when he said: “About the sizes that the things could be, like these tiny bugs could be the number that it should go [pointing to hundredths].” Another child explained this magnitude link between numbers and creatures saying: “The animal, so like, when it was just like 1, 2, 3, or it would be the frog, so like the bigger the animal, and if it was like, um, like 0.08 or something like that, it would just go a smaller and smaller animal.”

There are a variety of simultaneously linked representations in the two Dragon Box Elements games (Shapes and Triangles). These games include visual images, words for the shapes, and tracing and color options that provide cues to the mathematical connections. For example, one child was able to check his idea about the type of triangle he saw in the game by tapping the sides of the triangles. He explained, “I usually eyeball isosceles triangles. But the lines here help. In general the lines connected together are different lengths. I just tapped the sides to check.” When he tapped the sides of the triangle, if the triangle was isosceles, the game would display the word “isosceles” to link the word to the visual image (see Figure 13).

Figure 13. Simultaneously linked words and shapes in Dragon Box Elements Triangles.

In Dragon Box Elements Shapes, characters have shapes aligned with the geometric shapes children find in the game. As one child explained, “The monsters had the shape of what you had to make.” Children noted that, “At the beginning of levels, it tells you [the names and shapes within the game]....White words taught me how to make something new” because “they say the name of the shapes” (see Figure 13). This design feature is the simultaneous linking of words for the shapes (a text representation) with the visual images of the shapes (a pictorial representation).

Figure 14. Simultaneously linked representations in Angle Asteroids.

In Angle Asteroids, linked representations helped children connect with the mathematics because the measure of the angle is presented on the asteroid, the slide bar, and the angle after it is traced (see Figure 14). In Figure 14, the angle measure of 150 degrees is in an arrow pointing to the slide bar on the right of the screen, 150 degrees is in the center showing the traced version of the angle, and it is on the asteroid that is blown up (not pictured). Additionally, there are segmented lines around the board to provide benchmarks for the angle measures. The linked representations help children know which way to move the slider to shoot the asteroids. One child explained, “It helped me because the bar and the angles in the middle of the spaceship, they both worked together for me because they were telling me the angle.” Children were aware of the moving asteroids and the angles identified on the asteroids, saying “Some of the asteroids actually told me the angle.” One child explained her recognition of the benchmark angles with lines for every 5 or 10 degrees: “There were things on the screen like that numbered here [pointing to the angle numbers] and there are lines [pointing to the benchmark degrees] and I think each line was a 10 and an angle, or 5. That helped.”

The grid lines and numbers in Co-Ordinates Map Maker, cued children towards the mathematics in the game. One child noticed the simultaneous linking between the lines and the numbers and said, “I looked at the numbers and the lines dragged the numbers.” This child was describing the link between the grid lines and the intersection of the two lines to indicate the points on the coordinate map grid. Another child described the link between the numbers and lines, and explained how he would find a point, even without the linked representations: “They are numbers at the bottom and the sides and lines. If the numbers weren’t there, I would just count the lines until the next line intersects it to find it” (here, the child is referring to finding the coordinate point).

The positive learning benefits of linked representations have been reported in numerous studies in mathematics. For example, *simultaneous linking* is one of the five affordance categories shown to have a positive impact on learning with virtual manipulatives identified by Moyer-Packenham and Westenskow (2013/2016). Boyer-Thurgood's (2017) analysis of over 100 mathematics apps describes the linked and unlinked dynamic mathematical objects in the apps. Multiple studies report the positive effects of children recognizing links among mathematical representations in digital and non-digital mathematics environments (Beck & Huse, 2007; Burris, 2013; Rau, Aleven, Rummel, & Rohrbach, 2012).

Linked physical actions. The videos showed evidence of *linked physical actions* in five of the games, where children showed links between their physical actions and the mathematics. In the Dragon Box Elements Shapes and Traingles games, children must trace shapes with their fingers (see Figure 15). This tracing activity is an embodied action that externalizes the child's concept of the mathematics through the digital game. One child voiced their thoughts on this activity saying, "The shape of the monster you are making is the shape that you have to trace. This is going to be the triangle." The tracing activity reinforces the link between the number of sides of a shape (by tracing through each edge and vertex) and the requested shape (i.e., triangles or quadrilaterals). One child described the tracing process: "So how they had little lines over it, so you could go to it, so you could stay in the lines instead of slanting off, so the lines helped your fingers."

Figure 15. Embodied activity of child tracing shapes in Dragon Box Elements Triangles.

In other digital games, embodied actions allowed children to manipulate the dynamic mathematical objects. For example, Motion Math Zoom included a pinch to zoom design feature to help children navigate a dynamic number line. One child reported that he used his “hands, that if I went *tchoo* [making a sound effect and pinching his fingers together to make small numbers] it went *tchoo* [making a sound effect and making his hands small and making his hands wide]. If I went *tchoo* [opening his hand bigger and points to a large number] then it went *tchoo* [if the child zoomed the number line too much with his hands] it went *tchoo* out, too big then.” This can be seen in Figure 16.

Figure 16. Embodied action of pinch to zoom to manipulate the dynamic number line in Motion Math Zoom.

Math Planet Place Value allows children to manipulate the mathematical objects in a way similar to potential mental models of the object. When rounding numbers up, children tap an up arrow; when rounding numbers down, children tap a down arrow. Therefore, the directional arrows embody the directional action of the rounding. “If I put a point like the tenths, you would have to see if the next one was five or higher or lower. If it was 5, you tap up [child points up] and if it was lower you went down [child points down].”

In some games, the physical activity of the child was more closely linked to the mathematics, while in other games the physical activity was linked more abstractly. For example, children quickly recognized the link between the shape of the characters, the shape of the triangle on the screen, and the shape of the triangle that they were tracing with their finger in the Dragon Box Elements Triangle game. This linked physical action was concrete and externally visible. In contrast, children moved a slider in Angle Asteroids up and down, which caused a rotation motion of the rocket, indicating different angle measures. Making the connection between the up and down sliding motion and the rotating angle measure motion required an internalization and abstraction of the activity being performed by the child, which was a much harder link to make.

Children also used physical actions and gestures to explain the concepts they internalized from the digital games. For example, Smart Pirate Percent contained objects that represented real world physics, such as a bridge leveling out for equivalence and a seesaw tipping down to indicate the greater quantity. Balancing two objects physically mimics the balancing of an equation symbolically. Children used gestures when describing these features. One child said, “I like the teeter totter and the bridge thing. You had to put something on it to level it [gestures

leveling motion with hands similar to the motion in the game]. I also liked how, on the teeter totter, you had to get something to make it go that way [pointing to the high end of the teeter totter, which needed to be heavier to make the other side lift]. I learned how to make things equal...” The child’s recognition of the link between their physical actions and the mathematics in the games gave children the opportunity to internalize the mathematics represented. Additionally, after the initial interaction with the game, children then used these same embodied actions to externalize their thoughts as they advanced to tasks with more complexity.

Situated embodied experience in a digital game is grounded in the child’s perceptions of the mathematical actions in the game (Gee, 2005). There are multiple studies that report the important link between children’s mathematical actions and their abstractions of the mathematics (Alibali & Nathan, 2012; Bujak, Radu, Catrambone, MacIntyre, Zheng, & Golubski, 2013; Goldstone, Landy & Son, 2008; Osgood-Campbell, 2015). For example, Paek’s (2012) research with young children learning multiplication reported that the degree of embodiment of the mathematical concepts was a greater factor in the positive long-term results for their learning.

Discussion

The purpose of this research project was to examine how design features in 12 digital math games influenced children’s learning. The results showed that many of the games supported learning gains between the pre- and post-tests. The results also reveal eight prominent categories of design features in the digital games that help to explain the positive learning outcomes. The video data indicates that children were aware of the design features that supported learning (e.g., accuracy feedback, unlimited/multiple attempts, information tutorials and hints, focused constraint, progressive levels, and game efficiency) and that prompted mathematics

connections (linked representations and linked physical actions). Here we discuss the results using the lenses of ACAT and embodied cognition.

Design Features through the Lens of ACAT

The results of this study highlight the significance of the relationship between the subject (the child), the artifact (the digital math game), and the object (the mathematics) (Ladel & Kortenkamp, 2016) when children learn mathematics while engaged in playing a digital math game. Our first focus within Artifact-Centric Activity Theory is along the main axis, the subject-artifact-object center line. Through multiple examples, we see that children's recognition of the role of the design features helped them to focus on learning the mathematics in the games. In this relationship, between the child and the mathematics, the design features in the digital math games became a mediator for learning. This mediator changed the activity between the subject and the object. This mediation effect was evident in the children's interactions with design features in the digital games (e.g., feedback on the accuracy of the child's response, allowing the child unlimited attempts to find the answer, information tutorials and hints that provided scaffolded help, and levels that became more and more difficult as the game progressed). Ladel and Kortenkamp (2016) say that, "The artifact modifies various aspects (e.g., intensity, duration, etc.) of all mental processes as it replaces some functions with others" (p. 29). The artifact may, as we observed through various examples, abolish some previously necessary processes that the child needs to do to learn the mathematics. For example, the child no longer needs to keep count of the beads in the Montessori Division Board because the artifact is now performing this function for the child. This action frees up the child's cognitive processes to focus on something else during the interaction with the artifact and the object. As the examples in the results reveal, children recognized when they were receiving learning support through the design features in the

digital game. For example, children discussed how the design features promoted efficiency, they reported using the hints and tutorials, they enjoyed the challenge of progressive levels, and they appreciated feedback on the accuracy of their responses. In some cases, feedback, constraints, and hints allowed children to better refine their strategies and improve their accuracy on future attempts. In essence, children were externalizing their mental representations through the use of the artifact (digital math game) and, simultaneously, internalizing the mathematics that was represented by the artifact to them.

Our second focus within Artifact-Centric Activity Theory is along the upper right triangle, which includes the rules and principles that guide the design of the artifact based on the object. When a computer programmer or designer creates an artifact (a digital math game), she must analyze the object (mathematics), with all of its rules, properties and structures, to determine what design features to put into the artifact. These rules and properties in the design process must be based on learning principles and on the object. As seen in the 12 digital games selected for this study, not all digital games will include all design features. However, based on the pre- and post-test results, perhaps some of the games should have included additional design features. For example, the three digital math games that did not result in significant learning gains all lacked several design features (e.g., unlimited/multiple attempts, focused constraint, game efficiency, linked representations, and linked physical actions). The lack of certain design features, especially those that help the child to connect with the mathematics, may be vital to children's learning when playing a digital math game.

According to Artifact-Centric Activity Theory, the inclusion or exclusion of design features is a reflection of the programmer's own internalization of the mathematics topic (Ladel & Kortenkamp, 2016). If design features are limited, or if they are focused on only one type of

mathematical representation, the digital game may be designed with deficiencies. Selecting the right design features for a digital math game is not an easy task. In fact, other research studies have reported that a design feature that can help one child, can hinder another child (Bullock, Shumway, Watts, & Moyer-Packenham, 2017; Vig, Murray, & Star, 2014). Children experience interactions with the technology in different ways. For example, in a study with fifth-grade children, Moyer-Packenham and Suh (2012) reported that the children in three different achievement groups experienced virtual manipulative fraction apps in different ways. The features of some apps that supported pattern recognition were accessed by high-achieving students; conversely, the features that supported processes and procedures were accessed by low-achieving students.

Research shows that there are positive effects on learning when design features in games include a balance between challenge and skill (Pavlas, 2010). Games that provide an introduction, tutorials, helps and hints can support learning. But designers must make choices about the amount of information that is provided in the tutorial of the game. Too little information can cause children to be unable to complete the task, whereas too much information can limit children's efforts to discover strategies and make connections (Dabbagh, 2003; González-Calero, Arnau, Puig, & Arevalillo- Herráez, 2015).

Design Features through the Lens of Embodied Cognition

Embodied cognition is conceptual understanding of the mathematics, constructed by the learner through their embodied experiences (either mentally or physically), when the learner interacts with situations to make meaning of symbols and objects. Experiences stored in the brain are tied to the dynamic perceptions of our own bodies, feelings and experiences. This means that when a child plays with a digital math game, they are experiencing physically embodied actions

in the game that relate to mathematical meanings for the concepts and symbols (abstraction) they are internalizing. During this process, children may be recognizing links within the game that help them to identify patterns of cognitive inferences for the mathematical relationships they observe among the concrete representations in the game (e.g., an equation, a visual image of a triangle, or changing number line for base-10 quantities). These representations help the child to understand possible actions, affordances, and disaffordances of the mathematical representations (Gee, 2008). For example, when children moved the slider up and down in the Angle Asteroids game they had to perceive this possible action and mentally understand that it was linked to the rotation of the rocket ship and the measure of the angles in the game. These abstract mathematics concepts are formed and are understood by making inferences through structural understandings during the child's physical actions and experiences. The sensory motor aspects of manipulatives in digital environments allow children opportunities to explore the embedded embodied cognition of the mathematics afforded by the technology. For example, in the Smart Pirate game, the seesaw visual image is a representation of balancing of two equations, and the slider in the Angle Asteroids game is a sign used to change the measure of the angles in the game.

The design features in the games that enabled linking bear some similarity to Lakoff and Núñez's (2000) description of *grounding metaphors* and *linking metaphors*. Lakoff and Núñez describe grounding metaphors as cognitive mechanisms that allow the projection of everyday experiences onto abstract concepts (i.e., physically putting collections of objects together projects onto the abstract mathematical domain of addition in arithmetic). On the other hand, linking metaphors are cognitive mechanisms which allow the linking of arithmetic to other branches of mathematics (i.e., conceptualizing arithmetic in spatial terms to conceive numbers as points on a line to yield a more sophisticated abstraction associated with geometry). When

children in the present study *linked physical actions* (e.g., the pictorial image of five objects with the numeral “5” or the auditory number word “five”), they were abstracting the meaning of five through the use of a grounding metaphor to yield basic arithmetic understanding. When children in the present study *linked representations* with the mathematics (e.g., moving a slider up and down in Angle Asteroids to cause the rotation of a rocket to show angle measures), they used a linking metaphor as they recognized the slider as a sign system for the manipulation of the angle measures, which linked arithmetic with geometry as a more sophisticated abstraction. When there are multiple instantiations of representations (i.e., simultaneously linked features) in a digital environment, these provide information to children that afford a deeper conceptual understanding that is often impossible to recreate with physical manipulatives (Hansen, Mavrikis, Holmes, & Geranious, 2015). For example, Shin (2013) found that multiple linked representations helped middle school students with learning disabilities learn fraction concepts. In other studies, researchers have reported consistent positive effects on mathematics learning for linked representations (Pagar, 2013; Teck, 2013).

Botzer and Yerushalmy (2008) suggest that when a digital game allows the child to experience multiple embodiments of a concept (i.e., dynamic, symbolic, numerical) that this allows the child the opportunity to link concrete representations with the symbolic. One example of children experiencing these embodied actions was in the Smart Pirate Percent game. This game incorporates animations, which represent the physical reality of the mathematics concept, such as equality or greater than and less than. This encouraged children to make gestures that modeled the mathematical ideas presented in the game. Therefore, the game connected visually and conceptually to the mathematics that children were learning. This finding was supported by Alibali and Nathan’s (2012) research which showed that when mathematical knowledge is

embodied this comes from the bodily and neural systems of perception and action, in addition to being grounded in one's physical environment. Their research showed that teachers' and students' movements when explaining mathematical concepts include gestures that mirror the individual's conceptual understanding of the mathematical idea, and therefore one's gestures indicate that some types of mathematical cognition are embodied. In the two Dragon Box Elements Shapes and Triangles games, the animated monsters use words, colors, and visual representations of different shapes and types of triangles as linked representations that support the mathematics focus. In Motion Math Zoom, the characters range from the smallest amoebas to the largest dinosaurs, and these characters help the child to relate the magnitude of the characters to the magnitude of the numbers on the number line in the game.

Design features have been linked to *affordances* (i.e., *action possibilities*) by a number of researchers. For example, Clark et al. (2016) summarized their meta-analysis saying that: "...the results highlight the affordances of games for learning as well as the key role of design beyond medium" (p. 79). In two other meta-analyses, Moyer-Packenham and Westenskow (2013, 2016) reviewed 66 and 104 studies, respectively, to explain the positive outcomes across all of the studies. They summarized the findings into five main categories of affordances of virtual manipulatives that promoted learning: "focused constraint, creative variation, simultaneous linking, efficient precision, and motivation" (2013, p. 35). The design features identified by children in this study bear similarities with these results. Similarly, Sarama and Clements (2009) say that computer manipulatives can connect different representations to the symbolic, noting that "Computers help students link sensory-concrete and abstract knowledge, enabling them to build integrated-concrete knowledge" (p. 148). Again, this emphasizes the importance of linking representations when learning mathematics. Numerous other studies report the benefits of design

features and the affordances of educational apps and are aligned with our results (e.g., Baccaglini-Frank & Maracci, 2015; Bertolo, Vivian, & Dinet, 2013; Burris, 2013; Hensberry, Moore, & Perkind, 2015; Pettigrew & Shearman, 2014; Sarama & Clements, 2009; Way, 2011; Zhang et al., 2015).

Conclusion

This study sought to understand how design features in digital math games influence children's learning. The results show that children's recognition of the design features seemed to allow them to take advantage of many of the affordances offered by the digital games. Sarama and Clements (2009) describe the importance of "bringing mathematical ideas and processes to conscious awareness" (p. 147) saying that computer technologies can bring the mathematics to an explicit level of awareness for the child. While the presence of children's awareness of the design features may not guarantee that learning will occur, the absence of children's awareness of the design features may have negative impacts on learning.

Well-designed digital math games, whose learning designs and mathematics rules and principles are well-integrated with gameplay, can motivate children and result in positive learning outcomes (Boyce, 2014; Clark et al., 2016; Habgood & Ainsworth, 2011). As the results of this study showed, design features that provide feedback, that help children focus on the mathematics, that provide unlimited attempts, and that link mathematical representations allow children to embody mathematical ideas and develop conceptual and abstract understandings. It is important that children are aware of the design features, and that they use this knowledge to effectively navigate with the artifact (the digital math game) as they abstract and embody ideas about the object (the mathematics). Digital math games that include design features that promote

learning and mathematics connections are more likely to support children's mathematics learning.

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Appendix A

Paired-Sample T-Tests of Pre- to Post-tests for Each Digital Math Game

Experiment 1 (N = 46)	Pre	Post	<i>p</i> value
	M (SD)	M (SD)	
Montessori Division Board	2.500 (1.546)	3.804 (1.529)	0.001**
Motion Math: Bounce	2.457 (1.277)	2.630 (1.597)	0.430
Dragon Box: Elements	3.217 (1.263)	4.239 (1.196)	0.001**
Experiment 2 (N = 44)			
Angle Asteroids	1.705 (1.047)	2.455 (1.438)	0.002**
Motion Math: Zoom	2.159 (0.861)	2.659 (1.120)	0.010**
Chicken Coop Painter	2.159 (2.382)	2.432 (2.386)	0.070
Experiment 3 (N = 52)			
Dragon Box: Elements	1.558 (1.162)	2.385 (1.402)	0.001**
Math Planet: Place Value	1.942 (1.461)	2.923 (1.713)	0.001**
Co-Ordinates: Map Maker	3.385 (1.849)	5.096 (1.317)	0.001**
Experiment 4 (N = 51)			
Grid Lines	2.510 (1.826)	2.941 (1.654)	0.040*
Motion Math: Hungry Fish	3.980 (1.667)	4.216 (1.653)	0.248
Smart Pirates: Percent	3.941 (1.805)	4.373 (1.587)	0.016*

Note. M - mean; SD - standard deviation; Entries with * are significant at the $p < .05$ level. Entries with ** are significant at the $p < .01$ level.

Highlights

- Children made significant learning gains when using 9 of the 12 digital math games
- Children's awareness of the mathematics in digital math games impacted learning
- Eight categories of game design features supported children's learning
- Learning gains were tied to design features that linked representations to the mathematics
- Learning gains were tied to design features that linked physical actions to the mathematics