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Integrated steM Education through Open-Ended Game-Based Learning

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Science, technology, engineering, and mathematics (STEM) education continues to garner focus and attention from teachers, students, researchers, policymakers, and businesses due to the vast importance of technology in the world. The integration of STEM subjects has the potential to make learning relevant and more engaging for students, which can increase their mathematical knowledge. There is a need for further research though on how mathematics can be emphasized in the integration of STEM education. In my prior research, I have described three methods of integrated steM. I use the acronym steM to mean integrated STEM education that has an explicit focus on mathematics. In this paper, I focus on integrated steM education through open-ended game-based learning within a technological context. The possibilities for integrating mathematics and technology through open-ended game-based learning has increased in recent years. Recent research with this approach will be discussed along with recommendations for future work.

***Keywords*:** game-based learning, integrated STEM education, mathematics education, technology integration

The integration of science, technology, engineering, and mathematics (STEM) disciplines has the potential to bring together overlapping concepts and principles in meaningful ways. This is becoming more important because more jobs rely on technological advances that are driven by engineering, which relies on mathematics and science knowledge (United States Bureau of Labor Statistics, 2017). However, there is no widely agreed upon idea for how this best translates into K-12 education. There are different interpretations of STEM education that lead to different implementation models (Johnson, 2013). Further research is needed to investigate effective models for integrated STEM education (Lesseig, Nelson, Slavit, & Seidel, 2016).

Researchers have noted that mathematics is often not emphasized in the integration of STEM subjects (English, 2017; Fitzallen, 2015; Gravemeijer, Stephan, Julie, Lin, & Ohtani, 2017). In response to this, I have proposed that mathematics teachers and researchers focus on integrated steM. Integrated steM is the integration of STEM subjects that has an explicit focus on mathematics (Stohlmann, 2018). It is an effort to combine mathematics with at least one of the three disciplines of science, technology, and engineering, into a class, unit, or lesson that is based on connections between the subjects and that has open-ended problems. Further, integrated steM education is an approach that builds on natural connections between STEM subjects for the purpose of (a) furthering student understanding of each discipline by building on students' prior knowledge; (b) broadening student understanding of each discipline through exposure to socially relevant STEM contexts; and (c) making STEM disciplines and careers more accessible and intriguing for students (Wang, Moore, Roehrig, & Park, 2011).

There are three ways in which integrated steM can be implemented by mathematics teachers: engineering design challenges, mathematical modeling with science contexts, and mathematics integrated with technology through open-ended game-based learning (Stohlmann, 2018). Each of the three approaches involves the integration of mathematics with a different science, technology, or engineering (STE) focus. In this paper, I focus specifically on mathematics integrated with technology through open-ended game-based learning. The purpose of this paper was to draw on recent research to highlight implications for the development and selection of open-ended game-based learning to be used in the mathematics classroom.

Mathematics Integrated with Technology

Interest, discussion, and work around technology integration in education continues to grow as advances in technology permeate our daily lives. In order for students to be prepared to be successful in their lives and future careers, they need to have experiences with using technology. For mathematics education, technology integration should go beyond general educational technology usage. There are mathematics-specific technologies that can help students develop conceptual understanding and valuable 21st century competencies. This recommendation is supported by recent standards and by the National Council of Teachers of Mathematics (NCTM). For example, In the United States (U.S.), the Common Core State Standards (CCSS, 2010) indicate that mathematically proficient students "are able to use technology to explore and deepen their understanding of concepts" (p. 7). In addition, the NCTM Principles to Actions states that "an excellent mathematics program integrates the use of mathematical tools and technology as essential resources to help students learn and make sense of mathematical ideas, reason mathematically, and communicate their mathematical thinking" (2014, p. 78). The way that technology is integrated into the classroom is important in ensuring optimum learning outcomes for students. In game-based learning, technology integration should allow students to engage in more high-level thinking and have new experiences with mathematics that would be difficult without the technology.

There is a distinction between how technology is used as an *amplifier* and how it is used as a *reorganizer* of mental activity (Pea, 1985). Technology as an amplifier enables students to perform more efficiently tedious processes that might be done by hand. This does not change what students do or think but does save time and effort and improves accuracy. As a reorganizer, technology is capable of effecting or shifting the focus of students' mathematical thinking or activity. This can enable students to do more high-level thinking with a focus on looking for patterns and making and testing conjectures. Technology in this sense enables students to do something that they could not have done before.

Building on this work Puentedura (2006) has described a SAMR hierarchy (Figure 1). In this hierarchy, the two parts of the transformation level provide more details to technology as a reorganizer. Similarly, the two parts of the enhancement level provide more detail to technology as an amplifier. In game-based learning, technology integration should be used as a reorganizer or transformation.

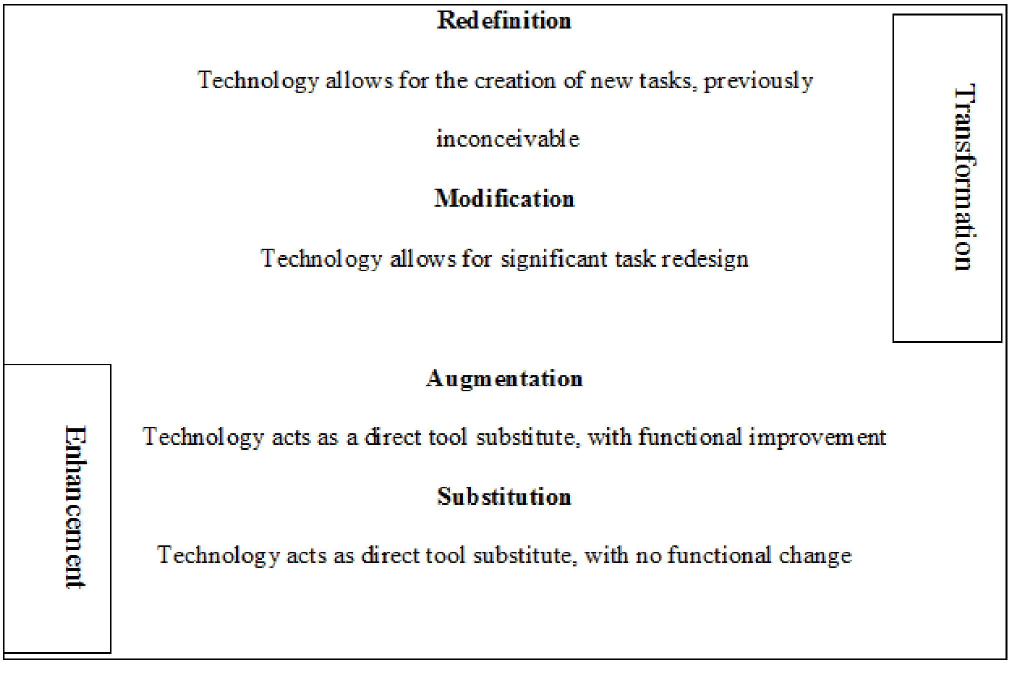

Figure 1. *The SAMR hierarchy.*

A recent review of the literature suggests that the potential to integrate technology in a transformative way is not being met. For instance, in a previous study, researchers used the SAMR hierarchy to classify studies based on the ways in which technology has been integrated in mathematics education since 2009 (Bray & Tangney, 2017). The findings of this previous work indicated that the majority (61%) of the 139 students were classified as augmentation in that the technology was used as a direct substitute for traditional approaches with some functional improvement. This result suggests that although innovative practices undoubtedly exist, the technology that could improve students' learning experience is generally not well implemented in the classroom (Hoyles & Lagrange, 2010).

Game-Based Learning

Game-based learning has drawn international interest and has been reported as an effective educational method that can improve students' motivation and performance in mathematics (Byun & Joung, 2018; Foster & Shah, 2015; Wang, Chang, Hwang, & Chen, 2018). Students enjoy playing technology-based games whether it is video games or apps on their phones. However, when used in the mathematics classroom, game-based learning is often not implemented with best practices for teaching mathematics in mind (Byun & Joung, 2018). A meta-analysis was conducted to look at the overall effect size of game-based learning on K-12 students' mathematics achievement. Seventeen studies were identified that had sufficient statistical data from a time frame of the years 2000 to 2014. The overall weighted effect size was 0.37, which is a small effect size. There were 71 authors in the studies reviewed for the meta-analysis, with only five of these authors having a background in mathematics education. This research demonstrates the need for further studies on effective game-based learning approaches and best practices in mathematics education.

For example, most of the games used in the studies involved drill and practice (Byun & Joung, 2018). One popular game includes students solving traditional, non-contextual practice problems in order to get more speed for a race car and attempts to take advantage of students' interest in videogames (Math-Play, 2019). However, in this type of game, students only receive feedback if the answers are correct or incorrect and do not receive support for improving their conceptual understanding. These types of games also emphasize that mathematics is about speed and focus related to the memorization of ideas. (Bay-Williams & Kling, 2015). Game-based learning for mathematics should move beyond drill and practice.

Another area that requires improvement in the implementation of game-based learning is for students to be able to work collaboratively or competitively. This has been suggested to be more effective than individual gameplay (Hung, Huang, & Hwang, 2014). A study in which this collaboration versus individual play was investigated involved 242 students with an age range of 11 to 15 years. There were four conditions in the study: collaboration and competition, collaboration control, competition control, and control. Overall, the game-based learning improved students' proportional reasoning, but the effects did not differ between conditions (Vrugte et al., 2015).

When implementing game-based learning, it is important for teachers to build on students' time with game-based learning by connecting the game play to formal mathematics. This can involve reflection prompts and whole-class discussion to develop further students' mathematical knowledge in relation to the games (Foster & Shah, 2015). A case study was conducted with middle school students that enabled the students to discuss their game play to highlight the mathematics in the games. Thirteen students in a rural school and fifty-one students in an urban school participated in one hour-long game-based learning activity with a tutor twice a week for five weeks. The games used came from NCTM's Illuminations website and the Education Arcade at MIT. The tutors took on the role of expert gamers who played the games with students and coached them on how to play better. Students at the rural school showed significant improvement on the state mathematics test, but the students at the urban school did not. Overall though, 95% of the students enjoyed the games and found them positive and engaging. The interactions with the tutors were focused heavily on mathematics. Eighty-seven percent of the interactions involved formal mathematical language, symbols, expressions, and terms (Ke, 2013). The students may have needed more time with the games for more of an impact on their mathematical understanding.

For game-based learning in integrated steM, I refer to games in which the mathematics is integrated into the gameplay in a substantial way other than traditional practice problems. When structured well through open-ended problems, technology-based mathematics games can engage students in mathematics and help develop their conceptual understanding. I will now discuss examples from Desmos and Calculation Nation that deserve research into how effective the games can be in helping increase students' motivation and develop their mathematical understanding.

Desmos

Desmos is an online graphing calculator, but also has a suite of classroom activities available with some of the activities being game-based. In the lessons, students can share ideas and ask questions of one another. The principles that guide the Desmos' team lesson development include the following:

- Use technology to provide students with feedback as they work.
- Use the existing network to connect students, supporting collaboration and discourse.
- Provide information to teachers in real time during class (Danielson & Meyer, 2016, p. 259).

Little research has been conducted on these activities, but they have the potential to enable teachers to develop students' conceptual understanding. The games can be used to help students make connections between multiple representations, to provide students feedback, and to enable students to do non-routine problem solving with a focus on conceptual understanding. One of the activities is called "Point Collector: Lines" (Desmos, 2019a). In this activity, students enter linear inequalities with the goal of maximizing the collection of blue points while minimizing the collection of red points. Students start by adjusting the shaded area without symbolic work and then move to entering linear inequalities. Figure 2 has one of the tasks that students work on in this activity. At the end of the activity, students create their own challenges that can be solved by other students in the class. Students can make connections between representations that can aid in developing their conceptual understanding.

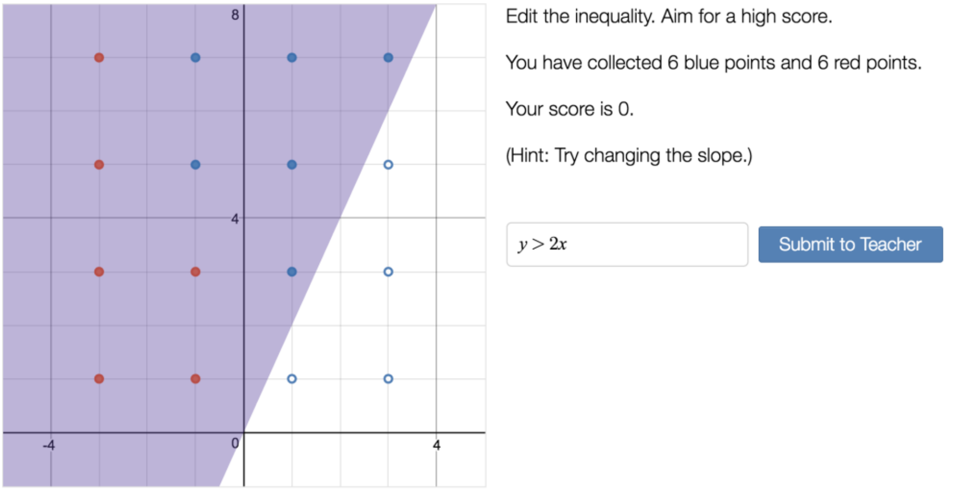

Figure 2. *Example task from point collector: lines activity.*

In my research, I had a class of middle school students use the Desmos online graphing calculator to play the game Battleship. The goal of the game was for students to make connections between symbolic and graphical representations of linear equations, as well as equations of circles. The students had voluntarily enrolled in a five-week Saturday STEM program at a large research university. The research was structured as a teaching experiment (English, 2003). The students were audio-taped and student work was collected including screenshots of the students' work in Desmos. Researcher field notes were also collected.

During the game, the students positioned ships of various sizes on a grid that their opponent could not see. Players took turns guessing the location of the ships and the game continued until all of one player's ships were sunk. The students used linear equations and restricted the domain or range so that the interval for their ships were 2 units, 3 units, and 4 units. The equations of circles were then used to try to sink opponent's ships using the roll of a die to determine the radius of each circle. Figure 3 provides an example of three guesses with equation 5 and equation 6 being hits, while equation 4 is a miss. For these examples, I placed the circles close to the line segments, but it would likely take students more turns to hit the ships. Students were actively engaged in the game, and the activity assisted students in making connections between representations of linear equations and circles (Stohlmann, 2017).

A basic version of the game, Desmos Battleship, can also be done using existing ships (see Figure 4). In this version, students can move the ships by changing the coordinates of the center of the ships before the game begins (Desmos, 2019b). Students can then take turns using either linear equations or equations of circles to try to hit their opponent's ships. In playing Desmos Battleship, it is important that students all work from the same coordinate grid by setting a common domain and range for the values of the x-axis and y-axis.

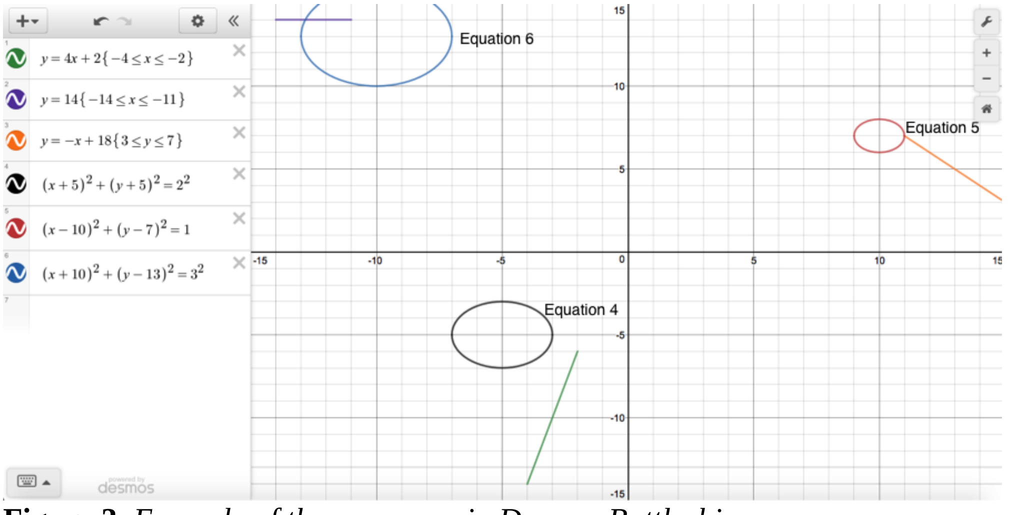

Figure 3. *Example of three guesses in Desmos Battleship.*

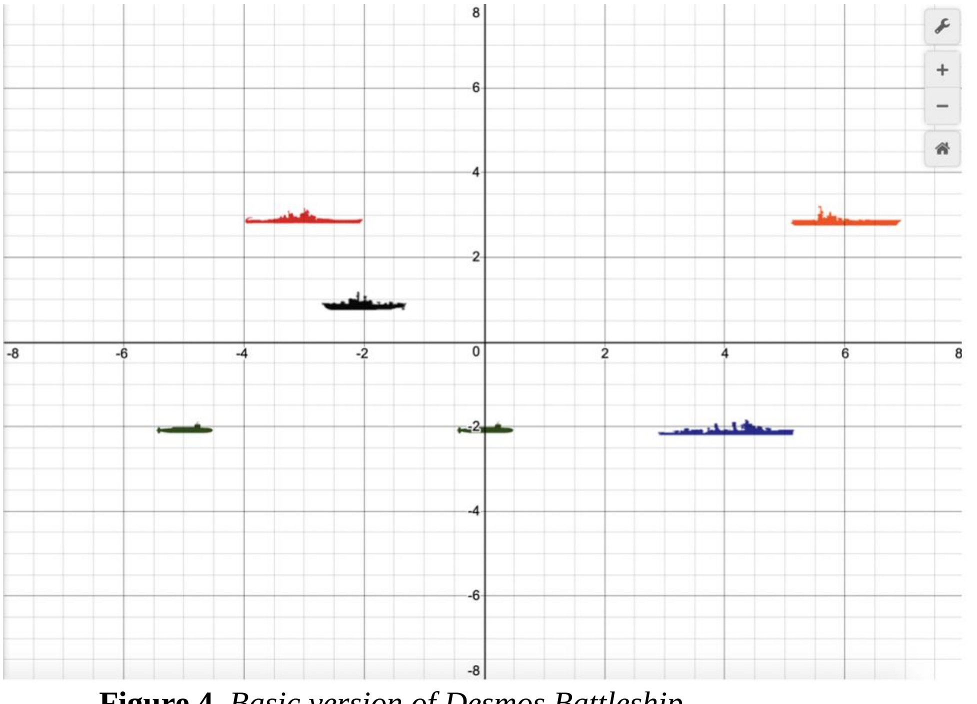

Figure 4. *Basic version of Desmos Battleship.*

I have also used the Desmos activity, Polygraph lines, with a class of middle school students in a teaching experiment (English, 2003), in which I collected student work, including the student work in Desmos, audio recordings, and researcher field notes. I analyzed the data with an interpretative approach by looking at the ways in which students used mathematical vocabulary in the game. In this game, sixteen linear graphs were given. One student selected one of the graphs and the other student asked yes or no questions to determine which graph had been selected. After playing the game several times, the students discussed what quality questions to ask and strategies for asking the least amount of questions. Through playing the game and subsequent discussions, students were able to make use of mathematical vocabulary including slope, positive slope, negative slope, horizontal line, vertical lines, origin, and quadrants (Stohlmann, In press). Desmos continues to develop their freely available activities, and further research is warranted on the effect of the games on students' mathematical understanding of linearity and motivation to learn mathematics.

Calculation Nation

Calculation Nation is a collection of free games from NCTM. Students can play the games against the computer or against other students that are logged in to the website (NCTM, 2019). The games are designed based on the vision put forth by NCTM for mathematics education in the *Principles and Standards for School Mathematics,* including the five process standards of problem solving, reasoning and proof, communication, connections, and representation (NCTM, 2000).

One of the games offered is called Ker-Splash, and it involves students opening or closing doors on ramps to collect coins that have x values, y-values, and constant values (see Figure 5). Opening or closing doors requires students to use their coins but can lead to collecting greater values depending on the path the students choose. In between turns, students combine like terms on their coins in order to free up more space on their game board to collect additional coins.

I implemented this activity with a class of middle school students that were participating in a four-week Saturday STEM program focused on game-based mathematics. Nineteen students participated. The students were ethnically diverse and reported generally doing well in mathematics. The data collection involved student work and researcher field notes.

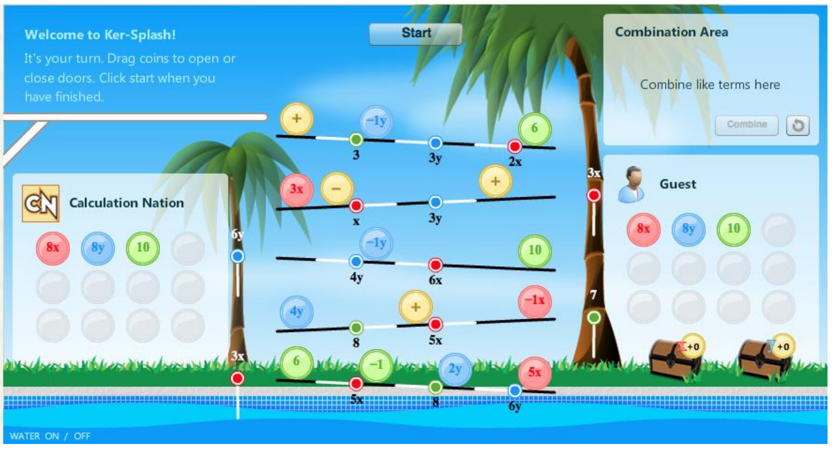

Figure 5. *Ker-Splash gameplay.*

The data were analyzed using the Quality Assurance Guide (QAG) to give the students' solutions on the open-ended activities a quality ranking (Lesh & Clarke, 2000). The QAG was designed both to evaluate solutions from mathematical modeling activities and to be used with open-ended activities as well (see Table 1).

Table 1
Quality Assurance Guide

Performance level	Description
(0) Requires redirection	The product is on the wrong track. Working longer or harder won't work. The students may require some additional feedback from the teacher.
(1) Requires major extensions or refinements	The product is a good start, but a lot more work is needed to respond to all of the issues.
(2) Requires only minor editing	The product is nearly ready to be used. It still needs a few small modifications, additions, or refinements.
(3) Useful for the specific situation given	No changes will be needed for the current situation.
(4) Sharable or reusable.	The solution not only works for the immediate situation, but it also would be easy for others to modify and use it in similar situations.

Students played this game individually versus another student in the room. After students had a chance to play this game multiple times, they met with their group to describe collaboratively a strategy on how to win the game. While playing the game, students could also ask advice from other group members. The following description was developed by one group as advice for how to do well in the game and was given a QAG score of 2:

> Pre-determine a route to send the ball, taking into account the negative numbers that will be collected. Make sure the amount you use to open or close a door will be less than the amount gained by the coins collected. Also, it should be noted, that there is limited space in which to store the coins. Don't open or close a door that will send the ball to collect coins that you can't collect because of the limited space. Don't forget to combine like terms during your opponent's turn.

Both during their turn and in between turns, students were using mathematics in order to try to do well in the game. In determining the path of the ball, students had to combine like terms for different problems. The example group's solution provided was given a QAG score of 2 because they needed to describe one more aspect of the game. In order to do well in this game, students had to keep in mind the number of x and y values of their opponent. When coins with a plus or minus sign were collected, they were added to the treasure chests on the bottom right of the screen. At the end of the game, the treasure chests served as a point multiplier for the x and y values. In this way, students improved strategic learning by thinking about what x and y values they collected in relation to what their opponent was collecting. Students found the game to be difficult, but gradually were able to develop better ideas for doing well in the game. Hearing other groups' thoughts helped this process. The five groups had an average QAG score of 1.8 from this game.

The students' mindsets were also investigated when determining the impact of the Saturday STEM program. Students played other Calculation Nation games and Desmos activities during the four weeks. There was a statistically significant difference between students' pre- and post-questionnaire scores related to their growth mindset. The students also improved on the quality of their solutions (Stohlmann, Huang, & DeVaul, 2018). Game-based learning enabled the students to participate in productive struggle. When playing games, students persevered in problem solving, trying new approaches, using all of their resources, and continuing to develop their ideas when encountering setbacks or failures. These are all characteristics that are connected with a growth mindset. If game-based learning can be used to instill growth mindsets in students, there are many benefits to implementing game-based learning within educational settings. Fostering growth mindsets improves students' academic performance (Yeager et al., 2016), increases students' motivation (Bostwick, Collie, Martin, & Durksen, 2017), and reduces inequities (Claro, Paunesku, & Dweck, 2016).

Discussion

Integrated steM is an effort to combine mathematics with at least one of the three disciplines of science, technology, and engineering based on natural connections between the subjects. One way to do this is through the integration of technology within mathematics through game-based learning, which has the potential to engage students and develop their mathematical understanding. In the past, game-based learning in mathematics education was generally limited to traditional practice problems. Moving forward, game-based learning within mathematics education should be done at the transformation level of the SAMR hierarchy (Puentendura, 2006). At this level, students engage in more higher-level thinking. The technology allows for significant task redesign or the creation of new tasks that were not feasible without the technology.

For example, during the Desmos activity, “Point Collector: Lines” (Desmos, 2019a), students make connections between representations and receive feedback in developing their mathematical understanding of linear inequalities. Students engage in higher-level thinking as they use reasoning and planning to solve challenges that have more than one valid answer. In order to determine what linear inequality to choose, students must visualize the graphical representation. They can then test their inequality and receive immediate feedback from the appearance of the linear inequality on the graph.

There are several important implications for the development and selection of games intended for use in the mathematics classroom. Games that are implemented should be worthwhile tasks. There are two main features of worthwhile tasks. First, the tasks have no prescribed rules or methods. Second, there is no perception that there is a specific “correct” solution method (Hiebert et al., 1997). With this design, students are more willing to share and discuss their mathematical thinking. It also enables students to activate their prior knowledge to assist in gameplay because there are multiple entry points.

The games selected for incorporation in mathematics education should be those that align with mathematics standards and mathematical learning objectives. In past research, this has been noted as an issue when games have been used (Chen & Hwang, 2014; Schenke, Rutherford, & Farkas, 2014). In order to ensure that the mathematics that is used in the games is made explicit, there should be time for discussion and reflection after gameplay. Teachers can also make connections to the gameplay in their other class activities. The absence of this process in which the teacher makes connections between the games and other class content and in which students are given time to discuss and think about the gaming experience has been suggested as a reason for why game-based learning might not lead to positive results (Rutherford et al., 2014).

As further games are developed, it is important that the games be designed to help students make connections between multiple representations, provide students feedback, and enable students to do non-routine problem solving with a focus on conceptual understanding. It has been noted that most game-based learning in mathematics has been limited to number and operations and algebra (Byun & Joung, 2018). Expanding the mathematical topics that are available should be done as long as the games are well-designed and enable mathematics teachers to implement effective mathematical teaching practices (NCTM, 2014).

Technology integration is an essential element of quality mathematics teaching. Technology-based games are a relevant context for students that can motivate them to engage in mathematical thinking and discussion. Further research is needed on the impact of game-based learning in the mathematics classroom when the games are well-designed and allow for open-ended mathematics.

The research discussed in this paper has demonstrated the potential of game-based learning in mathematics to be effective at increasing engagement and understanding through different representations. Desmos and Calculation Nation were two examples that were discussed, but other mathematical technologies also have the potential to incorporate game-based learning. As further work is done with game-based learning in mathematics, it is important that the games are designed at the transformation level of the SAMR hierarchy, are worthwhile tasks, are aligned with standards, incorporate multiple representations, provide students feedback, and are open-ended.

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