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Supporting primary students' learning of fraction conceptual knowledge through digital games

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Abstract

With the advent of mobile technologies, well-designed fraction apps can be used to help children gain fraction knowledge, a challenging topic for both teachers and students. The present pilot study adopted a quasi-experimental design to investigate whether children can learn fraction concepts equally well if half of the lesson time (20 min) is replaced with game-based learning. Keeping the total lesson time (40 min) identical, the control group (N = 33) received traditional instruction, and the experimental group (N = 32) was presented with a blended learning approach spending half of the class time (20 min) playing tablet-based fraction games, where each of the learners had their own tablet. The results suggested that in the posttest, the experimental group achieved similar learning gains to the control group and appear to have achieved better performance in the transfer test than the control group. This paper also discusses the efficiency of game-based learning, the mechanism of how fraction games might enhance learning, and the potential of integrating game-based learning in educational settings.

KEYWORDS
fraction learning, game-based learning, math learning, serious games

1 | INTRODUCTION

As a significant mathematical concept in daily life, fractions are crucial for later success in mathematics learning. From the perspective of numerical development, which is a process of broadening the set of numbers and requires children to accurately represent the magnitude of numbers, the learning of fractions expands children's understanding of numbers from whole numbers to rational numbers (Siegler & Lortie-Forgues, 2014). Fraction knowledge is the basis for learning decimals, percentages, and ratios, and the operations on fractions are fundamental for the formal symbolic computation of rational numbers (Ni & Zhou, 2005). Indeed, competence with fractions can predict gains in mathematics achievement (Bailey, Hoard, Nugent, & Geary, 2012). Analyses of large datasets from the United States and the United Kingdom showed that students' performance in fractions in the fifth grade uniquely predicted their general mathematics achievement in high school (Siegler et al., 2012). The relationship between fraction computation mastery and academic success even goes beyond math learning and is linked to learning in other disciplines, such as chemistry, physics, economics, and many other areas (Lortie-Forgues, Tian, & Siegler, 2015). This relationship between fraction mastery and other areas has led researchers to examine the effects of individual differences in fraction skills (Hallett, Nunes, Bryant, & Thorpe, 2012; Hecht, Close, & Santisi, 2003), the relationship between conceptual knowledge and procedural knowledge of fractions (Bailey et al., 2012; Booth & Newton, 2012), and the reasons why fractions are so difficult for children from both practical (Hansen, Jordan, & Rodrigues, 2015; Lortie-Forgues et al., 2015) and cognitive neuroscience perspectives (Huber, Klein, Willmes, Nuerk, & Moeller, 2014; Szűcs & Csépe, 2004). In addition, many other researchers have focused on designing alternative learning interventions to support fraction learning (e.g., Pelton, Francis Pelton, Smith, Anderson, Rail, & Reimer, 2017; Fuchs et al., 2013).

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Fraction learning is an ongoing challenge for both teachers and students in many countries (e.g., Martin et al., 2015; Siegler, Thompson, & Schneider, 2011). In 1978, over 20,000 students in eighth grade participated in a part of the National Assessment of Educational Progress and were asked to answer which whole number is closest to the sum of $\frac{12}{13}+\frac{7}{8}$. Only 24% of the students gave the correct answer, "2," from the options "1, 2, 19, 21" (Carpenter, Corbitt, Kepner, Lindquist, & Reys, 1980). In 2014, only 27% of the eighth graders gave the correct answer to this test item. Although substantial resources and efforts have been dedicated to improve mathematics (including fraction concepts and operations) teaching and learning and hundreds of studies have been conducted over the intervening three decades, students' performance on fraction arithmetic was not obviously improved (Lortie-Forgues et al., 2015).

1.1 | View of fraction learning as a critical stage in numerical development

Fraction learning represents a transition connecting the learning of whole numbers to the learning of rational numbers. Many researchers argue that children's difficulty with fractions is associated with their whole number knowledge and the theory of whole number bias, which refers to a tendency to apply the single-unit counting scheme of whole numbers to interpret fractions (Alibali & Sidney, 2015). Connecting meaning to different representation systems is crucial for math learning (Ni & Zhou, 2005).

The bipartite format of the fraction symbol helps children realize that rational numbers can be represented in different ways (Lortie-Forgues et al., 2015) but also represents a challenge. Children unfamiliar with fractions may see $\frac{2}{5}$ as representing two unrelated whole numbers, instead of seeing it as a part–whole relationship (Jigyel & Afamasaga-Fuata'I, 2007). The whole number bias also makes it difficult for children to understand whole numbers as decomposable units (e.g., falsely assuming $\frac{1}{4}$ as bigger than $\frac{1}{3}$ and $\frac{1}{2}+\frac{1}{3}=\frac{2}{5}$; Ni & Zhou, 2005).

Siegler et al. (2011) proposed the integrated theory of numerical development, which views fraction learning as the key point in mathematical development. Different from the theory of whole number bias, the integrated theory emphasizes the continuity between understanding whole numbers and fractions, as well as the differences between the acquisition of such, and understanding that real numbers underlie numerical magnitude. This theory also proposes that as the set of numbers is deepened, children need to understand the nature of magnitudes and connect those numbers to their magnitude, which means that all real numbers have magnitudes that can be assigned to a certain location on the number line (Siegler et al., 2011; Siegler et al., 2012). Keeping a positive mental number line in mind, children can realize that small numbers are presented on the left, large numbers on the right, and the magnitude increases from left to right (Bruer, 2008).

Students' knowledge of fraction magnitude plays a critical role in math learning (Booth & Newton, 2012). Magnitude comparison and number line estimation can both reflect children's understanding of numerical magnitudes (Siegler et al., 2011). The ability to accurately represent fraction magnitudes is crucial for both conceptual understanding and procedural mastery of fraction operations (Siegler, Fazio, Bailey, & Zhou, 2013); and this magnitude knowledge also predicts algebra readiness in middle school (Booth & Newton, 2012). Children who have a better understanding of the magnitudes of fractions can complete the fraction arithmetic operations more accurately because accurate fraction magnitude representations can help with estimating the results of fraction arithmetic operations (Siegler et al., 2011). In the early period of fraction learning, the accurate representation of magnitudes on a mental number line is of great significance (Siegler et al., 2011). Children whose number line estimation improved the most made most improvement on fraction arithmetic (Siegler et al., 2013). Fraction magnitude knowledge indicates that children may have already overcome the whole number bias and recognize that every fraction represents a magnitude, instead of deciding the magnitude based on the numerator or denominator of the fraction (Hansen et al., 2015). Understanding numerical magnitude is crucial for understanding both the whole numbers and fractions, and improving understanding of fraction magnitudes is an important objective in efforts to improve fraction knowledge (Siegler et al., 2013). If children are not able to gain knowledge of division and fractions, they may tend to give up trying to make sense of mathematics and depend on rote memorization instead in their subsequent mathematical studies (Siegler et al., 2012).

1.2 | Conceptual knowledge of fractions

There are two meaningful interpretations of fractions that pertain to rational quantity, part–whole and measurement (Hecht et al., 2003). Part–whole refers to that part of the object that is represented by a fraction symbol, and it appears to be the most accessible to school children (Mix, Levine, & Huttenlocher, 1999; Ni & Zhou, 2005). The part–whole interpretation provides the conceptual base for the other interpretations of rational numbers (Ni & Zhou, 2005). In order to understand the part–whole relationship, children need to recognize a fraction as one or more equal parts of an object, or one or more elements from within a group of identical objects (Fuchs et al., 2014). Because children already have experiences with sharing by age 5, this type of understanding is largely intuitive (Mix et al., 1999).

The second type of understanding, the measurement interpretation, mainly concentrates on "representing, comparing, ordering, and placing fractions on number lines" (Fuchs et al., 2014). A number line is useful to represent the measurement interpretation of fractions and is widely used to support the mastery of measurement interpretation (Booth & Siegler, 2006; Siegler et al., 2011). Compared with knowledge of part–whole, the measurement interpretation is less intuitive, and depends more on instruction to understand the features of fractions, and requires children to realize that there are an infinite number of fractions within a given segment of the number line (Fuchs et al., 2013). Fraction interventions with a number line are found particularly helpful for improving numerical representation

(Hamdan & Gunderson, 2017; Ninaus, Kiili, McMullen, & Moeller, 2017; Siegler et al., 2011).

1.3 | Educational potential of serious math games

Research has shown that serious games can support mathematics learning (e.g., Baker, Martin, Aghababyan, Armaghanyan, & Gillam, 2015; Gaggi, Ciraulo, & Casagrande, 2018; Gaggi & Petenazzi, 2019; Martin et al., 2015; Riconscente, 2013) and significantly increase student achievements in mathematics (e.g., Mayo, 2009) as long as they are properly designed (e.g., Pelton & Francis Pelton, 2011; Kiili, Moeller, & Ninaus, 2018). Drijvers (2015) stated that the design of the digital tool, the role of the teacher while using the tool, and the educational context in which the technology is embedded are critical factors to successfully incorporate digital technology in mathematics classes. Gaggi and Petenazzi (2019) pointed out that many technological tools intended for use to teach mathematics are designed by technology experts rather than those with insight to the problems of mathematics education. Thus, many commercial games for mathematics focus primarily on procedural knowledge rather than conceptual knowledge (Kiili et al., 2018). Besides being engaging, presenting challenges and providing feedback, educational games should present useful visual models to support sense-making, be designed to accommodate individual needs, and minimize distractions while maximizing usability and efficiency (Pelton & Francis Pelton, 2011).

The fraction games reviewed to support this study (*Refraction* [Martin et al., 2015]; *Pizza al Lancio* [Gaggi et al., 2018]; and *Semideus* [Ninaus et al., 2017]) and those both reviewed and used in this study (*Motion Math* and *Slice Fractions* [Riconscente, 2013]) were all designed with a goal of addressing these identified issues and applying best practices on the teaching and learning of rational numbers. All five of the games were either developed by the researchers themselves (Pizza al Lancio, Semideus, and Motion Math) or in partnership with educational institutions (Refraction and Slice Fractions). Conceptual knowledge of rational numbers is the focus of each game and is critical for success in playing each game. The games were created to address specific findings in rational number research. Refraction was designed based on the splitting construct, which research has shown to improve students' rational number understanding more than traditional textbook fraction curricula (Moss & Case, 1999 as reported in Martin et al., 2015). Slice Fractions and Pizza al Lancio are also based on the concept of splitting fractions, with Pizza al Lancio focusing specifically on equivalent and complementary fractions. Semideus and Motion Math were designed using number lines because fraction instruction emphasizing the measurement interpretation of fractions has been shown to be more effective than emphasizing the part–whole interpretation of fractions (Fuchs et al., 2016) and the part–whole interpretation of fractions does not support the development of the density concept or measurement interpretation (Kiili et al., 2018). Regardless of the interpretation of fractions used in the game, success in the game was dependent on the student's conceptual understanding of rational numbers rather than chance.

Other design features implemented in these games focus on the mechanics of the game play. Most of the games had one or more entry levels of play to allow students to become familiar with the interface, the controlling mechanisms, and rules of the game. Motion Math provided an intuitive interface developed after several iterations of the game to allow an easy entry to the game and provisions for quickly starting and stopping (Adauto & Klein, 2010). All the games provided immediate feedback to support understanding of the concept. In some games, scaffolding was provided (e.g., Semideus), or problems were personalized to the learner based on their performance (e.g., Motion Math). One of the games (Pizza al Lancio) left the scaffolding to the teacher and even allowed the teacher to create his or her own exercises at higher levels of the game.

1.4 | Present study

Educational games show a great potential for improving learning. Here, we intend to examine whether fraction games are helpful for fraction learning. Based on the theoretical framework of the conceptual knowledge of fractions, the fraction games can be categorized according to their target knowledge—that is, a part–whole or measurement interpretation of fractions. As for the first type of fraction games, which focus on the understanding of part–whole, some empirical studies could support the validation of these games. Through doing constant splitting in the fraction game Refraction, Martin et al. (2015) found that this game can help children to understand the meaning of fractions. In a pilot study to examine participants' cortical activations while playing Refraction, Baker et al. (2015) found that playing Refraction and math activities have similar neural processing patterns. In their study, the comparison between the pretest and posttest score of 4,128 third graders showed that playing fraction games can improve students' performance on fractions, and their understanding towards fractions gained in the game can transfer to the standard test. Another example of this type of fraction game, Pizza al Lancio, was found to possibly help children to understand equivalent and complementary fractions (Gaggi et al., 2018).

With regard to the other type of fraction games, which concentrate on using the number line to support the understanding of the magnitude of fraction numbers, a well-designed fraction game, Semideus, was found to be a useful tool to assess children's knowledge of fractions (Ninaus et al., 2017). Motion Math was also found to improve fifth graders' fraction knowledge (Riconscente, 2013).

Although technology has been frequently applied in K-12 classrooms, few studies examine the use of technology in the intermediate (elementary) mathematics setting (Carr, 2012), and most experiments appear to be conducted after students have already received instruction in fractions. Most studies at the elementary level appear to have focused on children older than 10, and few studies appear to have examined the effects of game-based fraction learning (e.g., Martin et al., 2015; Ninaus et al., 2017; Riconscente, 2013).

To extend the literature and seek evidence to support research findings, our pilot study focuses on the initial stages of fraction learning, conceptual knowledge of fractions, and on applying game-based learning in the classroom. We conducted a quasi-experimental study in a school setting, where we blended game-based fraction learning with school lessons (experimental group) and compared this learning environment with traditional classroom instruction (control group) to examine whether game-based fraction learning might provide a useful, or perhaps more efficient, approach to increasing students' conceptual knowledge of fractions. Parental permission for children to participate in this study as part of the Game-based Learning Experimental Program was obtained prior to beginning the experiment. In order to study whether the game-based fraction learning can effectively improve children's conceptual knowledge of fractions, pretest, posttest, and transfer tests were given. We proposed two hypotheses with regard to the comparison of the experimental group and the control group.

Using serious games in math learning is an innovative way to learn (Ninaus et al., 2017), and increasing numbers of studies indicate that game-based tasks could not only broaden the knowledge acquisition (e.g., Rondon, Sassi, & Furquim De Andrade, 2013; for a systematic review, see Boyle et al., 2016) but also have a positive effect on motivation and engagement (for a review, see Lumsden, Edwards, Lawrence, Coyle, & Munafo, 2016; Papastergiou, 2009). Thus, we expected that the experimental group should perform better than the control group in the posttest (Hypothesis 1).

Based on Dewey's theory that students should be engaged in significant learning experiences (Gwaltney, 1998), students' experiences with conceptually relevant apps on iPads might influence their academic achievement (Carr, 2012). While playing the two games, students should gain more experience with splitting fractions and manipulating the number line. Thus, we expected that through the learning experiences in the games, the experimental group will perform better than the control group on a transfer test, designed to examine magnitude understanding (Hypothesis 2).

In order to further investigate the different effects of fraction games using different fraction interpretations, we randomly subdivided the experimental group and presented them with two substantially different fraction games and anticipated that some additional differences might be observed. Game A, "Motion Math," emphasizes the measurement interpretation of fractions more than the part–whole interpretation of fractions, which is expected to help more with understanding the magnitude of fractions. This game focuses on helping children (8 years old and up) to master placing fractions on a number line and locating different representations of fractions on a number line. The underlying pedagogical design comes from the opinion that a number line can better be used to foster the numerical magnitude understanding, which is critical for fraction ability development (Siegler & Lortie-Forgues, 2014). Game B, Slice Fractions, emphasizes part–whole concepts and adopts splitting as the core cognitive approach, which is expected to help children aged from 5 to 12 with understanding the part–whole concept of fraction. These two games were chosen for three reasons: First, there is a consistency between the game content and the theoretical domain of fraction conceptual knowledge (Slice Fractions targets the part–whole interpretation, whereas Motion Math targets the measurement interpretation); second, they are different from the other fraction games, such as Refraction and Semideus, which place more requirements on players' problem-solving skills making them less suitable for younger children; and third, the chosen games could provide some embodied learning experiences in the learning process, especially because children can do physical splitting in Slice Fractions and physically seeking a position on a number line with Motion Math. The representation of fraction magnitude is crucial for both fraction conceptual knowledge and procedural knowledge (Siegler et al., 2013), and learning fraction knowledge through using a number line has been regarded as an effective way to learn fraction magnitude knowledge (Izsák, Tillema, & Tunç-Pekkan, 2008; Ninaus et al., 2017; Siegler et al., 2011). Thus, although our sample size was unlikely to yield significant results, and we were uncertain as to the relative benefit of the two fraction interpretations with young children, we added one additional hypothesis: Hypothesis 3, Group A will perform differently from Group B in the transfer test.

In summary, we were guided by three hypotheses in this pilot study:

Hypothesis 1 *The experimental group would perform better than the control group in the posttest.*

Hypothesis 2 *The experimental group would perform better than the control group on a transfer test, designed to examine magnitude understanding.*

Hypothesis 3 *Group A will perform differently from Group B in the transfer test.*

2 | METHOD

2.1 | Research design

This study adopted a quasi-experimental research design where two similar classes in third grade were randomly selected as the experimental group and the control group. The experimental group adopted a blended learning approach, with students spending half of the allotted class time (20 min) receiving traditional instruction, and the other half of the class time playing fraction games (20 min). The teacher for the control group taught fractions in the traditional way for the entire allotted class time (40 min). In addition, students in the experimental group were divided into two parallel subgroups: Group A played Motion Math, and Group B played Slice Fractions. Over the course of six class periods, the experimental group received 120 min of traditional instruction and 120 min playing a fraction game, whereas the control group received 240 min of traditional instruction, with the pretest, posttest, and transfer test occurring before, immediately following, and 3 days following the experiment.

2.2 | Participants

One public primary school was randomly selected from the three schools that were equipped with iPads in the Shunyi District, Beijing. Independent sample *T* tests were performed on the final math scores for all classes over the previous three semesters (fall semester in second grade, spring semester in second grade, and fall semester in third grade). We chose two third-grade classes whose mean math performance level was almost the same for the study. In total, there were 37 students initially in the control group and 39 in the experimental group. All of the students were 8 or 9 years old at the time of the study (all were born between Sep 1, 2007, and Aug 31, 2008). Each of the two classes had one child who was diagnosed with a learning disability based on the IQ and attention ability test administered by the school, and their data were excluded. Thirty-two students in the experimental class and 33 in the control class attended all the math lessons and completed a pretest, a posttest, and a transfer test. Thus, the final sample size for the experiment was 32 in the experimental group and 33 in the control group.

We divided the students in the experimental group into two randomly assigned parallel subgroups. Levene's test showed that there was no significant difference of the variance between the two groups of students' performance on the final math scores for the previous three semesters(p = .667), and an independent sample *T* test indicated that means of the final math scores of Group A and Group B were not significantly different, $t(30) = 0.493$, $p = .625$. At the end of the study, there were 18 participants in Group A (M = 91.50, SD = 7.01) and 14 participants in Group B (M = 90.27, SD = 6.92).

2.3 | Fraction games

Game A, Motion Math, uses a number line to help children understand the fraction magnitude and its corresponding point on the number line. There are three stages for learning fractions in the game: The first stage is focused on finding the corresponding point for a fraction number on the number line (e.g., $\frac{1}{3}, \frac{2}{5}$, or $\frac{3}{4}$); the second stage is the comparison of the magnitude between a fraction number and $\frac{1}{2}$; and the third stage requires players to make a connection between a fraction represented by a partly shaded circle and a corresponding point on the number line.

In Game B, Slice Fractions, children can have experiences with part–whole, as they are challenged to split an ice block with their knowledge of part–whole partitioning to match a corresponding fire block. In this game, players are expected to understand the link between the numerical magnitude and an area model, and they are expected to develop a better sense of the numerator and denominator notation.

2.4 | Study assessments

2.4.1 | Pretest and posttest

The pretest and posttest were exactly the same and were derived from published regional standardized tests and an authoritative test, which is a widely accepted way to test the learning outcome after fraction learning intervention (Riconscente, 2013). In this study, we selected some released items from the American National Assessment of Educational Progress and some items from the Third Grade Math Final exams of the past 2 years in Shunyi District. We took the following two factors into consideration when selecting the test items: the learning objectives of the unit of "Introduction to Fractions" and the proportion of daily homework questions assigned in third grade. In the end, we selected 20 items for the test and assigned 1 point for each item, giving 20 points in total. Some examples include "How many fourths make a whole?"; "What fraction of the figure is shaded?"; "Mark says $\frac{1}{4}$ of his candy bar is smaller than $\frac{1}{5}$ of the same candy bar. Is Mark right?"

2.4.2 | Transfer test: Magnitude comparison

Based on the curriculum standard in China, students in third grade need to master the comparison of fractions with the same denominator or numerator. The main pedagogical approach is to ask students to memorize the rules: "If the denominators are the same, the bigger numerator, the bigger fraction number"; and "If the numerators are the same, the bigger denominator, the smaller fraction number." The pretest and posttest mainly examined students' ability to compare fractions with the same denominators or numerators and make decisions based on the memorized rules (e.g., compare $\frac{1}{4}$ and $\frac{1}{5}$). However, whether children had mastered the magnitude comparison of more complex fraction numbers still needed to be investigated. To examine the relative transfer effect of the game experiences, we asked students to order three fraction numbers by magnitude with different denominators and numerators in each item. There were six items of this type (each item was assigned 1 point), which equates to solving 18 direct fraction magnitude comparisons along with an appropriate application of the transitive property (e.g., Please arrange the three fractions from least to greatest: $\frac{1}{3}, \frac{4}{5}, \frac{3}{4}$).

2.5 | Procedure

According to the curriculum standard for Grade Three of the Beijing Version of the mathematics textbook, the "Introduction to Fractions" consists of four knowledge points: (a) Basic understanding of a fraction; (b) Understanding a fraction number with numerator bigger than 1; (c) Simple comparison of fraction numbers with the same numerator or denominator; and (d) Addition and subtraction of fractions with the same denominators. Normally, teachers need seven to eight lessons to complete the instruction of this unit. Although the teachers of the two classes were not the same, some efforts were made to control for instructional equivalency. Before the experiment, the two teachers and researchers had a discussion and reached an agreement on the learning content of each lesson. All the teaching slides were provided by the researchers. The teachers of the experimental class and the control class taught the same content and used the same pedagogical method (i.e., following the teacher's handbook) in the first half of the lesson time; but in the last half of the lesson time, the control class spent time on doing extra exercises (with appropriate teacher assistance and feedback), and the experimental class spent time on playing computer games.

The two classes had the first lesson "Basic understanding of fractions" and then took the pretest. After that, the experimental class adopted the blended learning approach, spending half of the lesson time on instruction and half on playing the game for the following six lessons. Although students were playing the games, the teacher and researchers did not give any instruction except giving a short instruction on how to play the game before the first time playing. The teacher of the control class gave regular instruction for each of the following six lessons (40 min each time).

In the experimental group, every student was assigned an iPad/iPhone or a tablet by our researchers after the teacher's 20 min of instruction. After 20 min of fraction game playing experience, all the equipment was collected back. Although students were playing the games, teachers did not give any instruction or response to children to guarantee students' independent inquiry. Meanwhile, to minimize the chance that the students might download the game apps at home after knowing the game's name, researchers opened the game before the tablets were assigned, so students could directly click the begin button to begin the game.

In summary, we chose two fraction games with different cognitive strategies: One is part–whole, and the other is the measurement interpretation. Based on their previous math performance, the experimental group was randomly divided into two parallel subgroups. The playing time, location, teacher, instruction, and homework were all the same for students playing Game A and students playing Game B. To minimize communication between the two groups in class, the teacher gave students new seats, with students playing Game A seated on the left side and students playing Game B on the right side of the classroom. To control other instructional factors, students in the experimental groups were encouraged to work silently during the game playing time.

3 | RESULTS

3.1 | Experimental group and control group

3.1.1 | Pretest and posttest

For the 32 students in the experimental group, the mean on the pretest was 7.22, with *SD* of 2.661; the control group had 33 participants, and the mean on the pretest was 6.15 with *SD* of 2.539. Levene's test showed that there was no significant difference in variance on the pretest between the experimental group and the control group ($p = .992$), and an independent sample *T* test showed that there was no significant difference between the means of the pretests for the experimental group and the control group, $t(63) = 1.655$, $p = .103$, ES = 0.41.

On the posttest, the mean of the experimental group ($N = 32$) was 14.19 with $SD = 3.326$; the mean of the control group ($N = 33$) was 12.61 with $SD = 3.665$. Levene's test indicated that there was no significant difference ($p = .932$) in the variances of the posttest of the experimental and control groups. Within-sample *T* tests on the gain scores showed that both the experimental group, $t(31) = 15.56$, $p < .001$, $r = .662$, and the control group, $t(32) = 14.537$, $p < .001$, $r = .719$, made improvement after learning the unit of fraction knowledge. A one-tailed independent sample *T* test showed that the mean of the gain scores (posttest–pretest) of the experimental group was not significantly different from that of the control group, $t(63) = 0.815$, $p = .209$. Although the technology application was expected to enhance performance, the results did not support Hypothesis 1: The experimental group should perform better than the control group on the posttest.

3.1.2 | Transfer test

On the transfer test, the mean of the experimental group ($N = 32$) was 4.47 with $SD = 1.796$; the mean of the control group ($N = 33$) was 3.00 with $SD = 1.887$. Levene's test showed that on the transfer test, the variance of the transfer test scores of the experimental group and the control group had no significant difference ($p = .863$). A one-tailed independent sample *T* test indicated that on the transfer test, the mean score of the experimental group was significantly higher than that of the control group, $t(63) = 3.212$, $p = .001$, ES = 0.80. This result suggests that the experimental group may have had better performance in fraction comparison and gained better magnitude knowledge. However, given that no transfer pretest was administered and the control group had a lower general pretest result, this finding is uncertain. Hypothesis 2 has been tentatively supported: Through the learning experiences in the games, the experimental group will perform better than the control group on the transfer test, which examines the magnitude understanding.

3.2 | Subgroup comparison within the experimental group

In the transfer test, the mean of Group A ($N = 18$) was 4.67 with $SD = 1.680$; the mean of Group B ($N = 14$) was 4.21 with $SD = 1.968$. Levene's test indicated that the variance of the transfer test scores of Group A and Group B had no significant difference ($p = .131$), and the two-tailed independent sample *T* test showed that the mean of the transfer test scores of Group A and Group B had no significant difference, $t(30) = 0.701$, $p = .489$, ES = 0.25. Thus, we rejected Hypothesis 3: Group A and Group B in the experimental group will perform differently in the transfer test.

4 | DISCUSSION

4.1 | Educational potential of serious computer-based games

The three fraction games reviewed (Refraction, Pizza al Lancia, and Semideus) and two fraction games used in this study (Motion Math and Slice Fractions) all demonstrate the potential of serious computer-based educational games to support learning of fraction concepts. The unique affordances and efficiencies provided by the technology and the games provide experiences that can improve students' engagement and motivation as well as enhancing their understanding of fractions. The game designs, based on principles from both research on rational number learning and games, provide a model for other game developers to consider and address when designing future serious games.

4.2 | The effect and efficiency of using games in class

There was no significant difference in mean gain scores between the experimental group and the control group. With regard to the effect of using technology in a classroom setting, this result is also consistent with some studies that showed no statistical significance in mathematics achievement when using technology in a school setting, such as laptops (e.g., Rockman, 2004) and iPads (e.g., Carr, 2012). However, the results showing that the experimental group achieved a similar cognitive level as the control group although they spent half of the time playing a game could still suggest that children can gain knowledge from the experiences of playing games and that game-based fraction learning might provide a useful approach to increase students' conceptual knowledge of fractions.

From the perspective of the learning effect, the experimental group seemingly did better than the control group on the post-treatment transfer test. Results hint that the experimental group may have better knowledge of magnitude understanding than the control group. This result, if replicated with gain scores, would suggest that the proper use of educational games in teaching fractions can make learning more efficient.

Because there were no significant differences in mean scores on the transfer test between Group A and Group B, it suggests that both games have the potential to improve students' understanding of the conceptual knowledge of fractions. Game A helps students to correlate a fraction number to a point on the number line, and Game B helps students to do splitting of a shape. However, further research needs to be done to determine whether the fraction understanding gained through playing these games will have an impact on students' future learning of more complicated fraction concepts. For example, students in Group A had more experiences with a number line, and future studies are needed to see whether these students will have better performance in fraction studies than students who did not have such experiences.

4.3 | The mechanism of using fraction games to improve learning

In this study, the results showed that achievement of the experimental group was seemingly better than that of the control group when transfer was considered. So how might the fraction games help children learn? First, fraction games provide a context or model for students to construct fraction knowledge. Based on their learning experiences in the game, children may develop a deeper understanding of the concepts underlying fractions and construct a more stable model of fractions in relation to a number line.

The traditional and regular pedagogical method used in China to teach fraction comparison asks students to memorize and apply some rules: "If the denominators are the same, the bigger numerator, the bigger fraction number"; and "If the numerators are the same, the bigger denominator, the smaller fraction number." Although rote learning may help some students to acquire procedural knowledge in mathematics, this approach has limitations in helping children to develop a deeper understanding of the fraction magnitude. At the same time, with this method, children cannot deal with the comparison of more complex fraction numbers (i.e., both numerators and denominators are different). In our study, the experimental group appeared to perform a little better than the control group on the transfer test that focused on the comparison of more complex fraction numbers, which suggests that although the teacher's lectures did not cover this section of knowledge, the learning experiences in the game may have improved students' understanding of the numerical magnitude of fractions.

Compared with most of the digital fraction games that present simple quiz like questions as the main content, the two games we used in this study provided useful visual models to support the cognition process, and this is likely the main impetus for achieving any positive learning effects. Through Game A, children can build a connection between the magnitude of a fraction and its corresponding point on the number line and then sense the location of different fraction numbers based on their magnitude. In Game B, through splitting the figure, children can sense the relationship between the part and the whole and then understand the conceptual meaning of fraction. Meanwhile, the stimulus of the picture and the splitting process helps children to build the connection between an area of a shape and a fraction number. From the perspective of learning experiences, it seems that the integration of game-based learning and traditional instruction can expand children's cognitive experiences, by providing a context within which to gain knowledge, as well as some interactive visual/cognitive models that cannot be provided in a textbook.

Emotional factors also greatly influence math learning. Math anxiety correlates with poor performance in math tests, and good performance correlates to positive emotions (Riconscente, 2013). Both of the games in our study are very attractive based on the setting and level. Because children can make many attempts in the game, they do not need to worry about making mistakes, so they can easily get engaged in learning (Ronimus, Kujala, Tolvanen, & Lyytinen, 2014). Compared with regular school teaching, children tend to concentrate more on game-based learning (e.g., Chung & Chang, 2017; Liu, 2017; Singaravelu, 2008). Normally, students cannot maintain attention for 40 min in a lesson, and playing games in class can help to relieve some learning fatigue, while enjoying a pleasant learning experience. The fun features of the game may also be an important factor to motivate children to learn fractions consistently.

4.4 | Limitations

In this quasi-experimental study, four students in Group B were not able to attend all the lessons due to illness, and as a result, there were 18 students in Group A but only 14 students in Group B, this may have had an effect on the results. The final sample size for both Groups A and B was relatively small, and this may have impacted whether the study could show significant differences; a positive result may be found in ongoing research with a larger sample size. Similarly, because no pretest was administered for the transfer test, we are not confident that gains observed are entirely treatment based; to address this limitation, a future study might integrate a transfer test into both the pretest and posttest. Finally, future studies might investigate the relative effects on fraction understanding of fraction games founded on different underlying fraction models (i.e., part–whole or measurement) and the effects of playing such games on students' affective response to fraction learning.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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