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Impact of a game-based intervention on fraction learning for fifth-grade students: A pre-registered randomized controlled study

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Abstract

Background: Digital game-based learning is gaining increased attention from both researchers and educators for improving mathematics instruction. However, the evidence for game-based learning is mixed and research with rigorous research design and analyses are limited.

Objective: Here, in a pre-registered randomized controlled study, we investigated whether a fraction game designed collaboratively by educational experts and professional game developers may serve as a useful tool to enhance students' fraction knowledge.

Methods: We assigned French fifth graders to either an experimental group who used the game ($n = 110$) or a control group ($n = 78$) who received traditional instruction on fractions. Fraction knowledge was assessed pre- and post-intervention.

Results: Results show that students in the active control group had superior overall fraction performance than students in the experimental group at the end of intervention. However, the game had a positive effect on decimal learning. We also found a positive relation between game performance and overall fraction knowledge scores at post-test.

Contribution: The study highlights the importance of game metrics as indicators of personalized assessment tools. Given the increased usage of games in learning mathematics and the equivocal results on the effectiveness of these games, our study also highlights the importance of pre-registration and randomized controlled studies.

KEYWORDS

fifth graders, fraction, game metrics, game-based learning, mathematics

1 | INTRODUCTION

Fraction knowledge acts as a bridge between middle school and high school mathematical development. As such, it forms a crucial component of mathematical proficiency (Bailey et al., 2012). For example, fraction knowledge in fifth grade predicts gains in algebra and calculus (Siegler et al., 2012). Fraction knowledge is also associated with success in other domains like biology, chemistry, and physics (Lortie-Forgues et al., 2015). From a life skills perspective, individuals often encounter relational numerical concepts in their environment (Nunes & Bryant, 2008). For example, fractions are used every day when baking, estimating time or distance, measuring length, and making health

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and financial decisions (Rosenberg-Lee, 2021). However, fractions are particularly difficult to learn and teach (Pant, 2019). The general aim of the current study was to assess the impact of a game-based intervention on fraction learning outcomes of fifth grade students.

2 | DIFFICULTIES WITH FRACTIONS

Difficulties with fraction learning can be attributed to at least two reasons. First, students often experience difficulties in understanding the holistic magnitude of fractions, due to the so-called 'whole number bias' (Ni & Zhou, 2005; Van Hoof et al., 2013). The bias leads individuals to process the components of fractions (numerator and denominator) separately, usually because students overgeneralize natural number properties when processing rational numbers (Ni & Zhou, 2005). Second, students often struggle to make connections between the various interpretations of fractions. Behr et al. (1983) suggest five ways to interpret fractions: Part-whole, ratios, quotient, operators, and measurements. For instance, the part-whole subconstruct helps understand the concept of equipartitioning, the measure subconstruct focuses on the property of density of rational numbers, the operator interpretation aids in fraction multiplication, and the ratio builds the foundation for fraction equivalence (Charalambous & Pitta-Pantazi, 2007). Over-reliance on any one of these interpretations leads to constraints on understanding fractions (Kieren, 1993) and common struggles include the inability to comprehend the infinite ways in which rational number magnitudes can be represented (e.g., $2/4 = 1/2 = 0.50$) (Vamvakoussi & Vosniadou, 2010) Thus, successful learning of fractions involves a balanced understanding of all the different interpretations as well as their inter-relationships.

3 | DIGITAL GAME-BASED LEARNING AND MATHEMATICS EDUCATION

Research on digital game-based learning (DGBL) has shown potential for learning abstract concepts, supporting classroom instruction, and presenting content engagingly and innovatively (Al-Azawi et al., 2016; Prensky, 2001). However, a recent meta-analysis examining the effectiveness of DGBL in mathematics learning notes a low percentage (11%) of studies assessing the empirical effectiveness of games (Byun & Joung, 2018). Of the studies that did examine the effectiveness of games, the authors found a moderate overall effect size of $d = 0.37$. Additionally, the study also notes a staggeringly low percentage (7%) of authors with a background in mathematics education (Byun & Joung, 2018). Therefore, to better understand the effectiveness of DGBL in learning mathematics more empirical research studies with mathematics experts should be conducted.

The mixed findings on the effectiveness of DGBL require more rigorous experimental studies, with random assignment of participants in experimental and control groups and pre-registration of hypotheses, research design, and methods to limit analytic flexibility. It also requires a critical examination of the limitations of game-based learning. Specifically, there are at least two difficulties reported in the literature on digital games. A first difficulty pertains to the pedagogical validity of the games, that is, the game design and transfer of knowledge and skills (Linderoth, 2012; Tobias et al., 2014). Not all games are inherently educational and have the potential to facilitate learning (Linderoth, 2012). Because most technological tools focused on mathematics learning are generally designed by technologists or game experts (Gaggi & Petenazzi, 2019), they do not necessarily use insights from teachers or mathematics education researchers. A second difficulty is the ability to transfer the skills learned in the game to real-world problems or assessments (Barnett & Ceci, 2002; Rick & Weber, 2010). Indeed, even if games might improve some sets of skills, it is often not clear that this could be transferred to other related tasks. Therefore, it is important to use pre and post-test standardized instruments assessments to evaluate the effects of interventions (Bertram, 2020).

4 | DGBL AND FRACTION LEARNING

To our knowledge, there are five serious video games in the domain of fraction learning mentioned in the literature. Refraction (Martin et al., 2015) and Slice fractions (Cyr et al., 2019) are based on the concept of splitting fractions (part-whole interpretations of fractions). Motion math (Riconscente, 2013) and Semideus (Kiili et al., 2018) are designed based on the measurement interpretation of fractions and relied on fraction number lines. Finally, Abydos (Masek et al., 2017) includes high-level fraction concepts such as equivalent fractions, identifying least common multiples, addition, and subtraction of fractions.

While studies evaluating the games described above indicate some effectiveness, these studies (and the games) have several important limitations. First, the games all focus on a specific interpretation of fractions (Behr et al., 1983). Over-reliance on any one interpretation of the fraction may lead to misconceptions and constraints in understanding (Kieren, 1993; Pitkethly & Hunting, 1996). Second, some of the studies evaluating the effectiveness of games tend to have modest sample sizes, which raises power issues (Brysbaert, 2019). Third, studies evaluating Semideus (Ninaus et al., 2017), Refraction (Martin et al., 2015), and Motion math (Riconscente, 2013) did not include a control group. This makes it impossible to (1) know whether learning gains can be attributed solely to the game and (2) conclude about the effectiveness of the game relative to other methods of rational number instruction (including traditional classroom instruction). Finally, studies have not always used an exhaustive, standardized, or country-based assessment to test for fraction skills (Kiili et al., 2018; Martin et al., 2015). The studies that did use fraction test items from standardized assessments also vary in their selection of the test items, raising the possibility that the results are dependent upon that selection (Masek et al., 2017; Riconscente, 2013). This highlights the need for pre-registering hypotheses and methods when assessing the impact of an intervention (Bertram, 2020; Nosek et al., 2018). However, to our knowledge, there has not been any preregistered study on DGBL and fraction learning.

5 | THE CURRENT STUDY

In the current pre-registered randomized controlled study, we aimed to evaluate the effectiveness of a game-based training of rational number skills on fraction knowledge of children in fifth grade. The game, that is, Math Mathews Fraction, was designed by a math education researcher to ensure that the content of the game was specifically aligned with the French mathematics curriculum standards. The aim of the game was to complement fraction learning in the classroom with a focus on understanding and building connections with the multiple interpretations of fractions. Based on bridging the multiple interpretations of fractions (e.g., part-whole, measurement, and operator), we expected that Math Mathews Fractions might serve as a tool to help teachers teach the various interpretations of fractions in the classroom. In addition, the game includes elements of a personalized learning environment such as increased complexity of levels and modules, specific help through the journal feature, repetition of tasks depending on individual level performance, and real-time feedback for each user (wrong attempts decrease total points).

We pre-registered three hypotheses via the Open Science Framework. First, we expected a higher overall score on a comprehensive fraction knowledge test for the experimental group as compared to the control group at the end of the intervention. Second, we expected this effect to be specific to fraction learning, with no post-test difference in performance between the control and the experimental group on arithmetic fluency. Third, prior literature notes that learning with games increases student motivation and engagement which might lead to positive affective experience thereby desensitizing math anxiety (Chang et al., 2016; Ramirez et al., 2018), thus we expected the intervention might have an effect on children's mathematics anxiety levels (with higher post-test mathematics anxiety scores in the control group as compared to the experimental group).

6 | METHODS

6.1 | Participants

Participants were 193 fifth graders recruited from five public schools in Lyon, France. Data were collected for 2 years halfway during the school year (typically around the time when fraction instruction was practiced in class), that is, from December 2018 to February 2019 for year 1, from January 2020 to February 2020 for year 2. The experiment was approved by the school board and was performed following the ethical standards established by the Declaration of Helsinki. Parents gave their written informed consent and children gave their assent to participate in the experiment. Three schools were located in a neighbourhood in which the median equivalized disposable income is above the national median equivalized income of € 20,809 (i.e., € 26,190), whereas two schools were located in a neighbourhood in which the median equivalized disposable income is below that national median equivalized income (i.e., €19,032) (https://www.insee.fr/fr/statistiques). Enrolment in all public schools in France is mostly based on the neighbourhood in which the children live and is free of charge for parents. Therefore, the sample enrolled was most likely representative of the population of the district.

From the original sample of 193 students, children were excluded if they had a diagnosed disability ($n = 3$) or if their parents did not give consent ($n = 2$). Therefore, our final sample consisted of 188 students (mean age = 10.5; SD = 0.32; 91 males). The classes were randomly assigned to the two conditions (control and experimental) by lottery. The control group had 78 students and the experimental group consisted of 110 students.

6.2 | Pre-registration

The study was pre-registered using the AsPredicted.org template via the Open Science Framework at https://osf.io/zxm5c/. There were four main differences with the pre-registration. First, frequentist analyses are presented along with the pre-registered Bayesian analyses. Second, a delayed post-test could not be conducted in the second year due to Covid-19 and school closures in France. Third, the total number of children that were analysed ($n = 188$) was less than those pre-registered ($n = 240$). This was because of absenteeism, lack of parental consent, and diagnosed disability. This was also because we realized that the game was not appropriate for 4th graders and had to reorient our recruiting strategy towards fifth graders. Finally, the mathematics anxiety test used in the first year (Carey et al., 2017) was replaced in the second year by a more detailed test (Henschel & Roick, 2018) due to the difficulties encountered by students when filling the questionnaire. Particularly, students had difficulties understanding several sentences in the French translation of the original questionnaire.

6.3 | Measures

Both groups were tested for their (1) arithmetic fluency, (2) mathematics anxiety, and (3) fraction knowledge at two separate time-points (before and after the intervention). For information on the justification of measures check the pre-registered document.

First, arithmetic fluency was measured using the Math Fluency subtest of the Woodcock-Johnson III battery. The Math Fluency subtest is a timed test in which participants have to solve as many single-digit additions, subtraction, multiplication, and division problems as they can within 3 min (Woodcock et al., 2001). Raw scores range from 0 to 160. The test–retest reliability of the math fluency subtest is high, indicating temporal stability ($r_{12} = 0.95$).

Second, mathematics anxiety was measured using two different tests. Both these tests have been uploaded on the OSF (https://osf.io/fpzmr/). The modified abbreviated mathematics anxiety scale (Carey et al., 2017) was used in 2019 whereas the affective and cognitive mathematics anxiety test was used in 2020 (Henschel & Roick, 2018). For both tests, items were read aloud by the researcher or the teacher. Children were also given extra time, in the end, to fill the questionnaire or clarify their doubts. Both math anxiety measures have a high internal reliability (Cronbach's α is 0.89 and 0.92).

Third, fraction knowledge was assessed using a test that was designed in accordance with the French national curriculum standards. The test consisted of 24 questions with different items. Specifically, it assessed six competencies (Rodrigues et al., 2019): fraction concepts, fraction arithmetic, symbolic representation, fraction number line, word problems, and decimals. *Fraction concepts* were measured using a total of 10 questions (question no. 1, 2, 3, 4, 5, 10, 11, 16, 17, 18). The items assessed part-whole understanding of area models, set models, equivalence, comparing fractions, ordering fractions, and, mixed fractions. *Fraction arithmetic* skills were measured using 4 questions (Q. 12, 13, 19, 20). Each question had 3–5 items and participants were presented with addition and subtraction problems written in symbolic form. *Symbolic representation* was tested using two types of questions (Q. 6, 7) consisting of 4 items each. The first type was identifying the verbal representations of fractions (e.g., three halves) and writing the symbolic form ($\frac{3}{2}$). The second type was identifying the symbolic form and writing verbal representation. *Fraction number line* was assessed using two questions (Q. 8, 9). The questions involved placing four fractions on the number line (e.g., $\frac{8}{5}$, $\frac{4}{5}$, $\frac{16}{5}$, $\frac{10}{5}$ Q. 8a), and the other type involved finding the fractions marked on the number line. *Word problems* skills were measured using four-word problems (Q. 21, 22, 23, 24). Lastly, *decimal* skills were measured using two questions requiring conversion of the fraction to decimals and vice-versa (Q. 14,15).

Cronbach's α ranged from 0.719 to 0.832 across all six measures (fraction concepts: 0.815, arithmetic skills: 0.830, symbolic representation: 0.771, number line: 0.832, word problems: 0.719, decimals: 0.822), indicating acceptable to very good internal consistency. The inter-rater reliability for categorization of questions by three independent researchers for all the above measures was very good (Cohen's kappa = 0.84).

The fraction achievement test was scored using a template with correct answers by two independent research assistants and a researcher. The data entry was checked independently by two other research assistants. Any discrepancy in scoring or data entry was discussed among the three coders and if one of the coders was not convinced the item was marked for rechecking by a researcher in mathematics education in the lab. The inter-rater reliability between the final two researchers was very strong (Cohen's kappa = 1). For each item, the correct response was scored 1 and the incorrect/ no response (marked as 'do not know/?' by the participant) was scored 0. The percentage correct was calculated for each of the six competencies.

6.4 | Fraction game

Math Mathews Fraction is an educational video game developed by the studio Kiupe (https://osf.io/xn2k3) in collaboration with a mathematics education researcher (the last author of the current paper). The game is about the adventures of a pirate who has to collect gems (treasure) by solving different challenges (i.e., modules). The game progression is in line with the objectives and curriculum standards of the French school system for children aged 9–12. Thus, the play situations (i) increase in difficulty throughout the game and (ii) remain appropriate for children aged 9–12.

The modules are typically different types of questions involving rational numbers. Players must choose or construct the answer to proceed further. There are 13 modules based on the curriculum standards in the French school system (Table 1 and Figure 1). A detailed

TABLE 1 Description of the game modules and objectives in the French national curriculum

Curriculum objective	Modules	Fraction competencies
Make connections between different representations of fractions	Broken wheel	Fraction concept (part-whole, area = circle)
	Dragon	
Use fractions to divide quantities	Warrior	
	Weight door	
Place fractions on a graduated number line	Trapped passage	Fraction number line
Identify fractions on a graduated number line	Graduated bridge	Fraction number line
Use fractions to measure quantities	Totem	Fraction concept—Measure, length
Make connections between different representations of fractions	Organ	
Compare two simple fractions	Skull	Fraction concept—Ordering
Sorting fractions in ascending/descending order		
Establish equality between two simple fractions/equivalence	Pit	Fraction concept—Equivalence
	Trapped chest	Fraction arithmetic (Level 7–9, 11)
Compare two simple fractions	Spider	
Add fractions with the same denominator		
Solve word problems using simple fractions	Riddles	Word problem

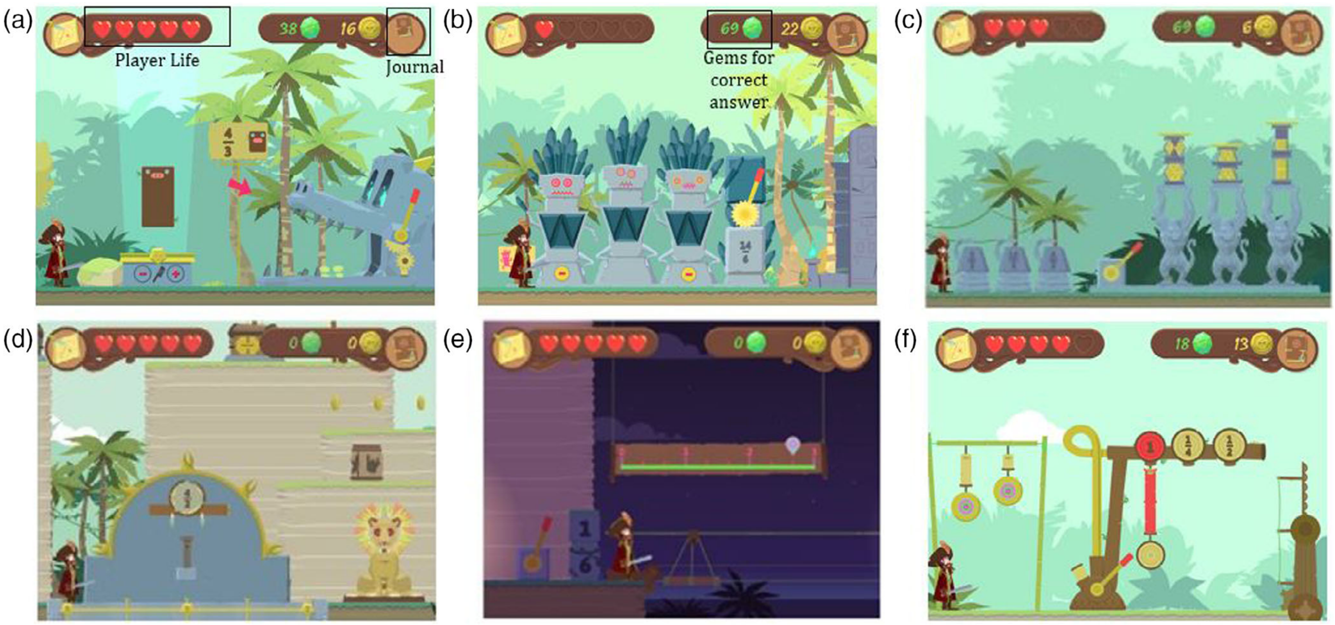

FIGURE 1 Examples of the interface of the game showing the different modules that include different representations of fractions. (a) Here the player has to split the block to feed the dragon 4/3. (b) Player must select 14/6 of the trapezoid surfaces to proceed. Here, the player has to select seven triangle blocks from the total of nine blocks. (c) Player must associate each fraction (3/2, 10/6, 6/3) to the shaded hexagons, trapezoids, and, rectangles. (d) Player has to place the fraction 4/2 on the 0–2 number line. (e) Player must move the square number blocks to indicate the fraction marked on the number line. (f) Player must find the segment that measures 1/4 and 1/2 of the red segment

description of these modules and the corresponding progression in the curriculum standards is uploaded on the OSF (https://osf.io/6efzd/). Each module is presented 10 times throughout the game and can be presented several times during a level. The game consists of 12 levels. Each level contains different modules which vary in difficulty depending on the level of the game. The modules include specific fraction competencies like fraction concepts, fraction arithmetic, word problems, fraction number lines, and decimals (Table 1). The game was played through an application pre-installed on the tablets. Each student had to create a profile with a pseudonym before starting the game. The first level was preceded by a small video to familiarize players with the basic controls and rules of the game as well as to guide them about the objective of the game. The game was configured in a way that each player had to correctly perform in all the modules that were visible to them in the game to finish the levels and only then could they proceed to the next level. The interface of the game also consists of a *journal* and a *calculator*. The journal was used to teach the player about the rules of each module and the fraction concepts involved in the module. Students could consult the journal anytime during the game by tapping on the icon.

6.4.1 | Game design principles for Math Mathews Fractions

While Math Mathews Fractions was not explicitly conceived using specific principles in minds, it nonetheless includes some key elements of game design like: identity, interactivity, immersiveness, adaptive problem solving, feedback, and freedom of exploration (Annetta, 2010; Kucher, 2021). For example, the game offers the players the choice to select their avatars before beginning the game. Prior research has indicated the importance of identity as a core element of educational game design (Annetta, 2010). Indeed, players who had more choice of avatars to represent themselves reported greater course satisfaction and engagement than the ones who had a choice only between male or female characters (Annetta, 2008). Math Mathews Fractions also includes meaningful interactivity between individual players and the game content. For instance, the game offers an engaging storyline where the pirate (player) has the goal to collect maximum gems and coins by solving fraction problems. Importantly, the game increases in complexity of content and gameplay, thereby providing challenge to the players and ensuring effective learning aligned with the curriculum standards. In addition to identity and interactivity, the game also consists of real-time feedback in the form of points accumulation (gems) and progression of levels (Shute, 2008). However, future versions of the game could focus on a more explanative feedback mechanism, which could provide students efficient ways to monitor their misconceptions (Mayer & Johnson, 2010). Lastly, the players have the freedom to choose different pathways in the game within a level.

6.5 | Game metrics

The Math Mathews Fraction game recorded the player's individual scores on each level. The data logged as per the pseudonym data profiles included:

i. Maximum level achieved: the highest level that a player successfully completed
ii. Number of attempts on each mini-game: number of times a player re-tried a module in a level before they moved on to the next module.
iii. Maximum points on a module: number of gems that could be obtained when the player correctly solved the module in a level.
iv. Obtained points on a module: number of gems that player collected on each module within a level.
v. Game performance: (obtained points/maximum points) × 100.

6.6 | Procedure

The study was conducted in eight sessions for 4–5 weeks. Before the study, teachers were presented with the objectives of the game and the practice book that could be used in the control group. Teachers were also given the tablets to play and understand the game before the sessions started. They were free to use the game either as part of instruction in the classroom or as independent work time for students. Thereafter, in the first week of experimentation, all students completed the pre-tests on two separate days. The first day included the arithmetic fluency and mathematics anxiety test and the second day assessed the untimed fraction achievement test. The following 4 weeks included paper-based practice sessions for the control group and individual game sessions for the experimental group (two 45 min pre-tests—four 45 min game-play and paper-based practice sessions—two 45 min post-test sessions).

6.7 | Implementation

6.7.1 | Active control group

Four teachers participated in the active control group. The sessions in this group were mostly divided into three-part. First, the session started with an introduction to specific fraction concepts. Second, after introducing students to the concepts, practice problems were solved either individually or in groups depending on the teacher's mode of instruction. All teachers were asked to select the problems from a specific book (Anselmo & Zucchetta, 2018) to match the competency and rigour of the experimental group (Figure 2). The exercise

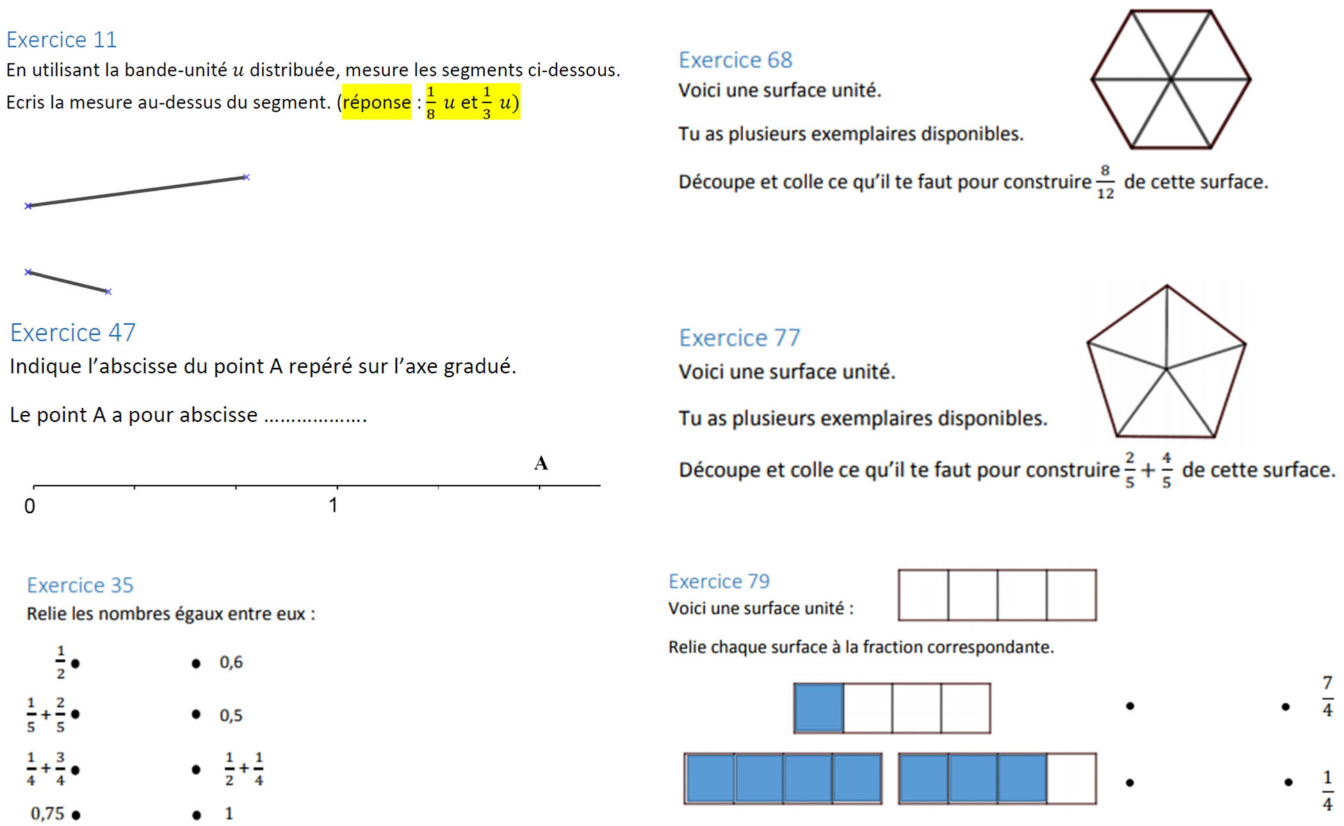

FIGURE 2 Examples of exercises practiced in the control group (in the original French). In Exercise 11, students have to using the unity band to measure the length of segments. In Exercise 47, students have to indicate the value of the marked point A on the number line. In Exercise 35, students have to match the equal numbers in the two columns. In Exercise 68, students are given different cut-outs of shapes. They have to cut and paste the shapes that correspond to 8/12 of the surface shown. In Exercise 77, students are given different cut-outs of shapes. They have to cut and paste the shapes that correspond to the sum of 2/5 + 4/5 of the surface shown. In Exercise 79, students are shown with a total surface. For each coloured rectangle on the left, they have to choose the correct fraction on the right

bank used by the teachers in the control group is also uploaded on the OSF. The last part of the session included a whole-group discussion of the problems with the teacher. The number of problems that were solved in one session was variable and depended on individual teacher practice.

6.7.2 | Experimental group

Six teachers participated in the experimental group. In the first session before starting level 1 all the students entered their initials to create a profile on the tablets and watched a short 1-min demo video to understand the game mechanics and the features of the game (e.g., journal, calculator). Students played the game individually on their devices but were allowed to seek guidance and help from their peers, teachers, and the experimenters. All students had the same device for all four sessions and logged in to their profiles to maintain the individual performance logs. While teachers were encouraged to use the game as part of instruction no teacher used the game to teach. That is, all the students played the game throughout the session asking for support or help only when they were stuck on a level or a problem. Even though the game included sound effects, the students had to keep the game muted in the classroom.

6.8 | Analyses

Missing data were removed listwise for the specific tests analysed (less than 15% of the data on each test). Post-test arithmetic fluency scores, post-test mathematics anxiety scores (separately for each year), and post-test fraction achievement scores were entered in frequentist analysis of covariances (ANCOVAs) with the between-subject factor Group (control, experimental). Pre-test scores were entered as a covariate to control for potential differences in baseline scores. Because frequentist statistics do not provide evidence for a null hypothesis, we turned to Bayesian statistics (Lee & Wagenmakers, 2013; Morey et al., 2016) to estimate the strength of evidence for both the null (no difference between groups, H0) and alternate hypothesis (difference between groups, H1). Following Jeffreys (1961), a $BF < 3$ was considered anecdotal evidence, a $3 < BF < 10$ was considered substantial evidence, a $10 < BF < 30$ was considered strong evidence, a $30 < BF < 100$ was considered very strong evidence and a $BF > 100$ was considered extreme evidence that our data are more likely under the alternate than the null hypothesis (i.e., BF_{+0}) or under the null hypothesis than the alternate hypothesis (i.e., BF_{0+}). Post-test scores were entered as outcome variables of Bayesian ANCOVAs with the between-subject factor Group (control, experimental) and pre-test scores as covariate. Finally, in an exploratory analysis, we also calculated frequentist and Bayesian bivariate semi partial correlations between the game metrics and the fraction competency scores. All analyses were performed with the JAMOVI software (The Jamovi project, 2019).

7 | RESULTS

7.1 | Baseline characteristics

The baseline characteristics for both groups and the in-game performance of the experimental group is reported in Table 2. The sample in the control group consisted of 78 students and the experimental group

TABLE 2 Baseline characteristics for control and experimental groups

	Paper-based tests		In-game metrics
Measure	Pre-test Mean (SD)	Post-test Mean (SD)	Mean (range)
Arithmetic fluency (*WJ-III*)			
Control	99.50 (21.89)	106.14 (20.30)	
Experimental	100.93 (18.52)	108.79 (20.68)	
Mathematics anxiety (Carey et al., 2017)			
Control	17.75 (5.47)	18.21 (7.54)	
Experimental	19.03 (6.27)	17.79 (6.64)	
Mathematics anxiety (Henschel & Roick, 2018)			
Control	1.84 (0.50)	1.71 (0.49)	
Experimental	1.76 (0.54)	1.63 (0.52)	
Fraction knowledge assessment			
Control	37.87 (16.62)	54.15 (19.94)	
Experimental	46.16 (19.82)	55.24 (18.19)	
Math Mathews Fraction (*Experimental Group*)			
Maximum level attained			7.71 (2–12)
Game performance			78.42 (56.33–98.83)

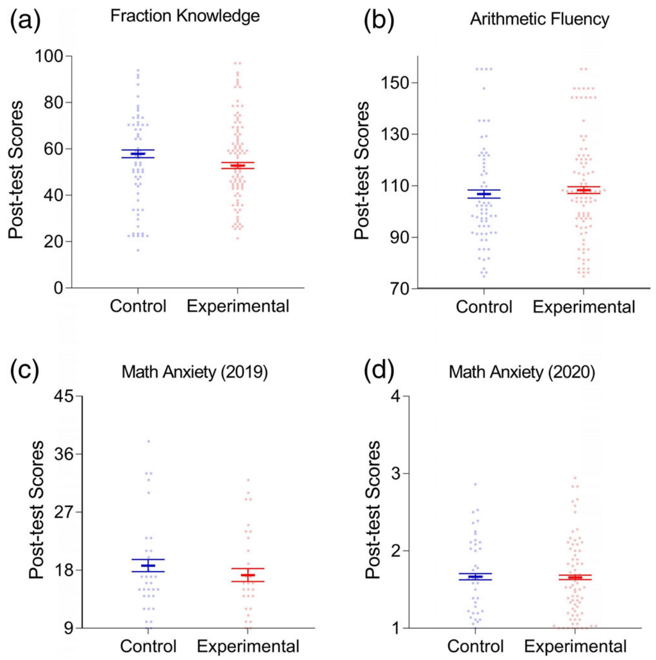

FIGURE 3 Student performance in the post-test (after controlling for baseline scores) for the control and experimental group. (a) Fraction knowledge. (b) Arithmetic fluency. (c) Mathematics anxiety year 2019. (d) Mathematics anxiety year 2020. Each dot represents the score of a student. Error bars depict SE of the mean

consisted of 110 students. Participants from the two groups did not differ in age (BF_{01} = 4.57, F (1,182) = 0.642, p = 0.424) and gender (χ^2 (1, N = 188) = 1.58, p = 0.209). At baseline, the groups did not differ in terms of arithmetic fluency (BF_{01} = 5.29, F (1,159) = 0.20, p = 0.656) or math anxiety (2019: BF_{01} = 2.82, F (1,59) = 0.728, p = 0.397; 2020: BF_{01} = 3.72, F (1,108) = 0.538, p = 0.465). Fraction pre-test scores were lower in the control than in the experimental group (BF_{10} = 5.95, F (1,163) = 7.80, p < 0.006). Note that pre-test scores were entered as a covariate in our main analyses to control for such potential differences in baseline scores. In terms of game performance, in the experimental group, students completed about seven levels (mean = 7.71) of the game with about 43% completing level 8 and beyond (*range* 2–12). The average overall game performance was 78.42% with a *range* of 56.33–98.83.

7.2 | Confirmatory findings

Post-test scores for each group are shown in Figure 3. First, in contrast to our prediction, fraction post-test scores were lower in the experimental than in the control group after controlling for pre-test scores (F (1,162) = 5.66, p = 0.019, η^2_p = 0.034), though Bayesian analyses only indicated anecdotal evidence for this difference (BF_{10} = 2.16). Second, in line with our predictions, there was no

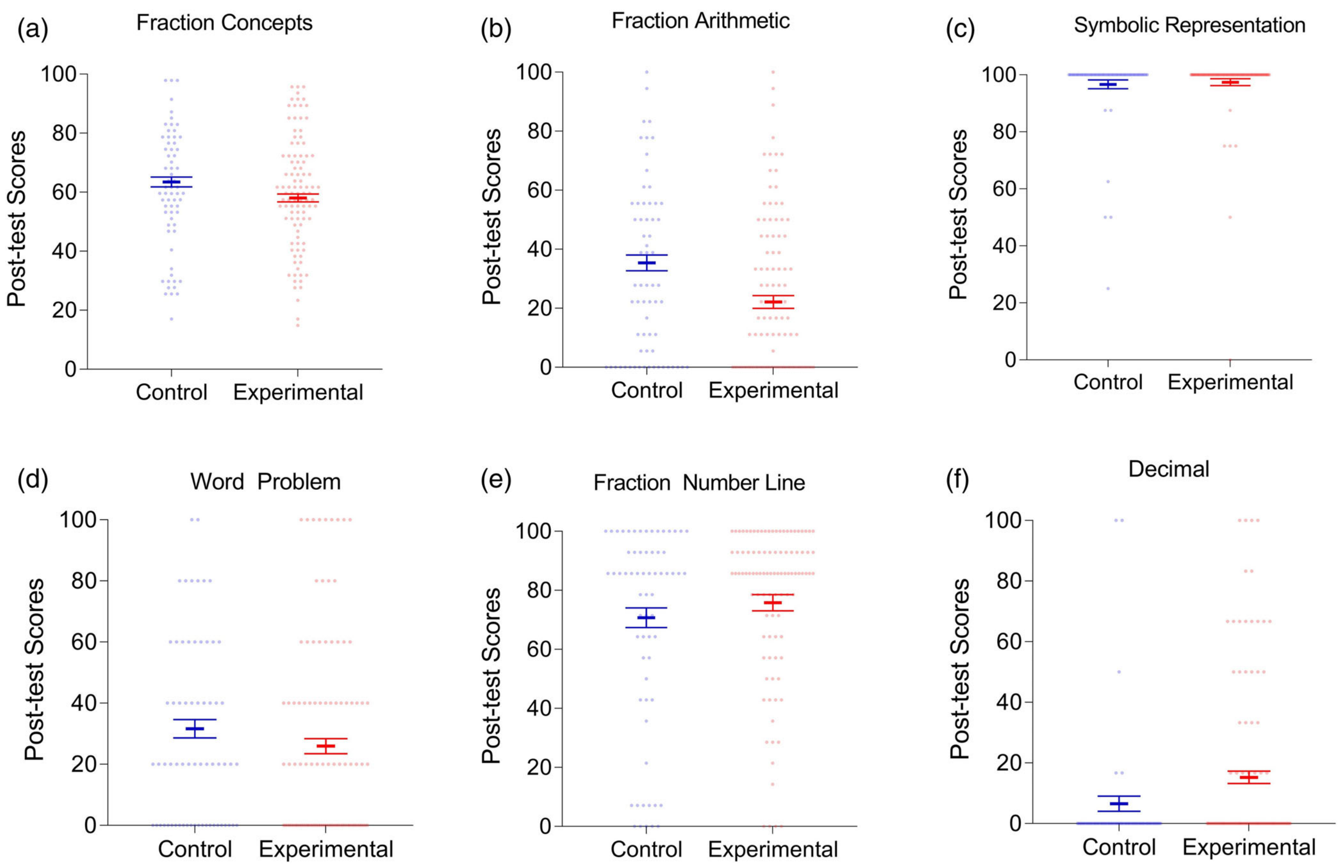

FIGURE 4 Student performance on different fraction competencies in the paper-based post-tests (after controlling for baseline scores) for the control and experimental group. (a) Fraction concepts. (b) Fraction arithmetic. (c) Symbolic representation. (d) Word problem. (e) Fraction number line. (f) Decimal. Each dot represents the score of a student. Error bars depict SE of the mean

TABLE 3 Semi partial correlations between fraction post-test scores and game metrics for the experimental group

			1.	2.	3.	4.
1.	Fraction post-test scores	*r*	-	-	-	-
		BF_{10}				
2.	Game performance	*r*	0.292**	-	-	-
		BF_{10}	**6.57**			
3.	Maximum level attained	*r*	0.182	0.356***	-	-
		BF_{10}	0.573	**50.093**		
4.	Number of attempts	*r*	−0.038	−0.601***	0.294**	-
		BF_{10}	0.139	**5.012e+7**	**6.999**	

Note: BF_{10} indicates the strength of the evidence for the alternative (there is an association between the variables). Bayes factors BF < 3 are considered anecdotal; 3 < BFs < 10 are considered substantial; 10 < BFs < 30 are considered strong; 30 < BFs < 100 are considered very strong and BFs > 100 are considered decisive. BFs > 3 are indicated in bold. All variables are controlled for baseline fraction pre-test scores.
***$p < 0.001$. **$p < 0.01$. *$p < 0.05$.

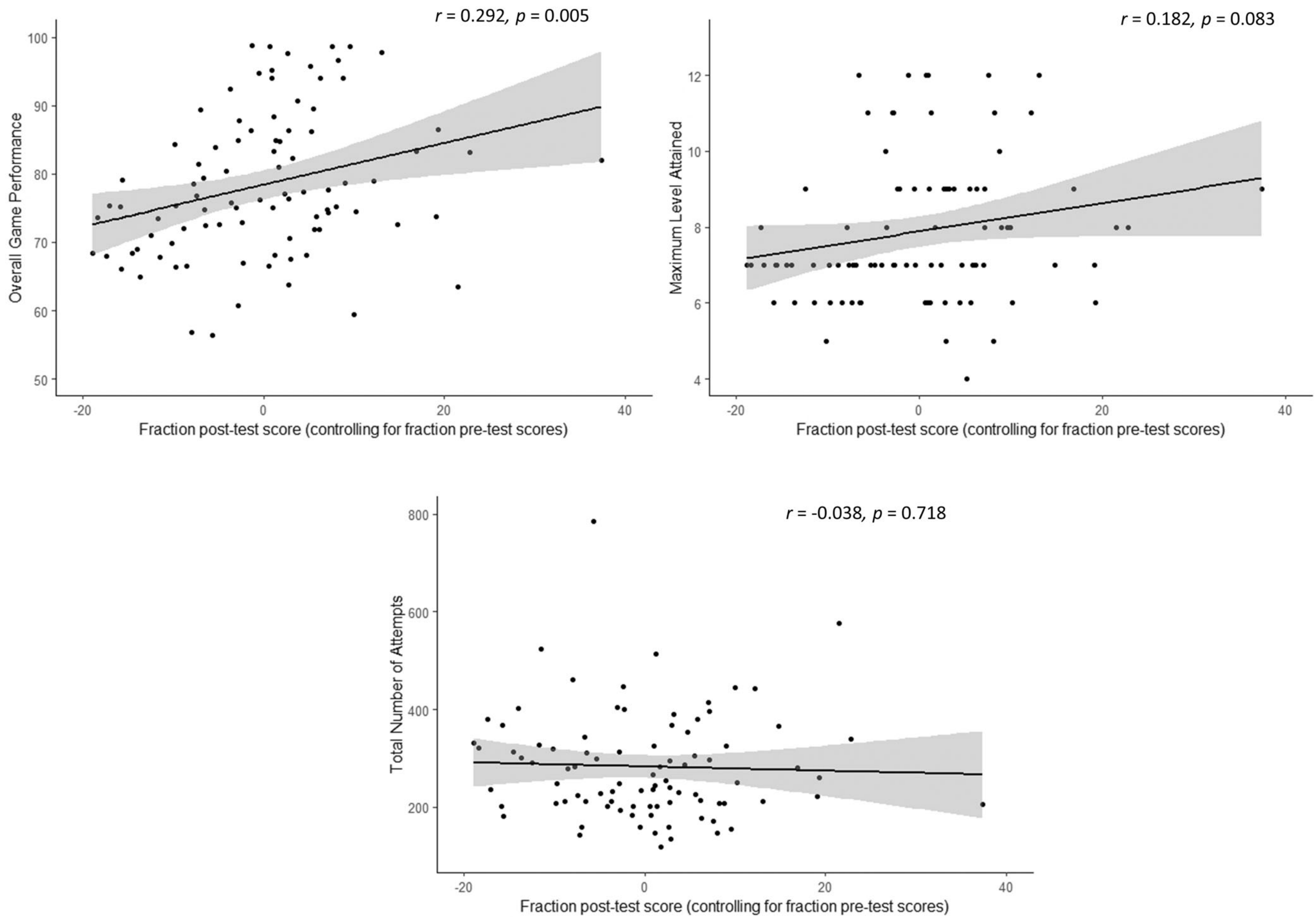

FIGURE 5 Correlation of fraction post-test scores and game variables. Grey shaded area indicates 95% confidence region for the correlation

significant main effect of group on arithmetic fluency post-test scores after controlling for pre-test scores (F (1,158) $= 0.53$, $p = 0.468$, $\eta^2_p = 0.003$). Bayesian statistics also indicated substantial evidence for a lack of difference between groups ($BF_{01} = 4.56$). Third, in contrast to our predictions, no significant main effect of the group was observed for post-test mathematics anxiety scores after controlling for pre-test anxiety scores (2020: F (1,107) $= 0.027$, $p = 0.871$, $\eta^2_p = 0.000$, 2019: F (1,58) $= 1.13$, $p = 0.293$, $\eta^2_p = 0.019$). Bayesian statistics indicated substantial and anecdotal evidence for a lack of difference between groups (2020: $BF_{01} = 4.73$; 2019: $BF_{01} = 2.46$).

7.3 | Exploratory findings: Are effects dependent on competency?

The fraction knowledge test assessed six major competencies: fraction concepts, fraction arithmetic, symbolic representation, word problems, fraction number lines, and decimals. It is possible that the intervention may affect some competencies more than others. Frequentist and Bayesian ANCOVAs were conducted on each of the six competency sub-scores (controlling for their specific baseline scores) (Figure 4). First, frequentist ANCOVAs revealed lower post-test scores in the experimental as compared to the control group on fraction concepts (F (1,162) $= 6.19$, $p = 0.014$, $\eta^2_p = 0.037$) and fraction arithmetic (F (1,161) $= 14.52$, $p < 0.001$, $\eta^2_p = 0.083$). Bayesian statistics indicated anecdotal evidence for a difference between groups on fraction concepts ($BF_{10} = 2.74$) and strong evidence for a difference between groups on fraction arithmetic ($BF_{10} = 99.41$). Second, there was no main effect of group (all Fs < 1.95, all ps > 0.164) on symbolic representation, word problems, fraction number lines. Bayesian statistics indicates a substantial evidence for a lack of difference between groups on symbolic representation ($BF_{01} = 5.40$) and fraction number line ($BF_{01} = 3.01$) and an anecdotal evidence for word problems ($BF_{01} = 2.44$). Third, frequentist ANCOVAs revealed higher post-test scores in the experimental as compared to the control group on decimals (F (1,161) $= 7.23$, $p = 0.008$, $\eta^2_p = 0.043$). Bayesian statistics also indicated substantial evidence for a difference between groups ($BF_{10} = 4.81$).

7.4 | Exploratory findings: Are effects dependent on individual differences in-game usage?

It is possible that the intervention may only affect the competencies of children who progressed the most at the game, thereby benefiting from its content. To test for this possibility, we used frequentist and Bayesian correlation analyses to identify relations between game metrics and fraction knowledge while controlling for fraction pre-test scores (Table 3 and Figure 5). Frequentist analysis revealed a significant positive correlation between overall game performance and fraction post-test scores (r (92) $= 0.292$; $p = 0.005$), indicating that greater overall in-game performance was associated with better fraction knowledge at post-test. Bayesian analyses also indicated substantial evidence for this correlation ($BF_{10} = 6.57$). However, maximum level attained (r (92) $= 0.182$; $p = 0.083$) and number of attempts (r (92) $= -0.038$; $p = 0.718$) did not correlate significantly with the fraction post-test scores. Bayesian analyses indicated anecdotal ($BF_{01} = 1.74$) and substantial ($BF_{01} = 7.198$) evidence for no association between the variables respectively.

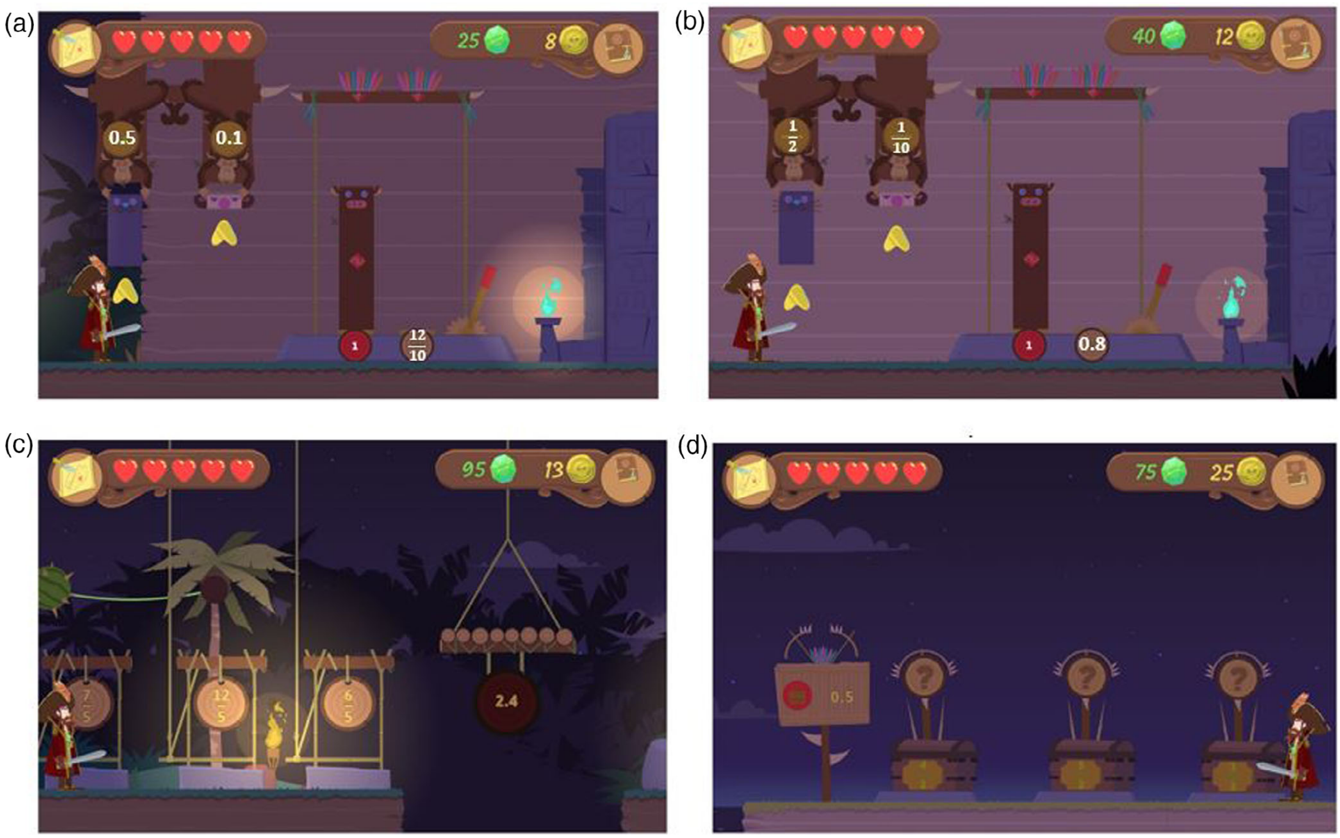

FIGURE 6 Examples of the core decimal concepts that were present in the game. (a) The player has to select the correct decimal blocks (0.1 or 0.5) to make the fraction (12/10). (b) Here, the player has to select the fraction blocks (8 blocks of 1/10 or 1 block of 1/2 and 3 blocks of 1/10) that corresponds to the decimal (0.8). (c) The player has to choose the correct fraction that corresponds to the decimal number (2.4). (d) Here, the player has to choose the correct fraction that corresponds to the decimal (0.5)

8 | DISCUSSION

In this pre-registered randomized controlled study, we examined the impact of a game-based intervention on fraction knowledge of fifth graders. We first discuss the findings of the impact of the game on fraction learning and then elaborate on the game metrics to better understand the game-based intervention and its impact on fraction learning.

8.1 | Active control group performs better on fraction knowledge than the experimental group

Contrary to our preregistered hypothesis, the students in the experimental group did not outperform the control group on fraction knowledge. These results are inconsistent with the nascent literature on game-based interventions and fraction knowledge development. We can see two potential reasons for the lack of positive difference between the two groups. First, it might be attributed to the limited instructional support in the experimental group. Indeed, the use of well-designed instructional support during DGBL can help learners focus on relevant information in the game that contributes to learning (e.g., modelling, reflection, context integration) (Wouters et al., 2008; Wouters & van Oostendorp, 2013, 2017). Though teachers were given two training sessions before the study began, these were limited to understanding the interface and objectives of the game. Our observations in the classroom also indicated that the teacher and student interactions were relatively limited in the experimental group (mostly when students asked questions about the game interface or a specific concept). Thus, students were essentially playing the game individually without much debriefing or intermittent instructional sessions by the teachers.

Second, in efforts to match the rigour and competency in both groups, we might have introduced a solid method to teach and practice fraction curriculum to the teachers in the control group. Classrooms in the control group included group-based learning with peer-to-peer interactions and also other concrete activities that were provided in the book (see Figure 2). Teachers who used the exercises from the book systematically could have inadvertently led the instruction using the Concrete Pictorial Abstract (CPA) method. The CPA method is an effective learning approach based on reconstructing knowledge through manipulation of concrete objects, representation of images, and abstract notation or symbols (Witzel, 2005). Indeed, the book provided tools for physically manipulating concrete objects and learning through images (Anselmo & Zucchetta, 2018). The use of this method in the control group might explain the slight advantage of that group on post-test scores.

8.2 | Experimental group performs better in decimal knowledge than active control group

Though the game did not show any impact on the overall fraction learning scores, exploratory analyses indicated that the game had a positive effect (with at least substantial evidence in Bayesian terms) for decimals. We can see two possible reasons for this finding. First, it is possible that the difference in performance between the experimental and control groups is due to the game focus on building connections between the two notations (fractions and decimals). This contrasts with the structure of the typical instructional sequence for rational numbers in traditional classrooms (i.e., fraction first, decimals next, and percentages last). Understanding and translating between multiple interpretations of rational numbers and the three notations (decimals, fractions, and percentages) is a requisite skill for mastery of rational number knowledge (Tian & Siegler, 2018). The importance of building connections between fractions and decimals is also highlighted by a curriculum intervention study in which fourth graders learned decimals before fractions (Moss & Case, 1999). Second, the difference between the groups in our study might also result from the type of decimal problems in the pre and post-test. These were limited to conversion of decimals to fractions and vice versa (e.g., $0.25 = ?$, $\frac{7}{10} = ?$). Interestingly, this is the key skill that was practiced by students in the game (see Figure 6) and could have potentially led to a larger effect on this particular measure (Hurwitz, 2019).

8.3 | Math Mathews Fractions does not lower math anxiety

Contrary to our hypothesis, the students in the experimental group did not report lower anxiety levels as compared to the control group. On the one hand, these results are inconsistent with some studies (Chang et al., 2016) and the idea that an increase in engagement through games and interactive platforms might encourage students to reappraise their math anxiety (Ramirez et al., 2018). On the other hand, they are in line with a recent meta-analysis that reveals digital games to have a negligible effect size (ES $= -0.13$) on reducing students' level of math anxiety (Dondio et al., 2022). Critically, non-digital games, games with longer duration of intervention, and those that included social interactions and collaborations had a greater effect on reducing math anxiety (Dondio et al., 2022). These variables might explain why our game, which is a single-player game that was not specifically designed to deal with math anxiety (Dondio et al., 2022), did not lower math anxiety.

8.4 | Overall game performance is related to higher performance on fraction post-test

The game metrics in the current study reflect different aspects of student learning such as accuracy (higher overall game performance), increased guessing (higher number of attempts), and progression on task (maximum level attained). Although we did not find any significant relationship between the level attained on the game and fraction post-test scores, we observed that overall game performance was positively associated with students' fraction knowledge at post-test. This indicates that better game performance was related to higher performance on post-training fraction learning outcomes. Importantly, by controlling the pre-test scores, the individual differences in game performance may explain post-training fraction knowledge and might not be an artefact of intelligence alone. These results are consistent with another game-based study where the overall game performance notes positive associations with both math grades and paper-based post-test scores (Kiili et al., 2018). Thus, in-game metrics might be useful for teachers to assess learning outcomes in real-time (Kiili et al., 2018; Serrano-Laguna et al., 2017; Zaki et al., 2020).

9 | LIMITATIONS

There are at least three potential limitations concerning the results of this study. A first limitation concerns the lack of qualitative data. A mixed-methods study is informative to determine the mechanisms involved in learning as well as to better understand the methods (Bertram, 2020). Classroom discussions, student interactions, and the type of questions asked during the game-based training would have enriched our quantitative measures. Additionally, while we did have a general idea of implementation of both interventions, future studies could potentially use qualitative methods to carry out implementation fidelity in both the classrooms. A second potential limitation is the passive role of teachers in the game-based group. The role of instructional support during DGBL cannot be undermined (Wouters & van Oostendorp, 2017). Despite conducting sessions for teachers to understand the objectives of the game and its interface, we did not provide a structured, rigorous training session on teaching with the game in the classroom. As a result, all teachers in the experimental group played a passive role in student learning, which might affect the outcome of the intervention. Additionally, increasing the timeline of the intervention could also have given the teachers time to get accustomed to the game in the classroom. The increase in timeline could have potentially helped the teachers to design and execute lesson plans with the game, thereby influencing learning outcomes. Additionally, because of school closures during the COVID-19 outbreak, we could not investigate possible long-term effects of the game-based training. Finally, due to the small number of classrooms included in the study it was not possible to account for classroom level effects arising from the nested nature of data. Thus, future studies with larger sample sizes could be carried out to model the nested structure of data.

10 | CONCLUSION

Here we evaluated the impact of a game-based training on rational number concepts. The game, Math Mathews Fraction was designed by a mathematics education researcher and game developers. By including an active control group that practiced fraction concepts matched on rigour and competency, we aimed to assess the effectiveness of the game with respect to traditional learning of fractions. Our results indicate that the game was not superior to traditional learning for overall fraction performance. However, the game had a positive effect on the learning of decimals. We also found a relation between the game metrics and overall fraction knowledge scores. This suggests that games such as Math Mathews Fraction might play a role in traditional classroom instruction by helping students learn specific fraction representations and supporting teachers to help build connections between fraction and decimal representations.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

All tests (translated and original versions) and anonymized scored data for each participant are available via the Open Science Foundation (OSF) at https://osf.io/zxm5c/. A brief demonstration of the Math Mathews Fraction game is available at https://osf.io/xn2k3.

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