The Impact of Digital Game-based Learning with a Mathematical Game Application on Calculation Abilities of Grade 4 Students

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Abstract: Calculation abilities are essential in elementary school mathematics and learning with game applications have been demonstrated to improve student's learning of mathematics, which is conducive to developing their calculation abilities. As one of the core mathematical skills, calculation abilities can be improved through continuous calculation practice. However, there is currently just a little research on the effects of using digital game-based learning (DGBL) with a mathematical game application in elementary school for developing students' calculation abilities. Therefore, 78 students participated in this quasi-experimental study to evaluate the possible influence of DGBL with a mathematical game application "Oral Math Hero" through iPads on the calculating abilities of fourth-grade students in a mainstream school in Mainland China. A mathematical game application was integrated into a four-week classroom activity for the experimental classes, with pre-test and post-test utilizing a standardized calculation abilities test: Abilita diCalcoloz Calculation Abilities-Memory and Training Group 6-11 (Cornoldi et al., 2002) for both experimental and control groups. Data analysis results using ANOVA showed that there were significant differences in students' calculation abilities when learning with the mathematical game application on iPad in mathematical classrooms, with significant differences in overall calculation abilities between the experimental group (n=40) and the control group (n=38) in grade 4. In other words, we found that after practicing calculations with the mathematical game application, students were more likely to achieve better calculation abilities, especially in terms of faster calculation speed, and lower error rates. However, there were no significant differences in numerical knowledge, learning with this mathematical game application might not lead to acquiring more mathematical knowledge. This study provides a realistic perspective for elementary mathematics educators and teachers to understand the potential of learning with the mathematical game application: it can be an effective tool to improve the calculation abilities of students in grade 4. The second stage of this project is to explore the reasons behind the results of the study, revealing possible factors of DGBL with the mathematical game application that may facilitate certain aspects of calculation abilities. Further suggestions are made to integrate DGBL into the elementary mathematics classroom.

Keywords: Digital game-based learning, calculation abilities, mathematical games

1. Introduction

Students' calculation refers to the abilities to understand patterns and relative quantities between numbers and to perform operations between numbers (addition, subtraction, multiplication, and division) in a more flexible way in mathematics (Feigenson et al., 2004; Tall & Dehaene, 1998). They are intrinsically important for mathematical performance at the elementary level (Cowan et al., 2011). Similar to elementary school mathematics curricula in different leading countries, grade 4 students have to master four operations (addition, subtraction, multiplication, and division) according to the latest curriculum standard in Mainland China, and they need to keep practicing calculation abilities to find easier solutions (Ministry of Education of the People's Republic of China, 2022). Students' performance and efficiency in calculation can be improved through constantly repeated practice (Imbo & Vandierendonck, 2008). However, repeated paper and pencil exercises are generally boring for students, and too many repetitions can make them lose interest to continue the practice and thus not effective to improve their calculation abilities (Chen et al., 2020). It can result in poorer mathematical skills and fewer arithmetic scores, which can have an impact on students' future performance in mathematics (Núñez Castellar et al., 2014).

Digital Game-based Learning (DGBL) is a learning approach that uses digital games as a means of delivering educational material. The use of mobile game applications in the class can help students to participate more actively in educational activities and achieve higher instructional goals and outcomes (Vasiliou & Economides, 2007; García-Bárcena & García-Crespo, 2007) because of its funny nature. Students are more likely attracted to participate in and thus learn and acquire new knowledge and skills during the games (Corti, 2006). As past research has found that using DGBL in mathematics classes encouraged students to stay on track and increased their engagement with the learning process (Jabbar & Felicia, 2015; Tsai et al., 2012). However, it is not known whether the use of these game applications can improve students' calculation abilities in mathematics. Besides, prolonged use of digital games for study may lead to game addiction, which can generate adverse effects on students' academic performance and affect their physical and mental health (Eyimaya & Irmak, 2021). Thus, many past research on calculation abilities focused on cognitive factors and the relationship between previous academic skills and interests (e.g., Maedamuerk et al., 2018, Commodari & Di Blasi, 2014), or focused on kindergarten students' numeracy (Tajudin et al., 2015; Zhu & Chiu, 2019), but less on the effects of digital games.

Therefore, the following research question is posed in this study: *Does learning with a mathematical digital game affect the calculation abilities of grade 4 students?*

2. Literature Review

2.1 Research gap derived from literature review

Research has found that digital game-based learning can be a promising educational approach that can help students easier to achieve targeted learning outcomes (Wang et al., 2022) and motivate students to learn because it generally provides timely feedback on task evaluation (Mathrani et al., 2016), promotes students' interest in learning and increases classroom participation (Ke, 2008; Tsai et al., 2012). However, other research on DGBL are still inconclusive in this issue. For instance, there is no significant evidence that DGBL can improve students' understanding of mathematical skills (Ke, 2008). Or Young et al. (2012) stated that limited data is supporting the validity of digital games in the field of mathematics.

According to recent studies, calculation abilities are important for students' mathematics learning and even affect their later mathematics performance in secondary and post-secondary schools (e.g., Cahoon et al., 2021). However, previous studies on calculation abilities more tended to focus on factors such as attention, including selective visual attention and the ability to suppress distracting information, and how they affect the accuracy of verbal calculations in second and third-grade students (e.g., Commodari & Di Blasi, 2014; Bigozzi et al., 2021). Other studies have explored the impact of play environments on elementary school students' flexible number knowledge and mathematical fluency, as well as the relationship between calculation and previous skills and interests (Brezovszky et al., 2019; Maedamuerk et al., 2018). There are only little studies on the effects of digital games on students' calculation abilities at the elementary level though there are studies about the speed and accuracy of calculation for first and second-grade students (Núñez Castellar et al., 2014; van der Ven et al., 2017; Núñez Castellar et al., 2015).

To sum up, based on the literature review, there is still a research gap: few studies have examined the effects of digital game-based learning on fourth graders' calculation abilities.

2.2 Theoretical framework

McCloskey et al. (1985) made a distinction between calculation abilities and the ability to comprehend as well as that of generating numbers. According to their model, the calculation system involved processing operational symbols, retrieving basic arithmetic facts, and performing calculated operations, in addition to numerical processing. These elements involved varying degrees in both mental and written calculations. Furthermore, any calculation work requires a certain level of number comprehension and generation (Commodari & Di Blasi, 2014). Based on Computing System Model, calculation abilities can be divided into three main dimensions: numerical knowledge, calculation accuracy, and calculation speed (Cornoldi & Lucangeli, 2004).

According to Dehaene et al. (1990), numerical knowledge is the set of abilities and knowledge that enables a student to comprehend numerical quantities and their conversions. A student's ability to perform mathematical calculations quickly and accurately can be defined and determined by the concept of calculation speed and calculation accuracy respectively (Jordan & Montani,1997). Based on these three key factors, Cornoldi et al. (2002) designed a standardized calculation abilities test: Abilita diCalcoloz Calculation Abilities- Memory and Training Group 6-11 (AC MT 6-11).

The strength of this framework is its ability to take the abstract concept of calculation abilities and visualize it into three dimensions for concrete measurement, thus performing a standardized proficiency test of whether students' calculation abilities have changed. As previously highlighted by Commodari and Di Blasi, (2014), any computation requires a certain level of calculation methods and knowledge and emphasizes the ability to perform calculations quickly and accurately.

In this study, three sub-abilities of calculation abilities as Figure 1 shows (calculation speed, calculation accuracy, and numerical knowledge) were used as the theoretical framework for a more accurate measurement of students' calculation abilities. AC MT 6-11 thus was adopted as an instrument of this study.

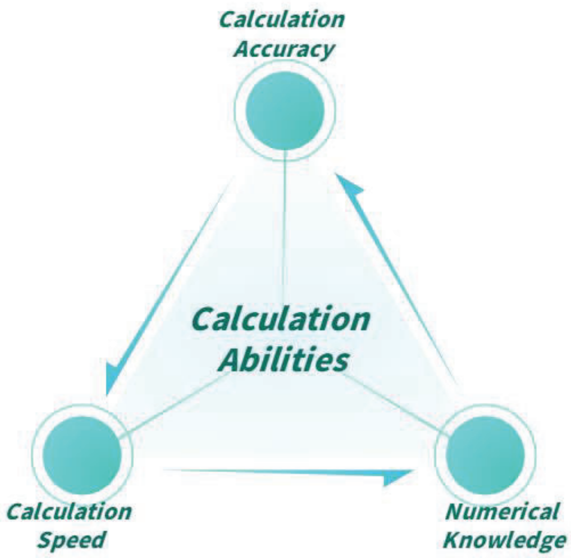

Figure 1. Framework for Calculation Abilities

3. Methodology

3.1 Procedures and ethical measures

The study was conducted in a school in Shenzhen, a southeast city in Mainland China covering Grade 1 to 9, and consent were obtained from the participating students and their parents, the mathematics teacher, and the school principal before the study was implemented. Since there are different classes for each grade in this school, the study used cluster sampling, with one class in grade 4 randomly selected as an experimental group (n=40). For the control group, another class taught by the same mathematics teacher in the same grade was selected as the control group (n=38). A total of 78 students participated in the study.

In this study, a pre-and post-test quasi-experimental approach was used, as shown in Figure 2. Three days before starting and after ending the intervention, all students took a pre-test and post-test of the calculation test (i.e. AC MT 6-11). A 40-minute teacher training was conducted before the pre-test to ensure that the teacher understood the purpose and principles of the study. Both the pre-test and post-test were completed in classrooms at the targeted school, with proctoring and marking completed by a mathematics teacher in the same grade level who was not teaching in the participating classes, and a 20-minute teacher training was held with the marking teacher to agree on the scoring requirements and rules for the calculation test before scoring the test.

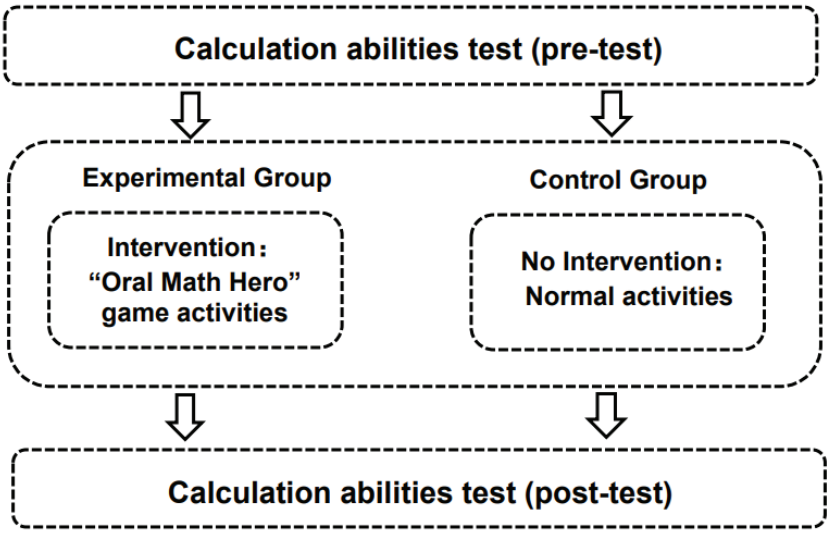

Figure 2. The Overall Research Design.

Before the main study, two additional teachers and six students from grade 4 were invited to participate in the pilot study to collect their opinions on the research instrument.

3.2 Intervention

3.2.1 The adopted mathematical game application

"Oral Math Hero" was adopted in the intervention of this study, and it was designed for elementary school students to practice mathematics in a fun way. As shown in Figure 3, students could choose the range of calculations and operations they want to practice. The game was based on players playing as different heroes, who need to fight monsters by answering questions then they got progressively harder. Students who gave correct answers could earn gold coins, and five consecutive correct answers unleashed a big move to defeat the monster. Gold coins could be used to buy higher-level hero characters. After each "battle" (stage), there was task feedback and a leaderboard to motivate students.

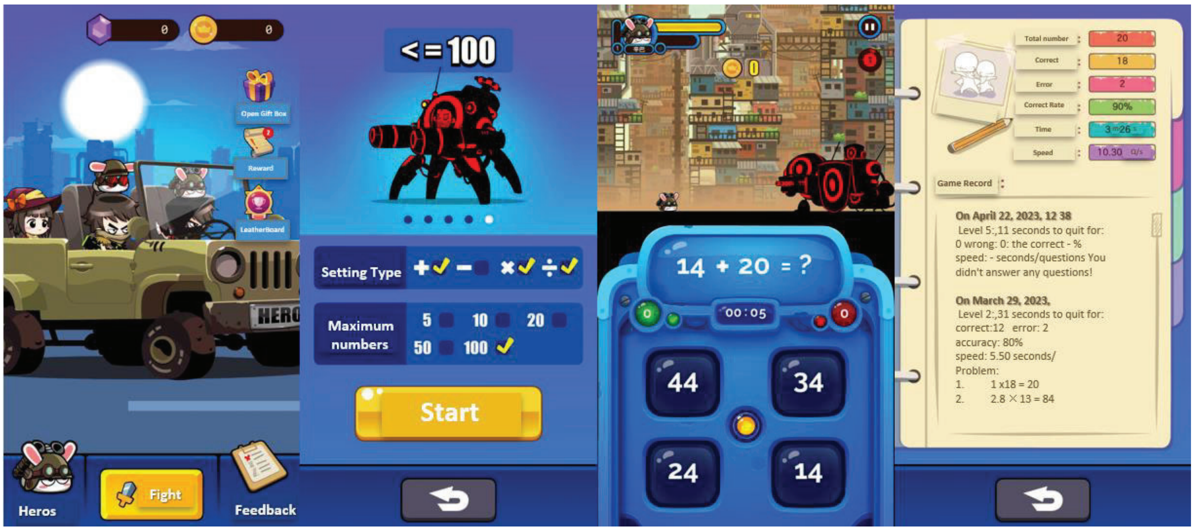

Figure 3. Some interface of *Oral Math Hero.*

3.2.2 Pedagogy

The experimental group experienced the intervention which was based on the pedagogical model of Play Curricular Activity Reflection Discussion (PCaRD) (Foster & Shah, 2015). The PCaRD model consists of four phases (gameplaying phase, classroom activity phase, reflection phase, and discussion phase) to help teachers effectively integrate digital games into their instruction in the classroom (Denham, 2019). During the month-long game-based intervention, students in the experimental group were required to engage in a 15-minute activity of the mathematical game "Oral Math Hero" three times a week on iPads provided by the school, while the control group maintained the traditional classroom practice activities without learning with the mathematical game application.

Before the intervention, the researchers provided clear instructions to the teachers, who designed lesson plans based on the PCaRD model, including the objectives, content, and game-based activities. During the gameplaying time, every student learned with an iPad, and during each 40-minute session, the teacher briefly delivered 20 minutes of mathematics lesson content and divided the subsequent 15 minutes into four sections based on the PCaRD model, as shown in Figure 4.

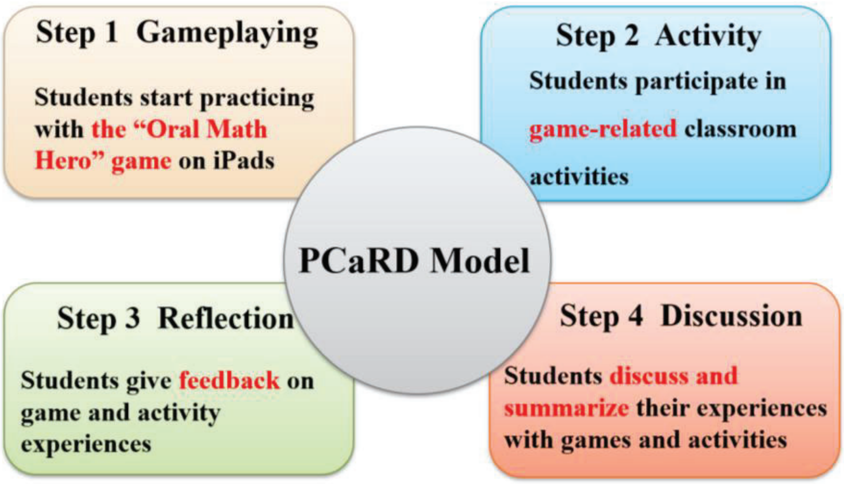

Figure 4. Intervention based on PCaRD model.

3.2.3 Calculation practice in the control group

To gain a more comprehensive understanding of the impact of the intervention on calculation abilities, while the experimental group implemented the classroom intervention of the mathematical game “Oral Math Hero”, the control group implemented the traditional calculation practice method, which is based on paper and pencil training, and performed oral calculation practice or calculation training in exercise books at the same frequency and duration as the experimental group.

3.3 Instrument

As stated, Abilita diCalcoloz Calculation Abilities Memory and Training Group 6-11 (AC MT 6-11) was used as a calculation abilities test in this study, which was a standardized calculation test that requires students to determine if students’ calculation abilities levels changed before and after the four-week intervention and were expected to take 40 minutes. The calculation abilities test included scores in three dimensions: numerical knowledge, calculation speed, and calculation accuracy (Cornoldi et al., 2002). There were eight tasks in this calculation abilities test: Written Calculation; Size Comparison, Word–Number Transcoding, Numerical Facts, and Number Ordering; Mental Calculation; Written Calculation2; Enumeration; and Numerical Facts (Cornoldi & Lucangeli, 2004). According to Cornoldi and Lucangeli (2004), the calculation abilities test is a psychologically trustworthy assessment of calculation abilities, and the sources of scores for the three dimensions of calculation abilities were shown in Table 1.

Table 1. *Sources of Scores for Different Dimensions*

Dimension	Scores
Calculation Speed	Time for answering Written Calculation, Mental Calculation, Enumeration, Written Calculation2
Numerical Knowledge	Combined score: Size Comparison, Word–number transcoding, Numerical facts, Number ordering
Calculation Accuracy	Total Error Scores

3.4 Data analysis

The pretest scores of the experimental and control classes in both grades were subjected to separate independent sample T-tests to ensure that there was no significant difference in the basis of calculation abilities between the two classes. After that, a single-factor analysis of variance was conducted for all pretest and post-test scores. Therefore, ANOVA (including Levene’s test of the quality of error variances) with a confidence interval of 0.95 is chosen to eliminate the effect of the intervention on the results and was followed by a normal distribution and homogeneity of the regression slopes to ensure that there was no interaction between the pretest scores and the intervention (“Oral Math Hero” game application). The above data are analyzed using IBM SPSS 28.0.

4. Results and Findings

4.1 Descriptive analysis

Cronbach's alpha was calculated using the pre-test results to ensure the reliability and reliability of the test before conducting the post-test. The reliability analysis showed that Cronbach's alpha was greater than 0.7 for all factors (αCS = 0.727, αCA = 0.841, αNK = 0.769), confirming that the standard calculation abilities test is a reliable research instrument. The results of the independent samples T-test ($p=0.930<0.05$) showed that there was no significant difference in the pre-test scores of the experimental and control groups in grade

4, which meant that the two groups had a similar basic level of calculation abilities before the start of the study. The normality test was performed on the pre-test and post-test data of the calculation abilities test, and since the sample size of each group was <50, the results according to the Shapiro-Wilk test ($p_{Pre-CS} = 0.056$; $p_{Post-CS} = 0.095$; $p_{Pre-CA} = 0.154$; $p_{Post-CA} = 0.085$; $p_{Pre-NK} = 0.280$; $p_{Post-NK} = 0.050$) were all greater than 0.05, so the collected data conformed to a normal distribution. The homogeneity of variance was tested using Levene's test, and the results ($p_{Pre-CS} =0.427$; $p_{Post-CS} = 0.882$; $p_{Pre-CA} = 0.237$; $p_{Post-CA} = 0.740$; $p_{Pre-NK} = 0.573$; $p_{Post-NK} = 0.622$) suggest that the differences in the overall variance of the groups are small.

The descriptive analysis of the pre-test and post-test results of the calculation abilities test was shown in Table 2. Students in the experimental group demonstrated a significant increase in calculation accuracy and calculation speed, whereas students in the control group demonstrated a slight increase in calculation accuracy but a decrease in calculation speed and numerical knowledge compared to the pretest. Meanwhile, students in the experimental group drastically dropped their numerical knowledge.

Table 2. *Descriptive Statistics of Calculation Abilities Test in Pretest and Posttest*

Dimension	Pretest		Posttest	
	Mean	Std. Deviation	Mean	Std. Deviation
Calculation Accuracy				
Experimental Group	3.88	3.560	6.03	11.173
Control Group	6.42	9.081	6.58	11.387
Calculation Speed				
Experimental Group	15.48	2.828	16.18	2.688
Control Group	18.34	1.805	17.00	2.857
Numerical Knowledge				
Experimental Group	38.58	5.679	33.55	0.959
Control Group	39.18	3.303	32.55	2.177

4.2 Analysis of variance (ANOVA)

According to the results of the T-test, there was no significant difference between the pretest scores of the experimental group and control group ($p=0.930>0.05$), indicating that the two groups of the fourth grade had similar bases. Therefore, a single-factor ANOVA was conducted to investigate whether there was a significant difference between the data of the experimental and control group.

Table 3. *ANOVA results of Calculation abilities in Experimental and Control Group*

	F	*p*	Mean Square
Overall Calculation Abilities			
Class	2.708	0.004*	126.323
Calculation Accuracy			
Class	3.908	0.004*	137.894
Calculation Speed			
Class	28.174	0.001*	160. 109
Numerical Knowledge			
Class	6.972	0.063*	19.385

The results (Table 3) showed that overall speaking, students in the experimental group had significantly higher calculation abilities than those in the control group ($p=0.004$).

Specifically, among the three dimensions of calculation abilities, calculation accuracy (p=0.004) and calculation speed (p=0.001) were significantly different between the two groups in the posttest. Therefore, it was possible to draw a conclusion that digital game-based learning with Oral Math Hero on iPad significantly improved the calculation abilities of the experimental group of grade 4 students, especially the students' calculation speed and calculation accuracy. However, no significant difference was found between the students' ability in the experimental and control classes in terms of numerical knowledge (p=0.063). Learning with this mathematical game application might not lead to acquiring more mathematics knowledge.

5. Discussion and Conclusion

Calculation accuracy, calculation speed, and numerical knowledge as three objective measurements were considered to measure the impact of digital game-based learning with a mathematical game application on the calculation abilities of grade 4 students (Cornoldi & Lucangeli, 2004). Specifically, we predicted that DGBL with the mathematical game application, in terms of calculation accuracy, calculation speed, and numerical knowledge, would be as effective as normal mathematics class activities in improving the calculation abilities of grade 4 students, and the experimental group would perform better than the control group. Consistent with this hypothesis, the results of the post-test showed that the experimental group had significantly higher overall calculation abilities test scores and scores in terms of calculation accuracy and calculation speed than the control group. Such findings generally confirmed some studies on the use of mathematical games in mathematics classrooms (e.g., Núñez Castellar et al. 2014; van der Ven et al. 2017; Castellar et al. 2015), suggesting that DGBL with the mathematical game can improve certain mathematical skills by increasing students' calculation accuracy and speed of mental computation. The findings are also in line with those of Miller and Robertson (2011) that elementary school students who played mathematical games had twice the calculation speed of control group students who did not play.

However, an unexpected finding occurred in this study: the numerical knowledge score gained in the post-test was lower for the experimental group than in the pre-test. More specifically, the findings of this study did contradict some previous studies (Brezovszky et al., 2019) that DGBL with mathematical game application did not improve students' numerical knowledge significantly. Three potential explanations for the observed phenomenon, each of which is not exclusive of the others. Firstly, it is plausible that the "Oral Math Hero" game did not affect numerical knowledge to a significant extent since it provided tasks of a less complex and purely arithmetic nature. Secondly, students might not think deeply about certain calculation rules, such as the multiplication exchange law or the distributive law, in order to complete the task quickly in the exercise. Thirdly, the superior calculation methods were not presented in the task feedback or the answer situation screen of the game, so students had no chance to achieve more numerical knowledge in this game.

There were several limitations to this study. Firstly, although we have explored the effects of DGBL on calculation abilities by standardized calculation abilities tests, how calculation abilities are altered by digital games, how it varies with the type and content of digital games, and how the afterschool environment may affect calculation abilities remains unanswered. Future research would be expected to examine how DGBL affects students' calculation abilities, taking the afterschool environment and the type and content of games into consideration. Secondly, the duration of the intervention (four weeks, 2-3 times per week) was relatively short and it was only used in the classroom, so its impact on students' calculation abilities might have been limited. In addition, the duration of this study lasted only one month, which enabled the study to explore the short-term impact of DGBL with mathematics games on students' calculation abilities but lacked a longer period of investigation to explore whether this impact would change according to the time change. Longitudinal trials and tracking of students' calculation performance over time might be used to offer an understanding of potential long-term impacts on students' calculation abilities.

Thirdly, the sample size of this study was relatively small, only 78 students, and the fact that all data were collected through calculation abilities tests in a mainstream school in Mainland China might have led to an under-representation of the study, limiting the generalizability of the findings to other educational settings or groups of students. In addition, the participants of this study were mainly focused on grade 4 students, with no attempt to cover the entire elementary school level or include students' and teachers' interviews, lacking multiple data sources to provide triangulation. A study on a larger scale involving after-school interventions in more districts with more sources of data such as classroom observations and individual interviews could be considered. Fourth, the study concentrated on the influence of DGBL with a mathematical game on students' calculation abilities while ignoring the impact of the game on students' basic mathematical skills, such as problem-solving, spatial thinking, numeracy, and sense of amount, as well as their motivation. Future research can investigate whether mathematical game impact students' motivation and other components of mathematics learning.

In conclusion, this study showed that DGBL with a mathematical game application, compared to traditional calculation practice, could improve the calculation abilities of fourth graders, especially in terms of calculation speed and accuracy. Nevertheless, to present a comprehensive picture of how learning with a mathematical digital game affect calculation abilities, the data of the second-stage qualitative research is now analyzed to explain in what ways students were affected by game settings or elements. After that, implications for future DGBL with a mathematical game application can be proposed and all these will be presented in a forthcoming paper.

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