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LEARNING MULTIPLICATIVE REASONING BY PLAYING COMPUTER GAMES

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Abstract

This paper reports about a large-scale longitudinal field experiment investigating the effects of online mathematics mini-games on second- and third-graders' multiplicative reasoning abilities. The study included students in regular primary education ($n = 719$) and special primary education ($n = 81$). There were three experimental conditions: playing multiplicative mini-games at *school*, at *home*, and at *home with debriefing at school*. In the control condition mini-games on other mathematical topics were played at school. For regular primary education, results showed that the mini-games were most effective in the home-school condition, where they promoted both multiplicative skills and insight (significant *d*s ranging from 0.22 to 0.29). In the school condition, an effect was only found for insight in Grade 2 ($d = 0.35$); in the home condition there were no effects. In special primary education, a significant effect was found for the school condition in improving multiplicative fact knowledge ($d = 0.39$).

Key words: mathematics computer games, multiplicative reasoning, primary education, special primary education

Introduction

Computer games are more and more becoming part of primary school mathematics education (e.g., Alexopoulou et al., 2006). The most important benefits of games are their motivational characteristics (e.g., Garris, Ahlers and Driskell, 2002), and their possibility to provide immediate feedback (e.g., Prensky, 2001). Also for students in special education, mathematics computer games are promising educational tools (e.g., Brown et al., 2011). Yet, although meta-analyses did show that in general the use of ICT in mathematics education positively affects learning outcomes (Li and Ma, 2010; Slavin and Lake, 2008), there is still insufficient evidence for the effectiveness of computer games in particular (Bai et al., 2012). The present paper aims to provide such evidence for the domain of multiplicative reasoning (multiplication and division), for both regular and special primary education.

In learning multiplicative reasoning, it is important to develop ready knowledge of number facts (the multiplication tables), and skills in calculating multiplication and division operations. In addition, students need to develop insight in, or understanding of, multiplicative number relations (e.g., Anghileri, 2006; Nunes et al., 2012). They should, for example, have insight into the factors of numbers and the properties of multiplication, like the commutative property (e.g., $3 \times 7 = 7 \times 3$) and the distributive property (e.g., $6 \times 7 = 5 \times 7 + 1 \times 7$). These three aspects of multiplicative reasoning ability – number fact knowledge, operation skills, and insight – parallel the three types of knowledge often distinguished in mathematics education: declarative knowledge, procedural knowledge, and conceptual knowledge (see, e.g., Miller and Hudson, 2007).

Though most of the computer games and other educational software currently used in mathematics education focus on number fact knowledge and operation skills (e.g., Mullis et al., 2012), computer games can also be employed for developing mathematical insight (e.g., Klawe, 1998). The instructional power of games that are focused on insight development is often related to the educational theory of experiential learning (see, e.g., Kebritchi, Hirumi and Bai, 2010). In such games, students can learn new concepts and rules by exploring and experimenting with different mathematical strategies and discovering which strategies are convenient. With experiential learning games, class discussion – also called debriefing – is important to promote reflection on and generalisation of what is learned (e.g., Garris et al., 2002; Klawe, 1998).

Educational games can be played in different settings. Playing in a formal setting at school has the advantage that all instructional aspects of the games can be exploited by discussing them in a lesson. However, playing in an informal setting at home has advantages as well. Besides the benefit of extra learning time (e.g., Honey and Hilton, 2011), playing at home may lead to increased learner control, which is often mentioned as an important motivating factor of educational computer games (e.g., Malone and Lepper, 1987). A possible approach that combines the advantages of playing at school and those of playing at home, is playing the games at home with a debriefing at school (see Kolovou, Van den Heuvel-Panhuizen and Köller, 2013).

Research question

Does an intervention with multiplicative mini-games – either played at school, played at home, or played at home and debriefed at school – affect regular and special primary education students' learning outcomes in multiplicative reasoning; i.e. knowledge, skills, and insight?

Method

Study set-up

To answer our research question we set up a large-scale cluster-randomised longitudinal experiment (see also Bakker, Van den Heuvel-Panhuizen and Robitzsch, 2015a, 2015b). The experiment included three experimental conditions with multiplicative mini-games – playing the games at school integrated in a lesson, playing the games at home without attention at school, and playing the games at home with a debriefing at school – and one control condition in which the students played at school mini-games on other mathematics topics. In the conditions where the games were played at home, the games were presented as a free-choice activity, not as compulsory homework. This was done to maintain the motivating aspect of playing the games.

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Grade 1										*Pretest:* Skills
Grade 2	Game period 1					Game period 2				*Posttests Grade 2:* Knowledge, Skills, Insight
Grade 3	Game period 3					Game period 4				*Posttests Grade 2:* Knowledge, Skills, Insight

Fig. 1: Time schedule of the study

The mini-games – short, focused games that are easy to learn (e.g., Jonker, Wijers and Van Galen, 2009) – were played in four game periods, two in Grade 2 and two in Grade 3, as is shown in Fig. 1 (for special education only the Grade 2 part of the study was performed). In each game period, 8 different mini-games were offered. Before each game period, the teachers were given a manual in which for each game it was described how it had to be treated in class.

A pretest of multiplicative reasoning ability was administered at the end of Grade 1. Posttests on each of the three aspects of multiplicative reasoning ability – knowledge, skills, and insight – were administered at the end of Grade 2 (for the special education students, to reduce test duration, the skills and insight test were combined into a skills/insight test), and at the end of Grade 3 (only for regular education). A description of the tests employed, as well as more information on the interventions, can be found in Bakker et al. (2015a, 2015b).

Participants

The study was conducted in the Netherlands and included schools for regular primary education as well as schools for special primary education. In the Netherlands, special primary education is meant for students with substantial learning difficulties, mild mental retardation, or mild to moderate behavioural or developmental problems.

We recruited 66 regular primary schools and 19 special primary schools. Through a matching procedure on a number of school characteristics, and random assignment, the schools were evenly distributed over the research conditions. For various reasons, such as teacher changes, organisational problems, and problems with computers, some schools dropped out in the course of the research project. Moreover, only those schools in which more than half of the games were treated were included in the analysis. Unfortunately, for the special education schools, due to large drop-out and low intervention fidelity in the home and home-school condition, we could only include the school condition and the control condition in the analysis. Our final sample consisted of 35 regular primary schools (n = 719 students; 112 in the school condition, 202 in the home condition, 78 in the home-school condition, 327 in the control group), and 5 special primary schools ($n = 81$ students; 40 in the school condition, 41 in the control group).

The mini-games

The mini-games offered in the experimental conditions were mostly adapted versions of multiplicative mini-games selected from the Dutch mathematics games website Rekenweb. Descriptions of all mini-games can be found in Bakker et al. (2015b). As an example, one of the mini-games is shown in Fig. 2. In this game the student makes rectangular groups of smileys and then determines the number of smileys in the group. The game offers practice in solving multiplication problems (either as memorised multiplication facts or, for example, by repeated addition). Furthermore, the game stimulates gaining insight into the relations between multiplication problems; for example, 3 rows of 5 is the same as 5 rows of 3 (commutative property), and if 5 rows of 3 is 15, then 6 rows is 3 more, resulting in 18 (distributive property).

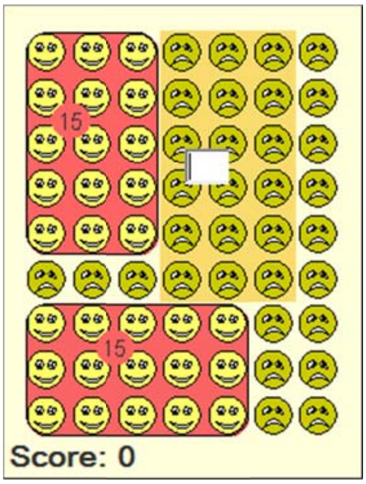

Fig. 2: Example mini-game “Making groups”

Data analysis

The effects of the interventions were investigated separately for the students in regular primary education and special primary education. For both samples, we employed linear regression analyses for each of the aspects of multiplicative reasoning ability, with posttest score as the dependent variable, and pretest score and condition dummy variables as independent variables. Additionally, we controlled for some student characteristics that were found to differ between conditions. Separate analyses were run for the effects of the intervention in Grade 2 (Grade 2 posttest score as dependent variable) and the intervention in Grade 2 and 3 together (Grade 3 posttest score as dependent variable). Missing test scores were handled using multiple data imputation (see Graham, 2009). The clustered data structure (students nested within schools) was accounted for by employing cluster-robust standard errors (see Angrist and Pischke, 2009; this could not be done for the special education students because of too few clusters, i.e., only 5 schools). Because of our directional hypothesis (we hypothesised the games to positively affect learning) we used one-tailed significance tests.

Results

For the students in regular primary education (Tab. 1), the games were found to be effective in enhancing skills and insight, but not knowledge. Specifically, in the home-school condition the intervention had a significant positive effect on both skills (*d* = 0.26 for the Grade 2-3 intervention) and insight (*d* = 0.29 for the Grade 2 intervention; *d* = 0.22 for the Grade 2-3 intervention). In the school condition the games only significantly affected insight, and only the Grade 2 intervention was effective (*d* = 0.35). No significant effects were found in the home condition ($p > .05$). For the special education students (Tab. 2), it was found that the games, played at school, were effective in enhancing multiplicative fact knowledge (*d* = 0.39), but not in enhancing skills/insight.

	Knowledge			Skills			Insight		
Condition	β_{ps}	*SE*	*d*	β_{ps}	*SE*	*d*	β_{ps}	*SE*	*D*
	Posttest Grade 2 (effect of Grade 2 intervention)								
School	0.01	0.24	0.01	0.10	0.24	0.09	0.39*	0.22	0.35
Home	-0.16	0.23	-0.16	-0.04	0.20	-0.03	0.21†	0.15	0.19
Home-school	0.08	0.26	0.08	0.21	0.20	0.18	0.32*	0.19	0.29
	Posttest Grade 3 (effect of Grade 2-3 intervention)								
School	-0.19	0.23	-0.20	0.10	0.18	0.09	0.15	0.19	0.13
Home	-0.05	0.16	-0.05	0.03	0.14	0.03	-0.02	0.12	-0.02
Home-school	0.16	0.13	0.16	0.28*	0.16	0.26	0.24*	0.12	0.22

Note. The pretest score, gender, age, parental education, home language, and general mathematics ability score were included as covariates. β_{ps} = partially standardised regression coefficient of the condition dummy variable predicting posttest score.
† $p < .10$. * $p < .05$. One-tailed.

Tab. 1: Effects of the interventions in regular primary education on knowledge, skills, and insight in Grade 2 and 3 (as compared to the control group)

	Knowledge			Skills/insight		
Condition	β_{ps}	*SE*	*d*	β_{ps}	*SE*	*d*
School	-0.01	0.15	-0.02	0.19*	0.11	0.39

Note. The pretest score, age, and general mathematics ability score were included as covariates. β_{ps} = partially standardised regression coefficient of the condition dummy variable predicting posttest score.
* $p < .05$. One-tailed.

Tab. 2: Effects of the intervention in special primary education on knowledge and skills/insight in Grade 2 (as compared to the control group)

Conclusion and discussion

For regular primary education, our study shows that the most effective way of integrating multiplicative mini-games in mathematics education is by offering them to students to play at home, and debriefing them at school. When the mini-games were offered in this way, they positively affected both students' skills in calculating multiplicative problems and their insight in multiplicative number relations (significant *d*s ranging from 0.22 to 0.29). Also playing the games at school, integrated in a lesson, was found to be effective, but only in promoting insight in Grade 2 ($d = 0.35$). Playing the games at home without attention at school did not affect students' learning of multiplicative reasoning.

The finding that the games were most effective when played at home and debriefed at school can be explained by this intervention having the combined advantage of playing at home (extra time on task, more learner control) and playing at school (debriefing). Playing at home without debriefing was not effective, indicating the importance of debriefing sessions in learning from the games. As proposed by, for example, Garris et al. (2002) and Klawe (1998), the debriefing sessions may have led students to reflect on what they had learned in the games, enabling them to generalise their learning beyond the game context. However, in our study the debriefing sessions may also have served as an encouragement for students to play the games at home. Indeed, in the home-school condition, the games were played more often than in the home-condition.

For special primary education, we found that the mini-games, played at school, were effective in promoting students' multiplicative fact knowledge, but not their multiplicative skills and insights. Yet, although there was no added value of the mini-games for skills and insight, an intervention with mini-games can still be seen as a "safe approach" to be employed as part of the multiplicative reasoning programme in special education, as learning outcomes were not different from those obtained in the control group.

The finding of an effect on knowledge but not skills/insight in special primary education is in contrast with our findings for regular primary education, where there were effects on skills and insight but not on knowledge. Possibly, for the special primary education students, who often are considerably behind in their learning, there was still much to improve in basic multiplicative fact knowledge. Also, multiplicative fact knowledge may, for these students, have been easiest to acquire from the game, because it requires least transfer (see, e.g., Shiah et al., 1994): multiplicative facts occurred in most games in the same way (with the × symbol) as in the textbooks and assessments. Students in regular primary education may have had enough opportunities for automatizing the multiplication tables in the regular mathematics curriculum, leaving room for the acquisition of more advanced types of knowledge. For them, the games were especially useful for acquiring insight, which may be related to the nature of the mini-games used, allowing for free exploration and experimentation (experiential learning).

The finding that the home and home-school condition were not adequately carried out by the special education teachers may indicate that having students playing mathematics games at home by themselves is not in line with the current practices of teachers in special primary education.

In conclusion, our study shows that both in regular and special primary education, mini-games can effectively be used to promote students' learning of multiplicative reasoning. Yet, the two school types appear to differ in terms of the aspects of multiplicative reasoning that are affected by the games, and in terms of the way in which the games can best be offered to the students.

In the course of our research project, it appeared that a large-scale study situated in school practice is hard to carry out. Because of teachers' busy schedules it was hard to find teachers willing to participate in a long-term study, and to motivate teachers in subsequent grades to continue the study. However, we think that conducting this research in real school settings to collect evidence for the effectiveness of mathematics games in (special) primary education was worth the effort. It provided us with knowledge of when mathematics mini-games are useful. Moreover, as the interventions were delivered by the teachers themselves, our results are directly applicable to the school practice.

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