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Effects of playing mathematics computer games on primary school students' multiplicative reasoning ability

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ABSTRACT

This study used a large-scale cluster randomized longitudinal experiment ($N = 719$; 35 schools) to investigate the effects of online mathematics mini-games on primary school students' multiplicative reasoning ability. The experiment included four conditions: playing at school, integrated in a lesson (E_{school}), playing at home without attention at school (E_{home}), playing at home with debriefing at school ($E_{home\text{-}school}$) and, in the control group, playing at school mini-games on other mathematics topics (C). The mini-games were played in Grade 2 and Grade 3 (32 mini-games in total). Using tests at the end of each grade, effects on three aspects of multiplicative reasoning ability were measured: *knowledge* of multiplicative number facts, *skills* in multiplicative operations, and *insight* in multiplicative number relations and properties of multiplicative operations. Through path analyses it was found that the mini-games were most effective in the $E_{home\text{-}school}$ condition, where both students' skills and their insight were positively affected as compared to the control group (significant *d*s ranging from 0.22 to 0.29). In the E_{school} condition, an effect was only found for insight in Grade 2 ($d = 0.35$), while in the E_{home} condition no significant effects were found. Students' gameplay behavior (time and effort put in the games) was in some cases, but not always, related to their learning outcomes.

1. Introduction

1.1. Educational computer games

Computer games have often been suggested as promising educational tools (e.g., Egenfeldt-Nielsen, 2005; Malone, 1981; Prensky, 2001; Tobias, Fletcher, Dai, & Wind, 2011). The most commonly mentioned benefit of computer games for education is their motivational aspect (e.g., Garris, Ahlers, & Driskell, 2002; Malone, 1981; Malone & Lepper, 1987; Prensky, 2001). In addition, games are assumed to be beneficial for learning because they can provide immediate feedback. Players often instantly see the consequences of their actions in the game (e.g., Prensky, 2001). Moreover, games allow players to try, make mistakes, and then try again without losing face (e.g., Gee, 2005). Because of this risk-free environment and the immediate feedback provided by the computer, players are stimulated to explore and experiment, as was pointed out by Kirriemuir (2002). In other words, games can offer students opportunities for experiential learning (e.g., Egenfeldt-Nielsen, 2005; Garris et al., 2002), enabling them to discover new rules and strategies.

Because of these presumed advantages, computer games are more and more becoming part of primary school education (e.g., Williamson, 2009). In accordance with the expected educational benefits of computer games, a meta-analysis by Wouters, Van Nimwegen, Van Oostendorp, and Van der Spek (2013) reported an overall positive effect of educational computer games in comparison to conventional instruction. However, when only randomized studies were taken into account, they did not find a significant effect. Furthermore, other review studies revealed that there is still insufficient experimental evidence for the effectiveness of educational computer games in the school practice (Tobias et al., 2011; Vogel et al., 2006; Young et al., 2012), and that large-scale in-class longitudinal studies are needed (Tobias et al., 2011; Young et al., 2012). Authors of review articles argued that studies on the effects of games and other educational software quite often suffer from methodological shortcomings, such as not using a control group (e.g., Vogel et al., 2006), not applying random assignment to condi-

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tions (e.g., Slavin & Lake, 2008), using a small sample (e.g., Bai, Pan, Hirumi, & Kebritchi, 2012), and not accounting for the nested data structure (e.g., Honey & Hilton, 2011; Slavin & Lake, 2008).

Also in primary mathematics education, computer games and other educational software are often used (e.g., Mullis, Martin, Foy, & Arora, 2012). Yet, also for the domain of mathematics, evidence for the effects of educational computer games is still insufficient, as is apparent from Bai et al.'s (2012) literature overview. Meta-analyses by Li and Ma (2010) and Slavin and Lake (2008) did show that in general the use of ICT in mathematics education positively affects learning outcomes, but in these analyses games were not taken as a separate category.

To gain evidence about the effectiveness of deploying computer games in mathematics education, we conducted a large-scale randomized experiment, with a longitudinal design. The focus was on mini-games in the domain of multiplicative reasoning (multiplication and division) in the early grades of primary school, where formal instruction of multiplicative reasoning commonly commences (e.g., Department for Education UK, 2011; NCTM, 2006; Van den Heuvel-Panhuizen, 2008).

1.2. Using computer games in mathematics education

1.2.1. Mini-games

A frequently used type of computer game in mathematics education is the so-called mini-game (e.g., Jonker, Wijers, & Van Galen, 2009; Panagiotakopoulos, 2011). Mini-games are short, focused games that are easy to learn (e.g., Frazer, Argles, & Wills, 2007; Jonker et al., 2009). They are often easily accessible (commonly free of charge), and usually have a flexible time duration; one game often takes only a few minutes and can be repeated endlessly (e.g., Jonker et al., 2009). Earlier studies have shown that mini-games have potential for mathematics education. In an evaluation study by Panagiotakopoulos, Sarris, and Koleza (2013), for example, positive learning outcomes were found in fifth-grade students who worked with a number mini-game. Furthermore, Miller and Robertson (2011) showed the effectiveness of handheld mathematics mini-games in improving 10- and 11-year-olds' mental computation skills.

1.2.2. Multiplicative number fact knowledge, skills, and insight

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, Bryant, Barros, & Sylva, 2012). They should, for example, have insight into the factors of numbers and the properties of multiplication (see, e.g., Chang, Sung, Chen, & Huang, 2008), 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 & Hudson, 2007).

Many of the computer games and other educational software currently used in primary school mathematics education focus on the first two aspects: number fact knowledge and operation skills (e.g., Mullis et al., 2012). However, computer games can also be employed for developing mathematical insight (see, e.g., Van Borkulo, Van den Heuvel-Panhuizen, Bakker, & Loomans, 2012). Jonker et al. (2009), for example, described a mini-game for enhancing primary school students' understanding of divisibility, and two studies reported by Klawe (1998) showed the effectiveness of computer games in fostering fifth-graders' understanding of several mathematical concepts. In fact, Ke (2009), in her review article, noted that games seem more useful to promote higher-order thinking than factual knowledge acquisition. 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, & Bai, 2010). In such games, students can learn new concepts and rules by experimenting with different mathematical strategies and discovering which strategies are convenient. To make this learning process happen, reflection is crucial, as is stated, for example, by Egenfeldt-Nielsen (2005) and Garris et al. (2002). Students can utilize reflection to generalize what they have learned, which leads to transfer. In this way, what is learned can also be applied outside the game (see, e.g., Tobias et al., 2011). However, many researchers argue that this reflection does not occur spontaneously in students (e.g., Leemkuil & De Jong, 2004). It is proposed that class discussion after playing a game is needed to encourage reflection (e.g., Egenfeldt-Nielsen, 2005; Garris et al., 2002; Klawe, 1998). In such a discussion – also called debriefing (e.g., Garris et al., 2002) – the learning points from the game are emphasized and different possible strategies are compared (e.g., Klawe, 1998). Indeed, Wouters et al. (2013), in their meta-analysis, found that interventions with computer games are more effective when the games are supplemented with other instructional methods, such as debriefing sessions, than when they are presented as a standalone activity. Also support before and during the game is assumed to foster learning (e.g., Leemkuil & De Jong, 2004).

1.3. Playing games at school vs. at home

Mini-games can be played at school (a formal setting) as well as at home (an informal setting; see, e.g., Honey & Hilton, 2011). Because of the involvement of the teacher, 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. Moreover, the teacher has control over whether the games are played. However, playing in an informal setting at home, which also occurs a lot (e.g., Ault, Adams, Rowland, & Tiemann, 2010; Jonker et al., 2009), has advantages as well. Jonker et al. (2009), for example, reported that the Dutch mathematics games website Rekenweb is visited mainly during after-school hours, which, for the students involved, implies an extension of the time that is spent on mathematics. According to researchers like Honey and Hilton (2011) and Tobias et al. (2011), an important characteristic of educational computer games is that their motivational effect can cause students to be involved in a learning activity for a longer time period than is regularly the case. In a study by Sandberg, Maris, and De Geus (2011), for example, primary school students who were offered a mobile game were found to voluntarily spend extra time on language learning, which led to increased learning. Besides the advantage of extra learning time, playing at home may imply that students have more control over the learning activity. This so-called learner control is often mentioned as an important motivating factor of educational computer games (e.g., Malone & Lepper, 1987), and can lead to improved learning. In a study by Cordova and Lepper (1996), for example, learner control in the form of choice of avatars and character names in a mathematics game resulted in enhanced learning outcomes. Freedom of choice concerning which game is played, and when and for how much time it is played, can also be considered an aspect of learner control (e.g., Wouters et al., 2013). When educational games are played in students' free time, this freedom of choice is larger than when they are played at school, which may lead to higher motivation in students, and consequently to higher learning outcomes.

A possible approach that combines the advantages of playing at school and those of playing at home, is to play the games at home with a debriefing at school. In this way, students are stimulated to reflect upon their experiences in the games (see Section 1.2.2).