Computers & Education 120 (2018) 13–28

Contents lists available at ScienceDirect

Computers & Education

journal homepage: www.elsevier.com/locate/compedu

Evaluating the effectiveness of a game-based rational number training - In-game metrics as learning indicators

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ARTICLE INFO

Keywords:
Interactive learning environments
Elementary education
Game-based learning
Mathematics
Rational numbers

ABSTRACT

It was argued recently that number line based training supports the development of conceptual rational number knowledge. To test this hypothesis, we evaluated training effects of a digital game based on the measurement interpretation of rational numbers. Ninety-five fourth graders were assigned to either a game-based training group (n = 54) who played a digital rational number game for five 30-min sessions or a control group (n = 41) who attended regular math curriculum. Conceptual rational number knowledge was assessed in a pre- and posttest session. Additionally, the game groups' playing behavior was evaluated. Results indicated that the game-based training group improved their conceptual rational number knowledge significantly more strongly than the control group. In particular, improvement of the game-based training group was driven by significant performance increases in number magnitude estimation and ordering tasks. Moreover, results revealed that in-game metrics, such as overall game performance and maximum level achieved provided valid information about students' conceptual rational number knowledge at posttest. Therefore, results of the current study not only suggest that aspects of conceptual rational number knowledge can be improved by a game-based training but also that in-game metrics provide crucial indicators for learning.

1. Introduction

Mathematics proficiency is crucial for educational, vocational, and personal life prospects in today's Western knowledge societies. Importantly, Parsons and Bynner (2006) stated that on an individual level, insufficient mathematical competencies may be even more detrimental to career prospects than spelling or reading deficiencies. Moreover, on a societal level, mathematical deficiencies can lead to immense costs (Gross, Hudson, & Price, 2009). Therefore, effective, innovative and engaging ways to teach basic numerical skills but also more complex mathematical capabilities, such as deep understanding of rational numbers, are needed to foster mathematical achievement.

Recent studies indicated that understanding the meaning of rational numbers and acquiring knowledge about rational numbers (i.e., fractions, decimals, and percentages) is crucial in working life and societal practices (ACME, 2011). In particular, research showed that proficiency with fractions is associated with students' success in algebra, which has been argued a gateway to STEM professions (e.g., Hansen, Jordan, & Rodrigues, 2017; Siegler, Duncan, Davis-Kean, Duckworth, Claessens, Engel, et al., 2012). Moreover, in everyday life, numerous instances, in cooking, interpreting shopping deals, and calculating loan rates etc., require

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https://doi.org/10.1016/j.compedu.2018.01.012
Received 14 March 2017; Received in revised form 15 January 2018; Accepted 16 January 2018

appropriate mastering of rational numbers. Importantly, however, rational numbers are one of the most difficult concepts to learn in primary school and even adults frequently fail to process them correctly (Gigerenzer, 2002; Siegler, Fazio, Bailey, & Zhou, 2013 for a review).

Given the difficulties that many children and even adults face with reasoning about rational numbers, traditional instructional methods should be reconsidered and complemented by new tools for enhancing rational number knowledge. In fact, previous research has indicated that digital learning games can support mathematics learning (e.g., ter Vrugte et al., 2017; Bakker, van den Heuvel-Panhuizen & Robitzsch, 2015; Riconscente, 2013; Li & Ma, 2010 for a review) as well as facilitate engagement in mathematics (Castellar, Van Looy, Szmalec, & De Marez, 2014; Ke, 2008; Kiili & Ketamo, 2017) – provided they are properly designed.

For instance, Devlin (2011) argued that well designed digital games can support numerical development and mathematical proficiency. However, many published mathematics games primarily address math facts and procedural knowledge, a focus that tends to be found in classroom practices as well. Procedural knowledge refers to sequences of actions that can be carried out to solve specific numerical/mathematical problems (Rittle-Johnson & Alibali, 1999). In the domain of rational numbers, knowing how to add fractions with different denominators is one example of such procedural knowledge. In contrast, the current study addressed conceptual knowledge of rational numbers. According to Schneider and Stern (2010) conceptual knowledge can be defined as knowledge of central concepts and principles and their interrelations in a particular domain of knowledge. In the domain of rational numbers (i.e., fractions and decimals in this study), conceptual knowledge refers to a combination of the general properties of rational numbers, such as understanding (i) fraction and decimal number notation, (ii) rational numbers as a unified system of numbers that can be placed on a number line according to their magnitudes, (iii) that rational number magnitudes can be represented in an infinite number of ways (equivalence), (iv) that there is an infinite number of rational numbers between any two rational numbers (density), and (v) the differences between whole number and rational number properties (e.g., Gabriel et al., 2012; McMullen, Laakkonen, Hannula-Sormunen, & Lehtinen, 2015; Siegler et al., 2013).

The number line estimation, magnitude comparison, and magnitude ordering tasks are common ways to study the development of conceptual rational number knowledge (e.g., Alibali & Sidney, 2015; McMullen et al., 2015; Siegler & Braithwaite, 2017). In the number line estimation task participants have to indicate the spatial position of a target fraction on a number line with only its endpoints specified (e.g., where goes 1/4 on a number line ranging from 0 to 1; e.g. Fazio, Kennedy, & Siegler, 2016; Link, Moeller, Huber, Fischer, & Nuerk, 2013; Siegler & Opfer, 2003). In fraction comparison tasks, participants are asked to either choose the larger or the smaller one of two fractions, to judge whether a statement about relative fraction magnitudes is true or false (e.g., 3/5 > 2/3), or to compare the magnitude of a given fraction to a "standard" value (e.g., is 3/7 smaller or larger than 3/5; e.g., Alibali & Sidney, 2015). Magnitude ordering tasks usually include three numbers. For example, in fraction ordering tasks, participants have to put the numbers in order from smallest to largest: 6/8; 2/2; 1/3 (e.g., McMullen et al., 2015) or are asked in which one of given sets the three fractions are arranged from smallest to largest (e.g., Hansen et al., 2017).

The study reported in this paper investigated the effectiveness of above described number line estimation, magnitude comparison, and magnitude ordering tasks in a game-based training context. To be more precise, we used our rational number game engine, *Semideus*, to develop a digital game for the training intervention (cf. Ninaus, Kiili, McMullen, & Moeller, 2016, 2017). This beta version of the Semideus School game focused primarily on conceptual rational number knowledge. Before we outline the more detailed aims and hypotheses of the current study we will first give a brief overview of the difficulties that students tend to face when learning rational numbers. The aim of the developed Semideus School game is to help students to overcome these difficulties. A detailed description of the game is provided in section 2.

1.1. Difficulties in learning rational numbers

There is accumulating evidence that even after considerable mathematics instruction many children fail to perform adequately even in simple rational number tasks (e.g., Siegler, Thompson, & Schneider, 2011; Siegler et al., 2013; Stafylidou & Vosniadou, 2004). As regards the origins of these difficulties, research on mathematics education suggested that most of students' difficulties with rational numbers can be attributed to inadequate instruction (Vamvakoussi & Vosniadou, 2010) that do not adequately take the recent developments in numerical cognition into account.

According to conceptual change theories, children form an initial conception of natural numbers as counting units before they encounter fractions and decimals. As a result, later on they draw heavily on this initial understanding of number magnitude to make sense of rational numbers (e.g., DeWolf & Vosniadou, 2015; Stafylidou & Vosniadou, 2004). The associated phenomenon called whole number bias originates from people's false belief that all properties of natural numbers can also be applied to rational numbers (e.g., 1/3 + 2/5 may be solved incorrectly by summing numerators and denominators, i.e., 1 + 2/3 + 5 = 3/8, cf. Ni & Zhou, 2005; Alibali & Sidney, 2015). Although an established understanding of natural numbers is crucial for the development of mathematical capabilities, the very same understanding of natural numbers may also interfere in mathematical reasoning when rational numbers are involved (Van Dooren, Lehtinen, & Verschaffel, 2015). The transition from a cardinal number system to a system that relies on relational properties is challenging and requires a considerable conceptual leap, in particular so, when new information to be learnt seems incompatible with existing conceptions (e.g., Siegler et al., 2011). Interestingly, the phenomenon of the whole number bias is not only observed in elementary and high school students, but also in adults and even in expert mathematicians (Alibali & Sidney, 2015).

The whole number bias has been found to cause difficulties in reasoning about the size of rational numbers (Van Hoof, Lijnen, Verschaffel, & Van Dooren, 2013), because children tend to treat rational numbers in terms of their whole number components. For instance, when comparing fraction magnitudes, children sometimes reason that the fraction that is constituted from the larger whole