Editorial: Is game-based math learning finally coming of age?

Kristian Kiili[1], Keith Devlin[2], Jari Multisilta[1]
[1]*Tampere University of Technology, {kristian.kiili, jari.multisilta}@tut.fi*
[2]*Stanford University, devlin@stanford.edu*

Acquisition of mathematical skills is crucial for today's society. Individuals who experience difficulties in learning basic mathematics can be at a great disadvantage in their professional lives. Nevertheless, fewer research efforts have been directed toward mathematical development and mathematical difficulties than toward some other areas of development, such as language and literacy [1]. In fact, it has been argued that at an individual level, insufficient mathematical competencies may be even more harmful to career prospects than reading or spelling deficiencies [2]. From a societal perspective, mathematical deficiencies can lead to significant costs. Thus, it is important to develop more engaging and effective methods that can be used to enhance children's conceptual understanding of mathematics, develop mathematical thinking processes, and improve arithmetical skills.

Digital games provide interesting possibilities to support and study mathematical development. Yes, whereas it is easy to find online mathematics training solutions, games, and apps, only a small fraction of existing mathematics learning games are (1) founded on theoretically sound principles, (2) integrate mathematics directly into the gameplay, (3) rely on good pedagogical practices, and (4) really utilize the possibilities that game technologies provide for learning.

Arguably the biggest problem is that the vast majority of video games available that set out to develop and test mathematics, focus on facts and procedures. To be sure, some of them do this very well, and provide learners and teachers with valuable supplementary tools. However, to date very few games focus on developing and measuring number sense [3] and mathematical thinking.

In large part, this is because developers set out to create games that fit into familiar pedagogic models. But it is also the case that it is considerably more difficult to develop games that develop and assess number sense and mathematical thinking. It can be argued that the lack of well-designed mathematics games has in fact hampered the research in this field, and as a result more high quality research about the usefulness of mathematics digital games is needed.

It is not only mathematics that players learn when they play digital games. Games can also teach problem-solving, collaboration and critical thinking. These skills are among the 21st-Century Skills or key competence skills that are considered to be crucial in evolving societies. According to Lewis and Smith [4] higher order thinking consists of problem solving, critical thinking, creative thinking and decision making. They define higher order thinking so that "higher order thinking occurs when a person takes new information and information stored in memory and interrelates and/or rearranges and extends this information to achieve a purpose or find possible answers in perplexing situations" [4]. The definition describes well the process of the gameplay of an ideal mathematics game.

The aim of this special issue is to shed light on the usefulness of mathematics digital learning games and provide knowledge to support the development of high quality games for learning mathematics.

The first three articles [5,6,7] contribute to research on number sense. Number sense is a central theme in current cognitive and developmental psychology, educational psychology and the (psychology of) mathematics education (e.g., [1, 8]). Number sense refers to abilities to rapidly and accurately perceive small numerosities, to approximate and compare numerical magnitudes, and to comprehend simple arithmetic operations [3, 9]. Development of games that facilitate number sense is important, because the acquisition of number sense seems to create transfer effects to other, and more complex, areas of mathematics.

In a first article, Pope and Mangram [5] report the results of a study in which they investigated the effectiveness of the *Wuzzit Trouble* game with respect to children's number sense. (See section 2.3 of their paper for an introductory discussion of the number sense concept.) In this quasi

experimental study, third-grade students (n = 59) played *Wuzzit Trouble* for a total of 120 minutes spread over a four-week period. The results showed that even such a relatively short engagement with *Wuzzit Trouble* increased the treatment group's number sense, as measured with a paper based mathematical test.
Pope and Mangram identified two features inherent in *Wuzzit Trouble* in particular that enhanced learners' number sense. First, *Wuzzit Trouble* promoted mathematical proficiency by requiring learners to attend to several mathematical constraints at once. Second, the game engaged players in an iterative problem solving process in which players created, tested, and revised their strategies as they solved the puzzles of the *Wuzzit Trouble* game.

In a second article, Fischer, Moeller, Huber, Cress, and Nuerk [6] introduce a spatial-numerical training exercise that was designed to improve children's arithmetic abilities. In their pilot study (n = 32), the experimental group conducted number-line estimation tasks on an interactive whiteboard by moving their whole body to the left or right (the number line ranged from 0 to 100 or from 0 to 1000). The results showed that the full-body numerical training led to greater improvements in all dependent measures than the two control trainings: 1) training on the same task without the full-body movement and 2) training on a different task with full-body movement. Fischer et al. conclude that full-body movement (embodied user interfaces) can enhance the efficiency of numerical trainings and can be incorporated into the classroom. Furthermore, they argue that similar training exercises could be successfully utilized in serious games and implemented for different technological platforms. In fact, the *Semideus* rational number game (for iPads) that is studied in the third article [7] is based on a similar number-line training approach.

The third article also focuses on number sense, and is strongly related to the first two articles of this special issue. In this article Kiili et al [7] report a study in which they investigated the usefulness of two different mathematics video games, *Semideus* and *Wuzzit Trouble*. The primary focus of the article is the possibility that games provide for assessment of learning. In the study, Kiili et al. validated the *Semideus* game as a rational-number test instrument, and used it as a pre- and post-test in a *Wuzzit Trouble* intervention study.
The learning outcomes measured were quantitively very similar to those revealed in Pope and Mangram's [5] study, but in this case the three-hour *Wuzzit Trouble* intervention led to a measured improvement not of integer arithmetic (which *Semideus* does not directly measure) but conceptual rational-number knowledge. Because the sample sizes in both studies were small, more research on this topic is needed. That caveat notwithstanding, Kiili et al. conclude that game-based assessment can create a more complete picture of mathematical knowledge than simply measuring students' task accuracy, providing in addition indicators of student misconceptions and conceptual change processes.

The fourth article investigates the use of the didactic possibilities in mathematics education of a real-time strategy video game called *Vector Tower Defense 2*. Hernández-Sabaté, Joanpere, Gorgorió and Albarracín [10] conducted a qualitative research study that aimed to identify mathematics learning opportunities (mathematical problem solving situations) in a commercial tower defence game. The authors analysed 10-12 years-old children's playing behaviour and identified different kind of mathematical learning opportunities.
They argue that the tower defence games can promote mathematical problem-solving processes. However, they also pointed out that students do not always try to solve problem situations in the game mathematically; a teacher or supporting game elements might be needed to facilitate the mathematical problem-solving processes. The authors provide examples of how the entertainment game can be extended to create a learning tool that trigger mathematical decision making and reflection processes.

Finally, the fifth article contributes to a very important serious games design issue – integration of game mechanics and learning content. In this article Kalloo, Mohan, and Kinshuk [11] propose a technique for mapping mathematics content to the game concept. The technique is based on mathematics learning pedagogy, the mathematics curriculum, game type categorization, game design patterns, and past research experience. In their article, the authors report the results of a preliminary evaluation of the technique conducted with amateur game designers. Although the technique has several limitations, the evaluation results indicated that it was useful and helped the game designers to design suitable mathematics learning games.

To summarize, all articles of the special issue focus on supporting mathematics learning with games, but their theoretical, methodological, and educational relevance is broader. First of all, the presented research shows that even relatively short mathematical game interventions can be effective. Second, well designed games can engage learners and facilitate a positive learning attitude. Third, games can provide non-intrusive ways to assess learners' mathematical knowledge and skills and support teachers work. Fourth, it is possible to achieve transfer, for example from the integer-based arithmetic of *Wuzzit Trouble*'s puzzles to the rational number tasks of *Semideus*.

The report of transfer will strike many as surprising, and clearly requires further investigation. It may be a consequence of a number of factors. One possibility is that the locus of learning is number sense (which is common to both integer arithmetic and fractions), rather than specific skills. But it may well be that other factors are also at play. We suggest some of these below.
Based on the contributions of this special issue, we can argue that games designed as complex performance tasks can enhance number sense, mathematical thinking, and overall problem-solving ability. But what features of games are the most significant in producing such outcomes? Some examples that need further investigation are (in addition the the development of number sense, mentioned above):

- increased engagement with mathematical ideas
- support for embodied numerisity [12] in games
- positive attitude towards – and a willingness to engage in – numerical practice and problem solving
- willingness to "play with the problem" before (or instead of) trying to find and apply a solution technique
- willingness to take risks and learn through failure
- growth mindset [13]
- fluid intelligence (*Gf*) – a complex human ability that allows us to adapt our thinking to a new cognitive problem or situation [14].

Mathematical puzzle games encourage, support, reward, and develop all of these traits, so it is possible that all play a role.

Of course, from the perspective of a student, teacher, or parent, the important issue is that the children who play such a game shows significant gains in number sense and problem solving ability. But from both a scientific perspective, and to inform the design of future learning games, we need to understand as best we can what is going on. Thus, we call for more high quality research on this topic.

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