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Research paper

Training numerical skills with the adaptive videogame "The Number Race": A randomized controlled trial on preschoolers

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ABSTRACT

Adaptive computer games offer an attractive method for numeracy training in young children. However, the evidence for transfer of learning to standard measures of numerical and arithmetic skills is scarce. We carried out a randomized controlled trial on a sample of preschool children of middle socio-economic status to evaluate the effectiveness of the freeware videogame "The Number Race" (Wilson et al., 2006). Children were randomly assigned to the training group or to the control group performing an alternative computer-based activity matched for duration and setting. The groups were matched for age, gender, and IQ. Training yielded large improvements in mental calculation and spatial mapping of numbers, as well as smaller improvements in the semantic representation of numbers. Our findings complement previous studies that showed beneficial effects for disadvantaged children, thereby suggesting that "The Number Race" is a valuable tool for fostering mathematical learning in the general population of young children.

1. Introduction

Proficient mathematical learning represents a key aspect of academic achievement and it is also an important skill for the 21st century competitive workforce [1]. Mathematical achievement can be considered a socio-economic goal from both a national and individual perspective. It has been estimated that an increase in half a standard deviation in mathematics and science performance can significantly enhance annual growth rates of GDP (i.e., gross domestic product) per capita of 0.87% [2,3]. Moreover, individuals with poor mathematical achievement are more likely to be unemployed, incur depression, or have trouble with law [4]. In light of this, early intervention in strengthening basic numerical skills may promote learning in later stages of development [5] and prevent failure in school mathematics. Recently, several low-technology math training programs (i.e., based on instruction and/or paper-pencil activities) have demonstrated efficacy in fostering number sense, numerical knowledge and math skills in young children [6–16].

There is also growing interest in the use of computer-based training to improve numerical skills and math learning [17]. Computer-based training offers several practical advantages compared to more traditional training programs: (i) presentation of information can readily exploit multiple sensory channels (e.g., visual and auditory); (ii) training is individually and progressively delivered (e.g., presenting small core concepts at the beginning and more complex problems later); (iii) reinforcement of acquired information is guaranteed by rapid positive feedback; (iv) learners can usually control their navigation through tasks and deploy an active style of learning; (v) training can be more entertaining, and the use of an adaptive algorithm based on individual performance substantially decreases the need for supervision [18]. Moreover, computer-based training may come in the form of interactive games, which provide an alternative way for learning and teaching, and may additionally decrease math anxiety, enhance time on task, combine learning and fun, place math content in an exploratory and challenging context [2,19]. It is also worth noting that videogame playing does not only improve game-related skills but it furthermore enhances a variety of cognitive abilities, in particular attention and executive control [20,21]. In the last decade, several computer games have been released with the aim to promote numerical and mathematical learning in both typically and atypically developing children [22–34].

In the present study we assessed the effectiveness of the Italian version of the freeware adaptive videogame "The Number Race"

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[35] (hereafter NR; the software can be downloaded from http://www.thenumberrace.com). The game is based of four principles: enhancing number sense, cementing the links between representations of number, conceptualizing and automatizing arithmetic, and maximizing motivation. The player competes against the software in a numerical comparison task by choosing the larger between two numerical quantities that range from 1 to 9. The numerical quantities can be represented either as object sets (i.e., non-symbolic), digits, or as the result of small additions or subtractions (which can also involve zero). Visual presentation is also supplemented (depending on game level) by the corresponding spoken number-words. The child is given the opportunity to select one of the numerical quantities, and the other quantity is then assigned to the opposing player controlled by the software. The difficulty of the task is modulated by varying the numerical distance between sets, the time limit for responding, and the format of the displayed quantities (from simple non-symbolic comparison to more complex symbolic calculation). An adaptive algorithm modulates these three dimensions in order to keep task difficulty optimally challenging (approximately 75% of accuracy) for each child, thereby working in the individual "zone of proximal learning" [36]. After each numerical comparison, the child is presented with a new screen in which she has to advance the game characters on a linear board for the number of spaces (i.e., cells) that correspond to the numerosities previously shown in the comparison trial. Though the numerical board is composed of forty cells (arranged in four rows of 10 cells each), all the numerical quantities presented in the game are smaller than ten (note that a version of the game with number up to 40 has been recently made available). The race ends when one of the players (i.e., the child or the computer) has reached the 40th position on the board. The game then proposes to start a new race and winning six races allows the player to unlock a new game character that can be used by the child. Verbal and sound feedbacks are continuously provided throughout the play to foster motivation.

At the easier levels, the child is instructed to select the larger between two non-symbolic numbers (i.e., sets of objects), which are progressively substituted by Arabic digits and arithmetic operations. The ability to compare the numerosity of two sets is at the heart of the number sense [37,38] and it is thought to be linked to math achievement [39–41]. Indeed, numerosity comparison has been found to be impaired in children with mathematical learning difficulties [42–44]. In addition, recent studies have demonstrated that training numerosity comparison or non-symbolic arithmetic has a positive transfer to symbolic numbers and math [45,46]. In a broader perspective, the ability to compare numerical quantities (non-symbolic and symbolic) and understand magnitude relationships between numbers and sets constitutes a foundational skill for young children [40,47–55].

The mixing of numerical formats in the game strengthens the connections between different numerical representations (i.e., non-symbolic, symbolic, verbal) [56]. In particular, the repeated association between digits and the corresponding non-symbolic quantities can consolidate access to numerical meaning via symbolic notation, which has been highlighted as a crucial deficit in developmental dyscalculia [57,58]. The game also fosters the spatial representation of numbers [59,60] by asking the player to move the game characters on a linear board, thereby associating the numerosity of the sets with an equal linear space. The ability to correctly place numbers on a visual line [61] (e.g., in the "number-to-position" task) supports the understanding of the magnitude relation between numbers in preschool children [62,63] and correlates with math achievement in primary school pupils [55,64]. Accordingly, children with math difficulties show a reduced accuracy in mapping numbers onto a spatial position [65–67]. Moreover, training spatial mapping of numbers is a useful tool for improving numerical skills in preschool children [10–12,68].

To the best of our knowledge, there are only four studies that formally assessed the effect of training with NR on numerical and mathematical competence [31,33,34,69]. The first study was an open trial (with no control group) carried out by Wilson et al. [33] shortly after the release of the game and it targeted primary school children with mathematical learning disability (i.e., dyscalculia). At pre-test, children completed a series of tasks assessing counting, transcoding between different number formats, enumeration, syntactic comprehension, arithmetic (e.g., addition and subtraction), and both symbolic and non-symbolic numerical comparisons. Children individually played the game in half-hour sessions over a period of five weeks, for a total average play time of 8 hours. Results demonstrated significant improvements in number sense measures (e.g., subitizing, numerical comparison) and subtractions. In a subsequent study, Wilson and colleagues [34] tested the NR in a sample of low socio-economic status preschool children. The study had a cross-over design and used commercial software targeting reading skills as control condition. The NR mainly improved the accuracy in comparing digits whereas the ability to compare non-symbolic numerosities did not improve. These results led the authors to conclude that the game fosters access to numerical meaning from symbols rather than improve number sense per se. Similar results were found by Rasanen and colleagues [31] in a randomized controlled trial on a sample of children with low-numeracy skills; NR specifically enhanced number comparison ability, but there was no evidence for an effect on other numerical skills. Finally, Obersteiner, Reiss, and Ufer [69] modified the NR in order to increase reliance on numerical approximation (approximate version of the game) as opposed to the use of exact numbers (exact version of the game). In a randomized controlled trial on first graders, the approximate version of the NR improved performance in tasks tailored to assess numerical estimation skills, whereas the exact version improved performance in tasks requiring exact representation of numbers, without any cross-over effect. Both versions significantly improved arithmetic performance.

The previous studies adopting the original version of the NR involved low-income preschool children or children with math difficulties in order to compensate for their poor basic numerical skills [31,33,34]. In the present study, we implemented a Randomized Controlled Trial (RCT) to assess the effectiveness of the Italian version of the NR [70] for enhancing basic numerical skills in a general sample of preschoolers (mostly belonging to families of middle socio-economic status). Thus, one important aim was to establish whether the NR might be a valid tool for training number skills in the general population of preschoolers. Moreover, we designed the study so that the training sessions mimicked a realistic school scenario (e.g., short sessions in large groups with minimal supervision), thereby respecting practical constraints that teacher or educators would face when using the NR as part of their curricular activities. Finally, we mainly based our analyses on measures of effect size to better highlight the practical significance (as opposed to just statistical significance [71]) of the results. We expected to replicate the findings of previous studies, with the training group demonstrating improvements in number comparison and arithmetic, relative to the control group.

2. Material and methods

2.1. Participants

Forty-five preschool children from a preschool located in north-eastern Italy took part in the present study after obtaining informed consent from parents or legal guardians. The study was