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Walk the number line – An embodied training of numerical concepts

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ABSTRACT

Basic numerical representations such as the spatial representation of number magnitude seem to develop during early childhood and predict later arithmetic abilities. Moreover, the concept of embodied cognition suggests that seemingly abstract representations may be based on bodily experiences.

An embodied intervention program was developed addressing the spatial representation of number magnitude. First-graders were trained to indicate the position of a given number by walking to the estimated location of that number on a number line on the floor. This training was compared to an identical number line training without task-specific full-bodily experiences.

Children showed more pronounced training effects after the embodied training than after the control training. These differential training effects even generalized partially to specific numerical competencies not trained directly. Thereby, these data corroborate beneficial effects of embodied processes for the training of seemingly abstract cognitive representations in general and for the amelioration of basic numerical representations in particular.

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1. Introduction

The acquisition of mathematical skills and possible numerical impairments are of great relevance for modern societies [7] both, for individuals and also for educational and economic systems in general [39,19]. On an individual level, insufficient mathematical competencies may be even more harmful to career prospects than reading and spelling deficiencies [8,39]. Regarding implications for society Beddington and colleagues [4] (see also [7,18]) argued that untreated learning difficulties can lead to immense costs. For instance, in the UK, the annual cost of low arithmetic skills has been estimated at £2.4 billion in general [19] and, if co-morbidities with literacy deficits are excluded, at £763 million per year. However, beyond current costs arithmetic skills may also significantly affect the future of societies. The OECD suggested that "an improvement of one-half standard deviation in mathematics and science performance at the individual level implies, by historical experience, an increase in annual growth rates per capita of GDP of 0.87%" ([38], p. 17). The OECD concluded that this could lead to sustained economic growth because time-lagged correlations show a reliable relationship between the improvement of arithmetic skills and later economic development.

With respect to the current study, it is important the aforementioned impressive numbers are suggested to be dealt with by means of numeracy interventions. Gross and colleagues [19] argue that about £1.6 billion of the £2.4 billion annual costs for the UK could eventually be saved if effective numeracy interventions are applied. Giving these numbers, the need for effective numeracy interventions improving arithmetical skills is obvious both for children with dyscalculia and also for low-performing children without formal clinical impairment. However, developing effective (numeracy) interventions is difficult and a matter of great debate. In fact, in a meta-analysis specifically focusing on methodological aspects of recent intervention studies (since 2000) Fischer, Moeller, Cress and Nuerk [15] found stricter evaluation designs (e.g., comparable control groups) to lead to smaller effect sizes. Taken together, we are still in need for effective numeracy intervention methods that are valid and sustainable. In this manuscript, we will propose and evaluate a new intervention concept incorporating two upcoming theoretical developments: first, the idea that complex arithmetic abilities build on basic numerical representations and second, the concept that seemingly abstract representations are based on our sensory and bodily representations (picking up on the concept of embodied cognition, e.g., [1]).

Already 20 years ago, evidence suggested that numerical competencies are not a unitary concept but can be differentiated into different basic numerical representations recruited systematically depending on the task at hand (e.g., procedural knowledge, arithmetic fact knowledge, etc., e.g., [49]; see also [13], for an

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overview of individual differences in arithmetic abilities). When looking at the development of numerical competencies it is important to note that more advanced arithmetical skills in school-age children seem to develop on the basis of more basic numerical representations some of them acquired at the beginning or even before school entry [34,24,25]. For instance, in a longitudinal study Moeller and colleagues [34] observed that children's addition performance in grade three was predicted reliably by their first-grade performance in tasks such as transcoding and magnitude comparison recruiting basic numerical–verbal and magnitude representations. This argument is further corroborated by a meta-analysis of mathematics intervention programs for elementary school children with special needs indicating that interventions which specifically train basic numerical representations are among the most effective (e.g., [26]; see [29] for a meta-analysis; see also [15], for a meta-analysis on methodological aspects of intervention studies). So, it seems particularly beneficial to concentrate on the underlying basic numerical representations when trying to promote children's numerical competencies.

Apart from the above mentioned representations, the ‘mental number line’ is another of these basic numerical representations (e.g., [36,32]). The mental number line describes a spatial representation of number magnitude along an analog number line which is assumed to be activated automatically whenever we encounter a number [43,35,10]. In western cultures the mental number line seems to be spatially coded with numbers ascending from left to right, associating relatively smaller numbers with the left and relatively larger numbers with the right side of space (for overviews see [12,53]). With the number line estimation task Siegler and Opfer [45] (see also [40] for earlier suggestions) introduced a method for specifically investigating the mental number line representation and its development in children. In the task participants are asked to estimate the position of a given number on an otherwise empty number line of which only the endpoints are specified (varying: 0–10, 0–100, 0–1000, etc.).

Recent studies using the number line estimation task indicate that the precision of children's mental number line develops with age and experience (e.g., [44]). Initially, they usually overestimate the spatial position of relatively smaller numbers within a given range (e.g., estimating 10 at the position of 40 approximately within the range 0–100; [33]). Only after they understood the equidistance relation of numbers on the mental number line (i.e., that the spacing between numbers is constant along the number line) children show a linear estimation pattern with a one-to-one correspondence of to-be-estimated and actually estimated number. Importantly, an accurate spatial representation is a reliable predictor of actual as well as future arithmetic abilities. For instance, Booth and Siegler [5] observed that children who performed better in the number line estimation task not only showed relatively better arithmetic abilities but also experienced less difficulties in learning new and unfamiliar addition problems. In line with this, Geary, Hoard, Nugent, and Bailey [16] showed children with developmental dyscalculia to present with impaired number line representations (see also [50,17]).

Furthermore, several studies indicated that it is possible to train the accuracy of the spatial representation of number magnitude in both typically developing children (e.g. [41,46,47,52]) as well as those with developmental dyscalculia [30]. Interestingly, Ramani and Siegler [41] found that playing simple linear number board games not only improves the spatial accuracy of the mental number line but also promoted the performances in other numerical tasks such as counting abilities, number naming, and number comparison that were not trained directly during the linear board game ([41,47]; see also [52]). Taken together, the results of these studies indicate that a training of the spatial representation of numbers corroborates more than just the adequate mapping of numbers onto the mental number line but generalizes to other numerical competencies. Interestingly, it seems to be the linear nature of the training games that specifically drives the beneficial effects. Comparing the use of linear number board games to colored [41] and circular ordered [47] board games, Siegler and colleagues observed that children's numerical competencies (in the trained but also in transfer tasks) improved most after playing the linear board game. Besides these behavioral data, Kucian and colleagues [30] also observed effects of a computerized number line training to lead to changes in neural brain activation. Activation patterns of children with dyscalculia became more comparable to those of typically developing children through the number line training. In summary, these findings support the claim that an improvement of accuracy of the mental number line is associated with better numerical performance in general and that it is the linear fit between the external training scheme and the internal number line representation, in particular, that drives the training effects observed.

Theories on embodied cognition proposing sensori-bodily foundations of higher cognitive concepts (including numbers) recently gained wide-spread recognition and empirical support (e.g. [51,1,2]). Employing the concept of embodiment, Fischer, Moeller, Bientzle, Cress and Nuerk [14] picked up on the fit between external and internal number line representation but expanded the idea of ‘moving along the number line’ as was previously pursued in playing linear number board games [41]. They realized a new and so far unique idea of training the spatial representation of numbers by using a sensorimotor training concept. Referring to theories of embodied cognition Fischer and colleagues [14] not only matched the training task with the underlying to be trained mental number line representation but also incorporated systematic full-body movements to allow for an embodied experience of the trained numerical concept. Using a digital dance mat Fischer et al. [14] trained kindergarten children with a number magnitude comparison task where children moved their whole body to respond. With the task presented on the floor in front of the dance mat children had to take a step to the left to indicate a given number to be smaller than a standard and a step to the right to indicate a number being larger than the standard. The results were very promising as they reflected more pronounced training effects on children's number line estimation performance after the embodied training compared to the control training. Additionally, a transfer effect indicating a specific improvement of children's counting principles was observed following the embodied training. This indicates that a systematic full-body experience corresponding to the underlying mental number line representation recruited in the training task added significantly to the training effect.

It is important to note that Fischer et al. [14] observed these beneficial effects of a bodily-sensory training even though the implemented movement in number space was limited to either one step to the left or right. Yet, as the mental number line is assumed to be continuous instead of categorical this raises the question why not train the mental number line as it is – in a continuous manner? Starting from this question, the current study aimed at investigating the influence of an embodied numerical training allowing for free and continuous movements in number space. By using the Xbox sensor system Kinect a number line of up to 3 m of length was realized that allowed for spatial number line estimations. As children had to solve the task by walking to a given number's position, they experienced the larger numbers as further distances to walk upon the number line as compared to the smaller numbers. However, while the control condition was identical with respect to trained content it only involved unspecific body movements not systematically related to number line estimation and thus without any systematic embodied experience

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