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Sensori-motor spatial training of number magnitude representation

Ursula Fischer · Korbinian Moeller · Martina Bientzle · Ulrike Cress · Hans-Christoph Nuerk

Abstract An adequately developed spatial representation of number magnitude is associated with children's general arithmetic achievement. Therefore, a new spatial-numerical training program for kindergarten children was developed in which presentation and response were associated with a congruent spatial numerical representation. In particular, children responded by a full-body spatial movement on a digital dance mat in a magnitude comparison task. This spatial-numerical training was more effective than a non-spatial control training in enhancing children's performance on a number line estimation task and a subtest of a standardized mathematical achievement battery (TEDI-MATH). A mediation analysis suggested that these improvements were driven by an improvement of children's mental number line representation and not only by unspecific factors such as attention or motivation. These results suggest a benefit of spatial numerical associations. Rather than being a merely associated covariate, they work as an independently manipulated variable which is functional for numerical development.

Keywords Number processing · Spatial-numerical association · Mental number line · Embodied cognition · Training · Magnitude comparison

U. Fischer (✉) · M. Bientzle · U. Cress
Knowledge Media Research Center,
Konrad-Adenauer-Straße 40,
72072, Tuebingen, Germany
e-mail: u.fischer@iwm-kmrc.de

K. Moeller · H.-C. Nuerk
Institute of Psychology, Eberhard Karls University,
Tuebingen, Germany

Introduction

Basic numerical competencies as predictors of future arithmetic achievement

The notion that children's early basic numerical competencies reliably predict their future arithmetic abilities has received growing interest in recent years (e.g., Booth & Siegler, 2008; Holloway & Ansari, 2009). One of these basic numerical skills thought to hold particular importance for mathematical development is the processing of the spatial representation of number magnitude.

Dehaene, Bossini, and Giraux (1993) proposed numerical magnitude to be represented in ascending order along a left-to-right oriented mental number line on which numbers are spatially coded and reflected in an analogue format. This number line representation is supposed to be accessed automatically whenever a number is encountered and it is assumed to develop as early as first grade of elementary school (Berch, Foley, Hill, & McDonough, 1999; van Galen & Reitsma, 2008). Throughout development, the accuracy of the positioning of numbers along the mental number line increases with age and experience (Booth & Siegler, 2008). The most direct measure for examining the spatial magnitude representation is the *number line estimation task* (e.g., Siegler & Opfer, 2003). In this task, participants have to indicate the spatial position of a given number (e.g., 37) on a hypothetical number line (e.g., ranging from 0 to 100). Accuracy of the number line representation is then inferred from the distance between participants' estimations and the actual positions of the to-be-marked numbers.

It has been shown repeatedly that the accuracy of children's number line representation influences their arithmetic achievement. For instance, Booth and Siegler (2008) observed that children with a more accurate number line representation performed better in arithmetic tasks and, more importantly, also learned answers to unfamiliar arithmetic problems more easily. These findings suggest a functional association between the quality of the mental number line representation and later arithmetical development. Accordingly, number line tasks have been included in successful intervention approaches for dyscalculia, such as the *Number Worlds Curriculum* (Griffin, 2003; originally published as *Rightstart*; Griffin, Case, & Siegler, 1994).

Seeing as the mental number line representation constitutes an association between numbers and space (as proposed by *A Theory of Magnitude*, see Bueti & Walsh, 2009), it has been found to be moderated by bodily experiences—such as in the case of finger counting (e.g., Fischer, 2008)—corroborating the notion of embodied cognition which will be introduced in the next section.

Embodied cognition

According to recent findings in neuroscience (e.g., Andres, Olivier, & Badets, 2008), the motor system not just controls and/or monitors actions, but may also contribute to cognitive representations. For example, Goldin-Meadow, Nusbaum, Kelly, and Wagner (2001) observed that being allowed to gesture while solving mathematical problems reduced children's cognitive load. Moreover, Gherri and Eimer (2010) found that preparation of a manual response on one side in space severely disrupted the direction of attention to stimuli on the other side, and explained these results by shared brain circuits responsible for the control of spatial attention and action.

As a possible explanation of such and other findings, several theories of *embodied cognition* have been proposed (see Wilson, 2002, for an overview). While these theories differ in their definitions of what exactly the term *embodied cognition* entails, the most basic interpretation is that human cognition is originally rooted in sensori-motor processes and thus determined by bodily experiences. Such an interaction between the cognitive and physical world has been theoretically elaborated by Hommel, Müsseler, Aschersleben, and Prinz (2001) in the *Theory of Event Coding (TEC)*. While TEC is not strictly speaking a theory of embodied cognition, it provides an interpretative framework for many of the respective findings. In contrast to traditional views on cognitive processing, TEC proposes that perceived and action-related events are coded, stored and integrated in a common network of *feature codes*. These feature codes register input from sensory systems and modulate activities of motor systems based on this input and internalized experiences. When a given stimulus is processed, it first activates all stimulus-related feature codes, both perceptual and action-related. Hommel et al. (2001) give the example of perceiving a cherry. This cherry activates the feature codes representing its attributes such as RED, ROUND, and SMALL. These feature codes are then integrated into the *event code* CHERRY that represents all features of an event in a shared medium. Activation of one feature code (e.g. RED) now facilitates further activation of other feature codes (ROUND and SMALL) if they are part of the same event code (CHERRY). Subsequently, when the event code CHERRY is activated, this facilitates both the perception of other objects that are red, round, and small as well as actions directed towards events that also hold these features. Inversely, selecting the features of a to-be-planned action will facilitate both the perception and the production of other events this action shares features with. In this vein, a task becomes easier to solve the more features are shared by (sensori-perceptual) stimulus and (bodily) response.

While Hommel and colleagues did not examine the connection of numerical magnitude and motor activity, the idea of an embodied representation of numerosity has been considered by other researchers (e.g., Domahs, Moeller, Huber, Willmes, & Nuerk, 2010). For example, finger counting habits (e.g., Fischer, 2008) have been shown to be strongly related to spatial numerical processing. Also, Gracia-Bafalluy and Noël (2008) found that an improvement in finger gnosis has a positive effect on arithmetic achievement. It thus seems plausible that performance in numerical tasks could be promoted when stimulus and response formats share common spatial attributes.

Applying sensori-motor spatial training to enhance basic numerical skills

Previous studies (e.g., Fischer, 2008; van Galen & Reitsma, 2008) on the relationship between the processing of numbers and their spatial representation typically examined this relationship in a correlational approach. Siegler and Ramani (2009) were among the first to investigate the interdependency of number and space in actual learning: They highlighted spatial attributes on the side of perceptual input but not on the response side. However, to entirely exploit the potentially beneficial influence of the spatial properties of numerical cognition on learning, it would be necessary to create the highest possible overlap in feature codes by not only presenting stimuli in a spatially organized perceptual format but providing subjects with the possibility of responding spatially as well.

Therefore, we developed a *sensori-motor spatial training program* in which children were trained on a magnitude comparison task. We ensured to increase the number of shared feature codes by using a *digital dance mat* that allowed for bodily responses as input device. This should subsequently lead to a stronger activation of the mental number line representation that shares the spatial features of the task's presentation and response format. As its activation increases, the accuracy of the mental number line representation should improve more in comparison to an identical training with non-spatial stimulus and response format using a tablet PC as input device.

Most importantly, we hypothesize two ways of transfer in this study: (i) Specific spatial-numerical transfer: Training on the dance mat should lead to larger improvements in spatial-numerical tasks than the control training. (ii) Generalizing transfer: Effects of the spatial-numerical training should transfer to other numerical tasks that do not directly address spatial-numerical associations.

Method

Participants

Twenty-two (nine girls and 13 boys) children aged 5–6 years ($M = 5;10$) were recruited from two kindergartens in the vicinity of Stuttgart. Three children were subsequently excluded from data analysis because they either missed training sessions or performed 1.5 SD slower than the other participants on the pretest. None of the children exhibited obvious attentional or verbal difficulties. Written informed consent was obtained from parents, and children were randomly assigned to the two conditions.

Tasks and materials

Children received training on a magnitude comparison task in an experimental and a control condition. In both conditions, they performed the same task with identical stimuli. The conditions only differed in respect to presentation and response format. While in the experimental condition, children's performance in the magnitude comparison task was supported by additional presentation of a spatial number line and the use of a dance mat for spatial-motor responses, in the tablet PC control condition neither presentation nor response format contained explicit spatial information. Both training conditions used identical stimulus sets with Arabic digits or square assemblies, with presented magnitudes ranging from 0–10 or from 0–20, and with fixed or variable standards (5 or 10). All children were trained in both conditions; however, evaluation was only conducted after each training condition with all above stimulus types was completed. Prior to the task, children were instructed not to count the number of squares in the assemblies but to estimate their quantity. Figure 1 depicts examples of items in the two conditions.

The dance mat's fields were arranged in a 3 × 3 layout of which only the middle row was used. To evoke a response the fields to the right and left of the central field had to be stepped on with both feet. In the tablet PC control condition, children responded by touching the display with an electronic pen.

Design and procedure

To provide all children with the possibility of training with the dance mat, we chose a parallel randomized cross-over design. One half of the children first trained on the dance mat and then on the tablet PC, while for the other half the order of training conditions was reversed. Each child received three training sessions per condition, each session consisting of 64 to 72 items and taking 10 to 15 min. The six sessions were carried out individually within a period of 3 weeks.

In the experimental condition, children were standing on the middle field of the dance mat and the trials were

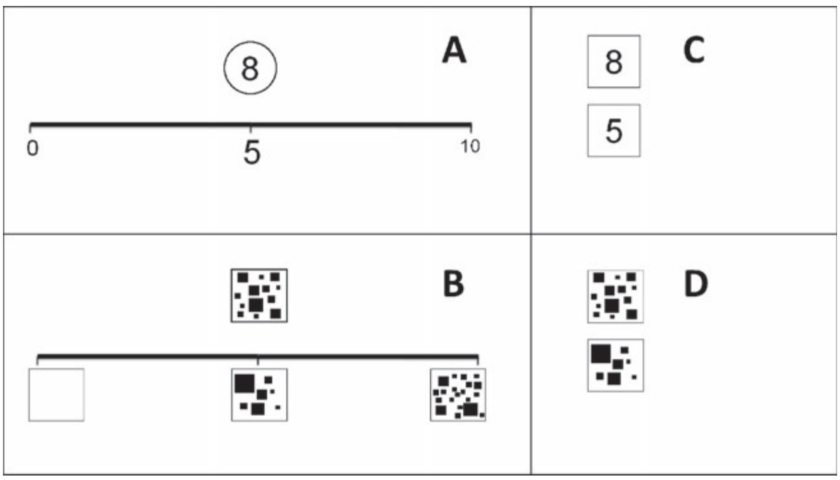

Fig. 1 Examples of stimuli in both presentation formats in the dance mat condition (with *A* Arabic numbers and *B* square assemblies) and in the tablet PC condition (with *C* Arabic numbers and *D* square assemblies)

projected onto the floor directly in front of them. Children had to compare the magnitude of a presented number/square assembly to that of a simultaneously presented standard. The standard was presented together with its position on a hypothetical number line. Children had to compare the two magnitudes by taking a step to the left for probes smaller and a step to the right for probes larger than the standard. Contrarily, in the control condition children only had to tick the larger of two numbers presented simultaneously on the tablet PC with no systematic spatial-numerical correspondence.

Pre- and posttests

To assess possible improvements, children's performance was tested thrice: prior to training, after training in one condition and again after training in the other condition. In a paper-and-pencil number line estimation task (e.g., Siegler & Opfer, 2003), children had to indicate the position of 18 numbers on lines ranging from 0–10 or 0–20. The relevant variable in these tasks was the distance between the children's estimates and the actual position of the number in millimeters. Moreover, to assess transfer effects onto other numerical competencies, we tested children on five subtests of the TEDI-MATH (Kaufmann, Nuerk, Graf, Krinzinger, Delazer, & Willmes, 2009) designed for the assessment of preschoolers: In the *counting principles* subtest, children's mastery of the verbal counting sequence and its flexibility is tested (e.g., counting in steps of two, counting backwards, etc.). The *object counting* subtest evaluates how well children can count objects (by having them count objects in a picture) and whether they understand relevant concepts such as cardinality. The *Arabic digits* and *number words* subtests assess children's knowledge of digits and number words by testing whether they can discriminate them from other symbols and words. Finally, in the *calculation* subtest, simple addition and subtraction problems are given in a pictorially supported format. We expected to find the largest improvements on subtests that tap most directly into children's understanding of magnitudes, namely the *counting principles* and *object counting* subtests.

Results

To analyze differences between the two conditions' effects on performance in the post-test tasks, we compared the improvement of children over the three dance mat training sessions to their improvement over the three tablet PC training sessions, regardless of which one of the two training blocks children received first. Therefore, paired *t*-tests were used to evaluate the significance of the improvement differences in the number line task as well as the TEDI-MATH subtests.

Specific spatial-numerical transfer: number line task

Data for the two order groups (starting with the dance mat or the tablet PC training) were collapsed because a repeated measures ANOVA yielded no significant main effect of condition order [$F(1,18) = 2.24$, $p = 0.15$] and no significant interaction effect between order and children's improvement in either condition [$F(1,18) = .76$, $p = 0.40$], suggesting that the order of conditions did not influence children's performance.

In line with our expectations, the increase in accuracy of the spatial position of children's estimates on the 0-10 scale was stronger after the dance mat training as compared to the tablet PC control condition [$t(18) = 2.17$, $p < 0.05$, tested one-sided, $d = .68$, see Fig. 2, Panel a]. However, no comparable dissociation of training conditions was present for estimates on the 0-20 scale [$t(18) = 1.00$, $p = 0.33$, $d = .19$].

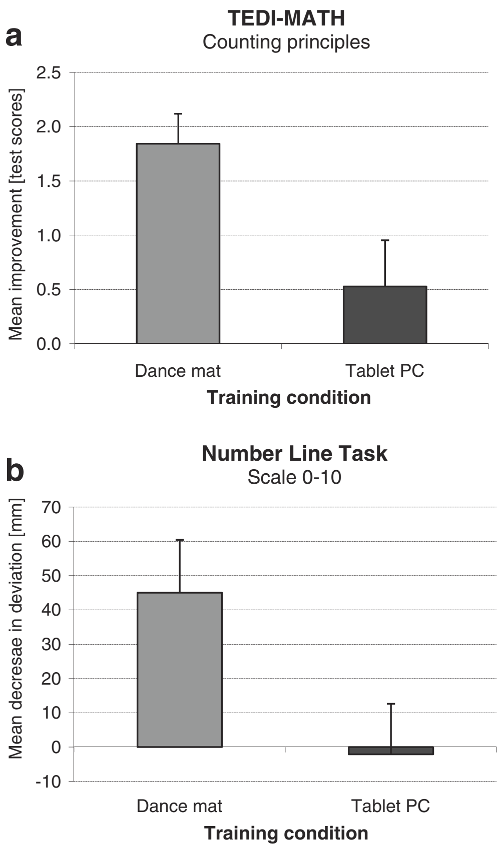

Fig. 2 Children's improvement in the dance mat and tablet PC conditions. **a** Mean decrease of deviation (in mm) between number as positioned by the children and true position of the number on the 0 to 10 number line task. **b** Mean of children's improvement (in test scores) on the *counting principles* subtest of the TEDI-MATH

Generalizing transfer: TEDI-MATH subtests

Again, since an ANOVA yielded neither a significant main effect of order [$F(1, 18) = .19$, $p = 0.67$] nor a significant interaction effect between order and improvement [$F(1, 18) = .06$, $p = 0.81$], the two order groups' data were collapsed. A reliable transfer effect of the dance mat training as compared to the tablet PC training was found in the *counting principles* subtest of the TEDI-MATH [$t(18) = 3.07$, $p < 0.01$, $d = .66$], but not in any other subtest or the composite score [all $t(18) < 1.71$, all $p > 0.10$].

Figure 2 depicts children's improvement between pre- and post-test for the number line task on the 0 to 10 scale (a) as well as the TEDI-MATH subtest *counting principles* (b).

Mediation analysis: spatial-numerical representation mediates generalizing transfer

Because we hypothesized the generalizing transfer in the TEDI-MATH subtest *counting principles* to be determined by an increasing accuracy of the mental number line representation, we conducted a mediation analysis as proposed by Preacher and Hayes (2004, 2008). Due to the small size of our sample, we employed a nonparametric bootstrapping method. The significant effect of condition (dance mat vs. tablet PC) on other basic numerical competencies (i.e., the counting principles subtest of the TEDI-MATH; total effect = –1.32, $p < 0.05$) was no longer significant after accuracy of the number line representation was added as a mediating variable (direct effect = –.99, $p > 0.05$). Most importantly, the analysis revealed a significant indirect effect of condition on other basic numerical competencies mediated by spatial number representation significant at the $p < 0.05$ level with a point estimate of –0.33 and a 95% BCa (bias-corrected and accelerated; see Efron, 1987) bootstrap confidence interval of –1.00 to –.04. From this, we conclude that the effect of condition on counting skills resulted from an improvement in the accuracy of the mental number line representation and not only from unspecific factors such as attention, motivation or general improvements.

Discussion

The present intervention study investigated the interrelation of physical and number space, motivated by findings suggesting an accurate spatial representation to be beneficial for further arithmetic learning and considerations on embodied cognition (Hommel et al., 2001). Based on these arguments we hypothesized that a sensori-motor spatial training of number magnitude should be more effective than a control training without physical-spatial elements and found both our hypotheses confirmed: (i) As expected, it was observed that children benefited more from a sensori-motor spatial-numerical training than they did from a non-spatial control training, since their accuracy in positioning a number in a number line estimation task in the 0 to 10 range increased more strongly. (ii) More interestingly, children's improvements also generalized to the subtest *counting principles* of the TEDI-MATH, which is not directly related to the spatial-numerical representation. Improvement in this subtest was again more pronounced after the sensori-motor spatial training as compared to the control condition. However, there was a lack of significant differences in improvement in all other subtests of the TEDI-MATH. The reason for those selective effects may be the specificity of the transfer effects of the trained representation, and possibly that some children already performed quite accurately in the pretest session. The results of the mediation analysis argue against a general effect of the experimental condition (e.g., via the reduction of cognitive load as observed by Goldin-Meadow et al., 2001) and hint at a specific effectiveness of the training. However, we also acknowledge the possibility that these specific numerical effects are further mediated by attentional and motivational aspects. We see the establishment of spatial-numerical training effects as a first step to promote the importance of spatial-numerical representation in intervention studies, but also agree that future studies should consider additional non-numerical factors such as attention, motivation, or cognitive load as possible additional mediators.

It is important to note that we used a rather strict numerical control training task (rather than a waiting list or a non-numerical control task). Therefore, it is not surprising that while sometimes children improved in both conditions, they did not always improve even more in the experimental condition. For instance, in the 0–20 number line task there was no difference in improvement, which might have been because the tasks were too difficult for our young participants. Nevertheless, it is remarkable that even in such low intensity (three sessions at 15–20 min), our training already lead to superior learning effects as compared to a non-spatial training using the same task and stimuli.

In our view, the greater success of the spatial-numerical training is also theoretically relevant. While correlations of spatial-numerical and overall arithmetic performance have been reported before, in this study spatial-numerical representations were manipulated as an independent variable. The results suggest that spatial representations are functional for and not a merely associated covariate of numerical development.

The current results within the TEC framework

The fact that the sensori-motor spatial training yielded better effects than the control training lends further support to the Theory of Event Coding (Hommel et al., 2001). According to the TEC, performing a certain task should become easier the more feature codes are shared by the perceptual input format, the physical output domain, and the engaged cognitive representation. We tried to realize this in the experimental condition. In particular, the significantly smaller training effects in the control condition argue for an important influence of shared feature codes for cognitive learning.

Nevertheless, based on the current design it is not possible to differentiate whether training effects stemmed from the spatial attributes of input or output format or an interaction of both. Also, we could not evaluate the effectiveness of different types of items (symbolic vs. nonsymbolic magnitudes; comparison to fixed or variable standards). Thus, future training studies should dissociate which combination of input and output format and what item type most effectively promotes learning. Because TEC suggests that all aspects, the visual-spatial numerical input, the motoric-spatial response, and in particular their interaction contributes to the training success, we would expect a training realizing the highest possible overlap in feature codes to be the most successful variant. In our view, our study paves the ground for such future work: It shows that efficiency of a training program can benefit from a manipulation of feature codes, suggesting the usefulness of future training studies based on these findings.

Conclusions and future perspectives

On a theoretical level, this training study goes beyond correlational approaches, showing that basic spatial-numerical training can cause greater benefits in numerosity learning than a non-spatial control training and that this benefit also extends to tasks tapping into other numerical competencies (e.g., counting).

On a practical level, our training can be easily employed in everyday learning because of the low intensity, the low costs and easy applicability. It seems promising to evaluate the effectiveness of sensori-motor spatial training of number magnitude representations in early therapy of children with math impairments, who have also been found to have deficits in very basic numerical abilities (e.g. Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009).

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