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Investigating the respective contribution of sensory modalities and spatial disposition in numerical training

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ABSTRACT

Recent studies have suggested that multisensory redundancy may improve cognitive learning. According to this view, information simultaneously available across two or more modalities is highly salient and, therefore, may be learned and remembered better than the same information presented to only one modality. In the current study, we wanted to evaluate whether training arithmetic with a multisensory intervention could induce larger learning improvements than a visual intervention alone. Moreover, because a left-to-right-oriented mental number line was for a long time considered as a core feature of numerical representation, we also wanted to compare left-to-right-organized and randomly organized arithmetic training. Therefore, five training programs were created and called (a) multisensory linear, (b) multisensory random, (c) visual linear, (d) visual random, and (e) control. A total of 85 preschoolers were randomly assigned to one of these five training conditions. Whereas children were trained to solve simple addition and subtraction operations in the first four training conditions, story understanding was the focus of the control training. Several numerical tasks (arithmetic, number-to-position, number comparison, counting, and subitizing) were used as pre- and post-test measures. Although the effect of spatial disposition was not significant, results demonstrated that the multisensory training condition led to a significantly larger performance

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improvement than the visual training and control conditions. This result was specific to the trained ability (arithmetic) and is discussed in light of the multisensory redundancy hypothesis.

Introduction

Embodied cognition refers to the idea that human cognition is rooted in the bidirectional perceptual and physical interactions of the body with the external world (Gibson, 2014; Wilson, 2002). Within this framework, our mental representations are influenced by the perceptual and motor systems including body shape and movement, neural systems engaged in action planning, and systems involved in sensation and perception (Glenberg, 2010).

Whereas mathematics is one of the most abstract domains of human cognition, there is ample evidence that different aspects of numerical processing are embodied. First, people raised in Western cultures usually associate increasingly larger number names with increasingly right-sided actions (Opfer & Furlong, 2011; Shaki, Fischer, & Göbel, 2012). This ubiquitous spatial–numerical association of response codes (SNARC) effect has been assumed to result from preferred sensorimotor habits and has been observed in several situations. For example, during numerical tasks using a two-alternative forced-choice paradigm (e.g., number comparison and parity judgment tasks), participants respond faster to smaller numbers (relative to the numerical range used in the experiment) with left-sided responses and to larger numbers with right-sided responses (Dehaene, Bossini, & Giraux, 1993; Dehaene, Dupoux, & Mehler, 1990). The intrinsic connection between numbers and space has also been found in tasks involving arithmetic problem solving (Masson & Pesenti, 2014; McCrink, Dehaene, & Dehaene-Lambertz, 2007). Addition and subtraction operations indeed involve spatial movements on the mental number line—a rightward displacement for addition operations and a leftward displacement for subtraction operations, that is, the operational momentum effect (Knops, Viarouge, & Dehaene, 2009; Masson & Pesenti, 2014; McCrink et al., 2007; McCrink & Wynn, 2004, 2009; Pinhas & Fischer, 2008). Finally, training or remediation programs fostering the use of a spatial (left-to-right) mapping of numbers have been shown to improve children's performance on a series of numerical tasks measuring number magnitude, number comparison, number positioning on a line (Ramani & Siegler, 2008), and even arithmetic abilities (Booth & Siegler, 2008; Kucian et al., 2011; Vilette, Mawart, & Rusinek, 2010). Spatial processing, therefore, could provide humans the sensorimotor roots of a deep understanding of the number concept (Dehaene & Cohen, 2007).

Another prime example that different aspects of mathematics are embodied is related to the fact that body-based counting systems have emerged across cultures and history (Bender & Beller, 2012). Finger counting is probably the most widespread of these systems given that most children in Western cultures use their fingers while learning to count and calculate (Butterworth, 1999). If it has been demonstrated that finger gnosis training could improve mathematics learning in young children (Gracia-Bafalluy & Noël, 2008), other studies recently suggested that body movements in general may boost children's understanding of abstract numerical concepts. Children's accuracy in positioning a number on a number line, for example, has been shown to increase more strongly after sensorimotor training requiring children to walk on the line than after control training without physical spatial elements (Dackermann, Fischer, Huber, Nuerk, & Moeller, 2016; Fischer, Moeller, Bientzle, Cress, & Nuerk, 2011). Manipulation of objects such as the one involved in playing linear number board games enhances children's numerical knowledge (Ramani & Siegler, 2008; Siegler & Ramani, 2008), and tactile exploration allows children to learn several abstract concepts more easily (for letter recognition and handwriting, see Bara & Gentaz, 2011; for geometry, see Pinet & Gentaz, 2008). In the study of Pinet and Gentaz (2008), for example, children were trained to recognize plane geometrical figures using two learning methods that differed according to the perceptual modalities involved in the exploration of the stimuli. Children either used their visual modality in the *classic* learning method or used both their visual and haptic modalities in the *multisensory* learning method. The ability to recognize the geometrical figures was better after the multisensory method than after the visual one. If this visuohaptic advantage is very well in line with theories of embodied cognition granting the body a central role in shaping the mind (Wilson, 2002), it is also very well in line with the intersensory redundancy hypothesis (Bahrick & Lickliter, 2000). According to this hypothesis, multisensory stimulation can enhance early perceptual, affective, and cognitive discrimination. Information simultaneously available across two or more modalities, therefore, is highly salient and may be learned and remembered better than the same information presented to only one modality. In line with this idea, it has been demonstrated that preschool children perform better in a numerical matching task when provided with multisensory rather than unisensory information about numbers (Jordan & Baker, 2011).

In the current experiment, we wanted to examine whether visuohaptic (multisensory) training of aritmetic could lead to higher improvement in basic numerical understanding as compared with a visual training condition. Moreover, because numerous studies have already demonstrated that spatial numerical training improved several numerical abilities (Booth & Siegler, 2008; Kucian et al., 2011; Ramani & Siegler, 2008; Vilette et al., 2010), we also wanted to examine whether the spatial layout of the materials used (linear vs. random) could affect the effectiveness of our training methods. To meet those aims, four arithmetic training methods were developed according to two factors: (a) the perceptual modalities involved in processing the arithmetic operations (multisensory vs. visual only) and (b) the spatial disposition of the materials used (linear or left-to-right oriented vs. nonlinear or random). To better evaluate the test–restest effect, a control (non-numerical) training condition was also used. Preschool children were randomly allocated to one of these five training groups and were tested with arithmetic and basic numerical tasks (number-to-position, number comparison, counting, and subitizing) both before and after training.

Because several numerical tasks were used as pre- and post-test measures, we were able to evaluate the respective contributions of sensory and spatial information to the understanding of arithmetic and basic numerical abilities. We expected (a) larger improvement of performance after the multisensory training than after the visual and control training, especially in the arithmetic and counting tasks entrained; (b) larger improvement of performance after the training conditions using left-to-right number–space mapping compared with random disposition, especially in the number-to-position and SNARC tasks because these tasks are assumed to rely on space processing; (c) no improvement of performance in the subitizing task because this ability is assumed to be a stable quantification process (Kaufman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982; Trick & Pylyshyn, 1994); and (d) no improvement of numerical performances in the control group or just a mere test–retest effect.

Method

Participants

A total of 86 preschool children participated in this study. However, 1 child was removed from the analyses because that child's scores were 2 standard deviations below the mean of the group in the pre- and post-test sessions. The remaining 85 children were recruited from a school in Walloon Brabant province (Belgium). All the children were 5 or 6 years of age (M = 5.26 years, SD = 0.68; 43 girls and 42 boys). Among the sample, 5 children were left-handed, 1 child was ambidextrous, and all other children (n = 79) were right-handed. Testing occurred at the end of the school year (from March to June) during 2 consecutive years. Procedures were approved by the research ethics boards of the Université Catholique de Louvain. Parents gave written consent for the participation of their children in the study. The sample size was determined by the number of participants we were able to recruit in the same school in 2 consecutive years.

Training

Four numerical training methods were created. Based on other studies examining the efficiency of the haptic modality in teaching geometry, handwriting, or letter recognition (Bara & Gentaz, 2011;

Pinet & Gentaz, 2008), our training conditions all consisted of three training sessions of approximately 20 min and involved small groups of 4 to 5 children.

The numerical training methods used differed according to two factors: (a) the perceptual modalities involved in processing the arithmetic operations and (b) the spatial disposition of the materials used to learn. Children used either their visual modality in the *classic visual* learning method or their visual and haptic modalities in the *multisensory* learning method. In each perceptual training, the spatial disposition of the materials was either linear or random, yielding four numerical training conditions: multisensory linear (ML), multisensory random (MR), visual linear (VL), and visual random (VR) interventions. Children were randomly assigned to a specific training condition ($n = 17$ per training condition; see Supplemental Table 1 in the online supplementary material for a repartition of the participants in each training condition).

In each training condition, children needed to perform addition or subtraction operations. The first session was devoted to solving 10 addition problems, the second session to solving 10 subtraction problems, and the third session to consolidating the first two sessions by asking children to solve five addition and five subtraction problems already trained in the first two sessions (see Supplemental Table 2 for a list of the operations trained). The arithmetic operations were presented visually by means of magnetized Arabic numbers positioned on a blackboard. Cards with a written Arabic digit (from 1 to 10) were placed in front of each child. To give their answer, children needed to choose the appropriate number card, position it upside down on an envelope, wait until all other children were ready, and then—all together—return the card to check the answer with the experimenter. The response procedure described above was chosen to ensure the involvment of each child in the training session. "Mickey" and "Donald" Walt Disney figurines were used to increase the attractiveness of our training methods.

In the ML group, children were placed in front of a 10-ball abacus with Mickey located on the left end of the abacus and Donald located on the right end (see Fig. 1, top left). At the beginning of each trial, the 10 balls were positionned on Donald's side. Children were first told that Donald needed to give a specific number of balls to Mickey. Accordingly, each child moved the corresponding number of balls toward the left side and put a clothespin after this series of balls. Then, depending on the operations trained, either Donald gave new balls to Mickey (addition) or Mickey returned a specific number of balls to Donald (subtraction). After each ball addition or removal, a clothespin needed to be attached to the abacus (after the added balls or just before the removed balls). This procedure was used to help children keep track of the two operands of the arithmetic operation presented.

In the MR group, children were presented with two small boxes (Mickey's box on their left and Donald's box on their right) (see Fig. 1, top right). At the beginning of each trial, the 10 balls were randomly positionned in Donald's box. Children were first required to give some balls to Mickey. Then, depending on the operations trained, either Donald gave new balls to Mickey (addition) or Mickey returned a specific number of balls to Donald (subtraction) and children needed to add or remove balls from Mickey's box. To help children keep track of the operands, the added or removed balls needed to be positioned on a lid next to Mikey's box.

In the VL group, a left-to-right-oriented line of 10 white cricles (see Fig. 1, bottom left) was positionned in front of children. For addition operations, Mickey and a box of precolored red circles were positioned at the left end of the line, whereas Donald and a box of precolored blue circles were positioned at the right end of the line. Children were told that Mickey was going to color circles in red and that Donald was going to color circles in blue. The two colors were used to represent both operands of the addition. For subtraction operations, Donald's box was empty at the beginning of each trial. Children were told that Mickey was going to color circles in red and that Donald was going to erase some of the circles colored by Mickey. The erased circles were positionned in Donald's box. The experimenter performed the operation by manipulating the precolored circles. Children's task consisted in finding the outcome of the arithmetic operation performed by the experimenter. In contrast to what happended in the multisensory training, children were only asked to look at what the experimenter was doing. They were not allowed to touch or manipulate the materials while the experimenter performed the operation.

In the VR group, the experimental procedure was the same as for the VL group except that a random position of 10 circles was used by the experimenter as a basis to perform the arithmetic opera-

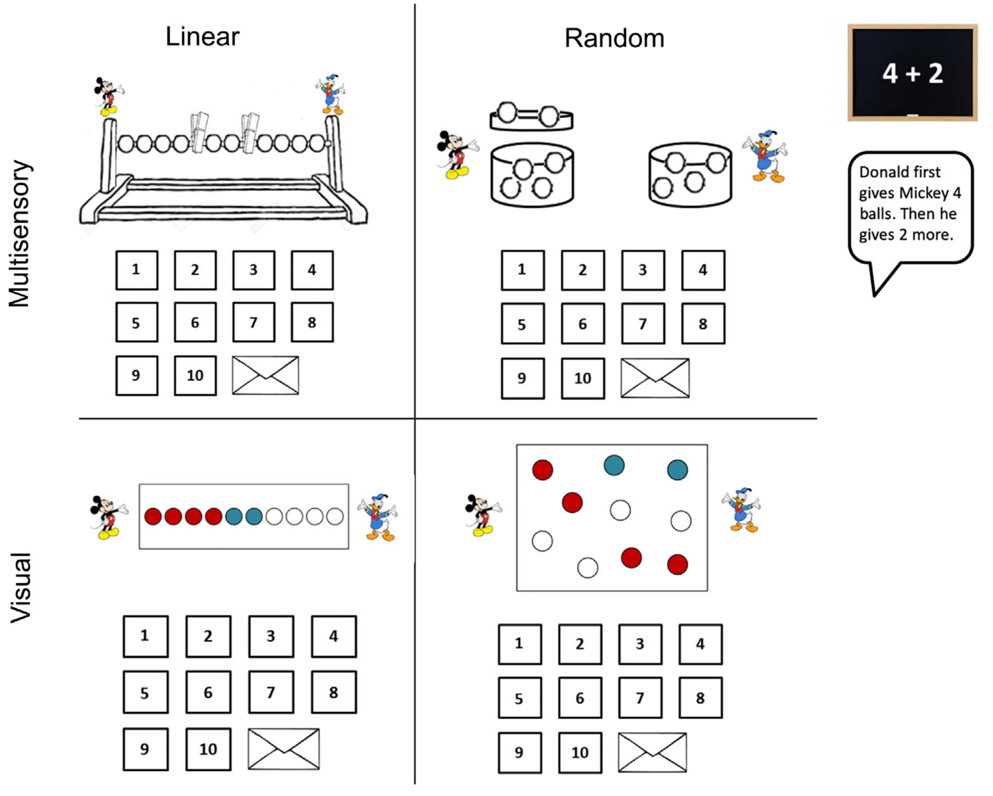


Fig. 1. Visual depiction of the four numerical training conditions.

tions (see Fig. 1, bottom right). The location of the circles was preestablished and fixed across training groups.

In the non-numerical control (CTRL) group (adapted from Honoré & Noël, 2016), stories of approximately 20 min were read to the children (a different story in each of the three training sessions). The meaning of three difficult words was explained in the context of each story: "dune" (*dune*), "mirage" (*mirage*), and "chèche" (*chech*) in the first story; "montagnard" (*mountain dweller*), "baluchon" (*bundle*), and "brise" (*breeze*) in the second story; and "picorer" (*to peck*), "miauler" (*to meow*), and "avoir la frousse" (expression to say *to be scared*) in the third story.

Pre- and post-training measures

Pretests were carried out by three different experimenters. As soon as all the pretests were done, the three training sessions started. Because we were interested in examining the short-term effect of our different training conditions, the training sessions were held over 3 consecutive days (by the first author) and the post-tests were carried out by two other experimenters blind to children's condition 1 or 2 days after the third training session.

The presentation of the tasks used and the result sections are organized into three different parts, with each one being related to one specific hypothesis. The first part presents the results of the tasks entrained (arithmetic and counting) and was intended to examine our first hypothesis: Is it possible to observe a larger improvement of performance after the visuohaptic training than after the visual and control training? The second part presents the results of the spatial tasks (number-to-position and number comparison) and is related to our second hypothesis: Is it possible to observe a larger improvement of performance after the training conditions using a left-to-right number–space mapping? The third part of our result section presents the data of the subitizing task that corresponds to our control task.

Tasks entrained

Arithmetic operations

Children were required to perform 10 simple addition and 10 subtraction operations, each involving two quantities that could be represented with one-digit numbers. A non-symbolic collection of animals always represented the first operand, whereas the second operand was always represented as a symbolic Arabic number (see Fig. 2A et B). Half of the operations (5 additions and 5 subtractions) was trained during the training sessions, and the other half consisted in untrained operations (see Fig. 2C). The experimenter gave the following instructions for the addition operations: "Can you help me count the animals? Look here. There are two rabbits. If three others arrive, how many will there be?" Instructions were similar for subtraction operations: "Look here. There are eight mice. If six mice leave, how many are left?" Responses were recorded by the experimenter, and 1 point was given for each correct answer, giving a maximun total score of 20. Percentage of correct responses was calculated.

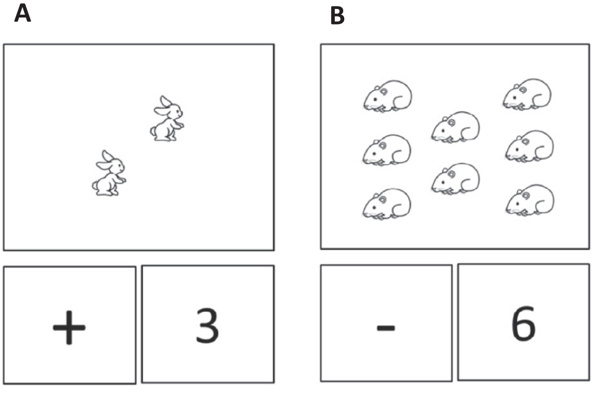
Counting

To assess the knowledge of the counting word sequence, children were first asked to count orally as far as possible. Here, 1 point was given when the couting range fell between 1 and 10; 2 points were given for a counting range of 11–20; 3 points were given for a range of 21–30; and 4 points were given when the child was able to count beyond 30. Children were also required to count up to 9 and up to 6, to count onward from 3 and from 7, to count from 5 to 9 and from 4 to 8, and to count down from 7 and from 15. Here, 1 point was given for each correct response. All these items were drawn from the TEDIMATH Battery (Van Nieuwenhoven, Grégoire, & Noël, 2001). The maximum total score was 12.

Spatial tasks

Number-to-position

The number-to-position task (Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Opfer, 2003) was composed of 18 horizontal black lines 1 mm wide and 23 cm long. Each line was labeled 1 at its left end and 20 at its right end (see Honoré & Noël, 2016, for a similar procedure). The lines were presented in the middle of four different white sheets of



C

Additions		Subtractions	
Trained	*Untrained*	*Trained*	*Untrained*
2+4	2+3	3-2	3-1
1+6	4+1	6-4	5-2
4+5	2+8	8-6	7-3
5+3	1+9	10-3	9-6
7+1	2+6	9-7	10-8

Fig. 2. (A and B) Examples of stimuli for addition operations (A) and subtraction operations (B). (C) List of trained and untrained addition and subtraction operations.

paper (21 × 30 cm, five lines per page). The sheet was laid in front of participants' midline. Children were told that they needed to show where they thought different numbers (all the numbers between 2 and 19) would fall on the line by marking the location with a pencil. The numbers were randomly and auditorily presented by the experimenter. Each line was covered after it was marked to ensure that children were not biased by their previous responses. There was no time restriction. Three children (one child from the CTRL group, one from the VL group, and one from the VR group) were unable to perform the task. They did not understand the instructions and, therefore, were removed from the analyses of this task.

Number comparison

In this computerized task, children were presented with an Arabic digit and were asked to judge whether it was smaller or larger than 5 (Dehaene et al., 1993). The Arabic digits used were numbers 1–9 (except for 5). Children were instructed to respond as quickly and accurately as possible by pressing one of two response keys. The task comprised two response assignments. In the first condition (the congruent condition), the "smaller than 5" response was assigned to the left response key, whereas the "larger than 5" response was assigned to the right response key. In the second condition (the noncongruent condition), the reverse assignment was used: the "larger than 5" response to the left key and the "smaller than 5" response to the right key. To help understanding of the instructions, small and large snowmen were associated with the appropriate response key (see Crollen & Noël, 2015, and Crollen, Vanderclausen, Allaire, Pollaris, & Noël, 2015, for a similar procedure). The order of the response assignment was counterbalanced across participants. Stimuli were delivered and reaction times were recorded using E-Prime. Each Arabic digit was presented four times in each condition, giving a total of 64 trials [number (8) × presentation (4) × response mode (2)] randomly presented in two experimental blocks. Each trial began with the presentation of a fixation cross for 500 ms. An Arabic number between 1 and 9 (except 5) then appeared in the center of the computer screen and remained on the screen until participants responded. The interstimulus interval ranged from 800 to 1200 ms. Eight practice trials were given before starting each response assignment. One child from the VL group was removed from the analyses due to technical problems.

Control task

Subitizing

Children were briefly presented, on the computer screen, arrays of one to six dots and were asked to say out loud how many dots were presented as accurately as they could (Attout, Noël, Vossius, & Rousselle, 2017). Stimuli were presented on a gray background with the E-Prime experimental software. Each trial started with the presentation of a central red fixation cross for 500 ms, followed by the display of the target collection of one to six dots for 250 ms. The collection was then immediately occulted by two successive masks of 100 ms. Finally, a screen with a question mark was presented until participants gave their response orally (see Supplemental Fig. 1). A numerical pad was used by the experimenter to type children's responses. The stimuli consisted of one to six randomly arranged black dots of equal size (6 mm in diameter) plotted randomly in the cells of a 6 × 6 virtual matrix. Each numerosity was presented six times in different configurations. By contrast, the mask consisted of dots of heterogeneous size and covered the whole surface of the screen. The experiment started with six practice trials.

Results

Analyses of variance (ANOVAs) were conducted to analyze the data. The Greenhouse–Geisser correction was applied when the sphericity assumption was violated. However, for ease of comprehension, non-corrected degrees of freedom are reported. Because the reaction times in the number comparison task were not normally distributed, they were logarithmically transformed. Moreover, analyses were performed on the median reaction times to avoid any contamination of the results by outlier data.

Tasks entrained

Arithmetic

The percentage of correct responses was calculated in the arithmetic task and submitted to a repeated-measures ANOVA with session (pretest or posttest) as the within-participant variable and modality (multisensory, visual, or control) and linearity (linear, random, or control) as the between-participant factors. Results demonstrated a significant effect of session, $F(1, 80) = 61.05$, $p < .001$, $\eta_p^2 = .43$. Children's performances were indeed higher in the post-test session ($M \pm SE = 64.29 \pm 2.70\%$) than in the pre-test session ($M \pm SE = 48.41 \pm 2.91\%$). The modality and linearity effects were not significant, $F(1, 80) = 0.06$, $p > .80$, $\eta_p^2 = .001$ and $F(1, 80) = 0.02$, $p > .80$, $\eta_p^2 = .001$, respectively. However, there was a significant Session × Modality interaction, $F(1, 80) = 3.88$, $p < .05$, $\eta_p^2 = .05$. To further examine this Session × Modality interaction, we measured performance improvements from pre-test to post-test in the multisensory and visual training groups by calculating a learning measure as follows: score post-test – score pre-test. A one-way ANOVA with modality as the between-participant factor was then carried out on this measure and confirmed the effect of modality on this learning measure, $F(2, 84) = 5.46$, $p < .01$. Bonferroni post hoc tests higlighted that children's performance improvements were larger in the multisensory training group ($M \pm SE = 22.35 \pm 2.58\%$) as compared with the control group ($M \pm SE = 6.18 \pm 5.15\%$, $p = .002$) and visual group ($M \pm SE = 14.26 \pm 2.78\%$, $p = .05$) (see Fig. 3A). No other interactions were significant, $F(1, 80) = 1.40$, $p > .20$, $\eta_p^2 = .01$ for the Session × Linearity interaction; $F(1, 80) = 0.22$, $p > .60$, $\eta_p^2 = .003$ for the Session × Modality × Linearity interaction.

Counting

In the counting task, a 2 (Session: pretest or posttest) × 3 (Modality: multisensory, visual, or control) × 3 (Linearity: linear, random, or control) ANOVA was performed on the accuracy scores (transformed in percentages). This analysis showed a significant effect only of session, $F(1, 80) = 33.57$, $p < .001$, $\eta_p^2 = .30$. Children's accuracy scores were larger in the post-test session ($M \pm SE = 77.84 \pm 1.98\%$) than in the pre-test session ($M \pm SE = 68.72 \pm 2.29\%$). There were no effects of modality, $F(1, 80) = 0.15$, $p > .70$, $\eta_p^2 = .002$, or linearity, $F(1, 80) = 0.25$, $p > .60$, $\eta_p^2 = .003$. No interaction was higlighted either, suggesting that the performance improvement was similarly observed in every training condition (see Fig. 3D).

Spatial tasks

Number-to-position

In the number-to-position task, the absolute deviations to the true number position (i.e., absolute deviation score, hereafter called |DS|) were carefully measured as follows: |participant's number estimation–true number|. However, the 2 (Session: pretest or posttest) × 3 (Modality: multisensory, visual, or control) × 3 (Linearity: linear, random, or control) ANOVA performed on this measure did not higlight any significant main effect (see Fig. 3B), $F(1, 77) = 0.47$, $p > .40$, $\eta_p^2 = .006$ for the session effect; $F(1, 80) = 1.72$, $p > .10$, $\eta_p^2 = .02$ for the modality effect; $F(1, 80) = 0.79$, $p > .30$, $\eta_p^2 = .01$ for the linearity effect. No interactions were highlighted either, $F(1, 77) = 0.86$, $p > .30$, $\eta_p^2 = .01$ for the Session × Modality interaction; $F(1, 77) = 0.45$, $p > .50$, $\eta_p^2 = .006$ for the Session × Linearity interaction; $F(1, 77) = 0.85$, $p > .30$, $\eta_p^2 = .01$ for the Session × Modality × Linearity interaction.

Number comparison

In the number comparison task, a 2 (Session: pretest or posttest) × 3 (Modality: multisensory, visual, or control) × 3 (Linearity: linear, random, or control) × 2 (Condition: congruent or noncongruent) ANOVA was first performed on the accuracy scores. This analysis did not highlight any significant effect (see Fig. 3C). The same 2 (Session: pretest or posttest) × 3 (Modality: multisensory, visual, or control) × 3 (Linearity: linear, random, or control) × 2 (Condition: congruent or noncongruent) ANOVA was then performed on the logarithm of the median reaction times (for correct responses). For ease of comprehension, however, non-transformed values (in milliseconds) are presented in the text. One child from the VL group was removed from the analysis because that child failed to give

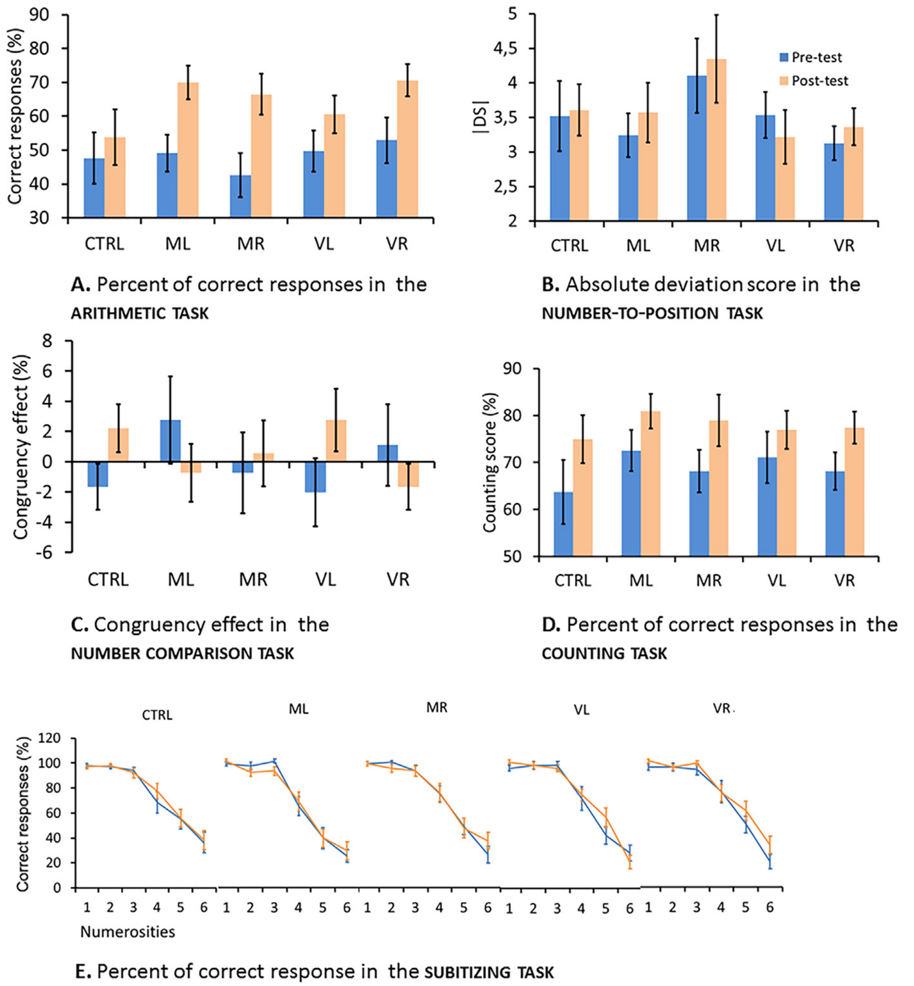


Fig. 3. Children's performances in the different numerical tasks before (in blue) and after (in orange) each training condition: (A) arithmetic task; (B) number-to-position task; (C) number comparison task; (D) counting task; (E) subitizing task. Bars represent standard errors of the mean. CTRL, control; ML, multisensory linear; MR, multisensory random; VL, visual linear; VR, visual random; |DS|, absolute deviation score. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

any correct response in the non-congruent condition of the post-test session. The results demonstrated an effect of session, $F(1, 79) = 18.64$, $p < .001$, $\eta_p^2 = .19$. Children responded faster in the post-test session ($M \pm SE = 1263.27 \pm 53.09$) than in the pre-test session ($M \pm SE = 1430.07 \pm 58.71$). This analysis, however, failed to demonstrate the presence of the SNARC effect. The condition effect was indeed not significant, $F(1, 79) = 1.69$, $p > .10$, $\eta_p^2 = .02$, suggesting that children were not faster in the congruent condition ($M \pm SE = 1328.39 \pm 56.98$) than in the incongruent condition ($M \pm SE = 1364.95 \pm 53.39$). The modality and linearity effects were not highlighted either, $F(1, 79) = 0.01$, $p > .90$, $\eta_p^2 = .001$ for the modality effect; $F(1, 79) = 0.06$, $p > .80$, $\eta_p^2 = .001$ for the linearity effect. Only one interaction (Condition $\times$ Linearity) was significant, $F(1, 79) = 9.10$, $p < .01$, $\eta_p^2 = .10$. To further examine this interaction, the difference between the congruent and noncongruent conditions (i.e., congruence effect) was first calculated in each session and in each training group. A negative value indicated that children responded faster in the congruent condition than in the noncongruent condition. This measure was submitted to a one-way ANOVA with the linearity variable as the between-participant factor. Results confirmed the effect of linearity, $F(2, 83) = 6.32$, $p < .01$, and post-hoc tests demonstrated that the linear training groups ($M \pm SE = -160 \pm 45.72$) were different from the control group ($M \pm SE = -0.62 \pm 256.18$, $p = .02$) and random group ($M \pm SE = 4.31 \pm 37.97$, $p = .001$). The control and random groups were not different from each other ($p > .60$). The congruence (SNARC) effect, therefore, was larger in the linear training groups. However, this effect was not related to the training condition given that it did not interact with the session variable.

Control task

Subitizing

A 2 (Session: pretest or posttest) × 6 (Numerosities: 1, 2, 3, 4, 5, or 6) × 3 (Modality: multisensory, visual, or control) × 3 (Linearity: linear, random, or control) ANOVA was performed on the accuracy scores (transformed in percentages). This analysis did not show any significant session effect, $F(1, 80) = 2.64$, $p > .10$, $\eta_p^2 = .03$, but demonstrated a main effect of numerosity, $F(5, 400) = 225.91$, $p < .001$, $\eta_p^2 = .74$. An inspection of Fig. 3 reflected the existence of the subitizing range (1–3), which is characterized by a steep decline in performance starting at 4 in every training condition; numerosities 1, 2, and 3 were indeed not different from each other (all *ps* > .10), whereas numerosities 4, 5, and 6 were different from all the other numerosities (all *ps* < .001). There was no main effect of modality, $F(1, 80) = 0.25$, $p > .60$, $\eta_p^2 = .003$, no main effect of linearity, $F(1, 80) = 0.50$, $p > .40$, $\eta_p^2 = .06$, and no significant interactions. As expected, therefore, arithmetic training did not lead to an enlargment of the subitizing range. This was true in every training group (see Fig. 3E).

Discussion

In this study, we wanted to evaluate the respective contributions of sensory modalities and spatial orientation for basic arithmetic learning. To do so, preschoolers were trained to solve simple addition and subtraction operations. The numerical training methods differed according to the perceptual modalities (multisensory vs. visual) and the spatial disposition of the materials used (linear vs. random) (see Fig. 2). To evaluate whether training arithmetic could induce some learning transfer, children were tested on an arithmetic task as well as on other numerical abilities (number comparison, number-to-position, counting, and subitizing) both before and after training. A control training group in which children needed to listen to stories was finally created to test whether the performance improvement was due to the numerical training or to a mere test–retest effect.

Multisensory versus visual training

Our results demonstrated that the multisensory training induced a larger improvement in arithmetic performance as compared with the visual and control training methods. This observation is very well in line with previous experiments demonstrating an advantage of the haptic modality in understanding abstract concepts such as letter recognition, handwriting quality (Bara & Gentaz, 2011), and geometry (Pinet & Gentaz, 2008).

Our results are also in accordance with theories of embodied cognition granting the body a central role in shaping the mind (Wilson, 2002). According to these theories, cognitive skills emerged from elementary perception–action processes that are rooted in concrete real-life interactions (Gibson, 2014; Glenberg, 2010). Involving haptic manipulation or body movements for education purposes, therefore, could improve learning by providing additional cues for representing abstract concepts. We should acknowledge, however, that participative learning was enhanced in our multisensory training. So, we do not know whether it is the passive versus active distinction or the multisensory versus unisensory distinction that is important for education puproses. We also do not know whether coupling other sensory modalities (audition and vision or audition and touch) or using the haptic modality alone would have produced the same effects.

Even though these issues deserve to be further studied, our data are nevertheless well explained by the intersensory redundancy hypothesis (Bahrick & Lickliter, 2000, 2002). *Intersensory redundancy* refers to a particular type of multisensory stimulation in which the same information is presented simultaneously to two or more sensory modalities. It arises from an interaction between an organism and its environment, makes information highly salient, and therefore can direct attention and play a foundational role in cognitive development (Bahrick & Lickliter, 2002).

Because it was recently demonstrated that finger gnosis predicts a small part of variance in initial arithmetic competencies (Newman, 2016; Wasner, Nuerk, Martignon, Roesch, & Moeller, 2016), it could be interesting, in the future, to compare the efficiency of multisensory and finger-based intervention practices.

Linear versus random training

Much evidence has suggested the existence of a close link between numbers and space (see Crollen, Collignon, & Noël, 2017; de Hevia, Vallar, & Girelli, 2008, for reviews). Although addition and subtraction operations are assumed to involve movements on the mental number line (Knops et al., 2009; Masson & Pesenti, 2014; McCrink et al., 2007; McCrink & Wynn, 2004, 2009; Pinhas & Fischer, 2008), and despite the fact that our linear training conditions were left-to-right oriented, we did not find any advantage of the linear training over the random condition.

Our results could perhaps be explained by the age of the children tested. The SNARC effect, which is probably the most widespread demonstration of the strong association between numbers and space, has been linked to writing and reading direction. It was observed in 7-year-olds when explicit processing of numerical magnitude was required in a magnitude comparison task and in 8-and 9-year-olds when the numerical information was not explicitly processed in a parity judgment task (Imbo, Brauwer, Fias, & Gevers, 2012; van Galen & Reitsma, 2008). The children involved in the current study were 5 or 6 years old. Therefore, they were tested before the acquisition of writing and reading and, accordingly, did not systematically present the SNARC effect. Therefore, it is possible that the spatial characteristics of our training methods were irrelevant for children of that age. In accordance with this idea, previous experiments showing a link between spatial mapping of numbers and numerical competencies either tested children over 7 years of age (Booth & Siegler, 2008; Kucian et al., 2011; Vilette et al., 2010), used number-to-position training with Arabic digits (Booth & Siegler, 2008; Fischer et al., 2011), or did not directly contrast training involving linear and random spatial disposition (Dackermann et al., 2016; Fischer et al., 2011; Ramani & Siegler, 2008). It is true that some operational momemtum and SNARC-like effects have been found in younger children (see McCrink & Wynn, 2004, 2009, for the operational momentum effect; see Bulf, de Hevia, & Macchi Cassia, 2016, and Patro & Haman, 2012, for the SNARC-like effect). However, these effects were highlighted with nonsymbolic stimuli, whereas symbolic stimuli were included in all the tasks of the current study. With symbolic stimuli, SNARC effects were demonstrated in Chinese kindergarteners (Yang et al., 2014) but were observed later in Western children (7- and 8-year-olds: Gibson & Maurer, 2016; 5.8-year-olds: Hoffmann, Hornung, Martin, & Schiltz, 2013). Indeed, when preschool children need to perform a magnitude judgment task requiring exact number knowledge (as in the current study), the SNARC effect seems to emerge only at 5.8 years. It is linked to proficiency with Arabic digits and emerges from formal or informal schooling (Hoffmann et al., 2013), which is not the case with the 5-year-olds tested in the current study. Although previous studies demonstrated that number–space mappings were related to arithmetic abilities (Georges, Hoffmann, & Schiltz, 2017; Moeller et al., 2012), we failed to conclusively highlight the opposite relation (an influence of arithmetic training on the strength of number–space mappings). Because our study involves a small sample size, however, it could be interesting to examine whether such an effect could appear with more participants.

Learning transfer

Performance improvements were observed in three different tasks: counting, number comparison, and arithmetic. However, the improvements observed in the counting and number comparison tasks were not specifically due to the numerical training. An increase of performance was observed in the different numerical training conditions but was also observed in the control training. Therefore, we cannot exclude the possibility that this global session effect actually reflects a test–retest effect. In the arithmetic task, in contrast, performance improvements were larger in the mutlisensory numerical training conditions as compared with the control training condition. This suggests that the multisensory training had a specific effect on the trained task (arithmetic) and did not generalize to other numerical abilities.

Limitations

The current article cannot exclude the fact that children simply used counting and did not really perform arithmetic computations during the training. However, counting can be seen as the means by which children begin to make sense of addition and subtraction. The end product of learning to add and subtract indeed corresponds to being able to retrieve addition and subtraction "facts" from memory. However, this retrieval strategy develops gradually (Resnick, 1989), and before children can make full use of it they need to deploy other strategies to enable them to find sums or differences. One such strategy is counting. For addition, the procedure that children typically use first is counting out two sets of objects (one for each of the addends), combining the two sets, and then counting the newly combined set (counting all). For subtraction, children typically represent the larger quantity (the minuend), remove the smaller quantity (the subtrahend) from the minuend, and then count what is left. Then, progress toward the mature strategy of retrieval is a process of gradual refinement and abandonment of counting with a complementary gradual use of retrieval. Improving children's counting abilities, therefore, can lead to arithmetic ability improvements as well. By asking children to perform, in the third training session, some of the operations already trained in the first two sessions, we wanted to accelerate this gradual refinement.

Finally, we cannot exclude the fact that our numerical training actually helped children to process continuous dimensions covarying with numbers such as density and surface area. Within this context, the multisensory training could be causing children to experience numbers as discrete entities, whereas the visual condition may still allow children to look at them as some kind of continuous quantity—making the multisensory stimuli more "countable" and "precise" for matching to symbols. This alternative interpretation does not, however, invalidate our conclusion according to which the multisensory training leads to larger performance improvements than the visual training alone.

General conclusions

In this article, we suggested that intersensory redundancy could boost the development of arithmetic abilities. By conducting a training study, we were able to evaluate the functional relationship between multisensory information and arithmetic learning in healthy children. In the future, it would be worthwhile to consider whether a multisensory teaching of arithmetic could boost the understanding of arithmetic in children presenting numerical disabilities.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2019.104729.

References

Attout, L., Noël, M. P., Vossius, L., & Rousselle, L. (2017). Evidence of the impact of visuo-spatial processing on magnitude representation in 22q11. 2 microdeletion syndrome. *Neuropsychologia, 99*, 296–305.

Bahrick, L. E., & Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy. *Developmental Psychology, 36*, 190–201.

Bahrick, L. E., & Lickliter, R. (2002). Intersensory redundancy guides early perceptual and cognitive development. *Advances in Child Development and Behavior, 30*, 153–187.

Bara, F., & Gentaz, E. (2011). Haptics in teaching handwriting: The role of perceptual and visuo-motor skills. *Human Movement Science, 30*, 745–759.

Bender, A., & Beller, S. (2012). Nature and culture of finger-counting: Diversity and representational effects of an embodied cognitive tool. *Cognition, 124*, 156–182.

Berteletti, I., Lucangeli, D., Piazza, M., Dehaene, S., & Zorzi, M. (2010). Numerical estimation in preschoolers. *Developmental Psychology, 46*, 545–551.

Booth, J. L., & Siegler, R. S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology, 41*, 189–201.

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development, 79*, 1016–1031.

Bulf, H., de Hevia, M. D., & Macchi Cassia, V. (2016). Small on the left, large on the right: Numbers orient visual attention onto space in preverbal infants. *Developmental Science, 19*, 394–401.

Butterworth, B. (1999). *The mathematical brain*. London: Macmillan.

Crollen, V., Collignon, O., & Noël, M. P. (2017). Visuo-spatial processes as a domain-general factor of numerical development in atypical populations. *Journal of Numerical Cognition, 3*, 344–364.

Crollen, V., & Noël, M. P. (2015). Spatial and numerical processing in children with high and low visuo-spatial abilities. *Journal of Experimental Child Psychology, 132*, 84–98.

Crollen, V., Vanderclausen, C., Allaire, F., Pollaris, A., & Noël, M. P. (2015). Spatial and numerical processing in children with non-verbal learning disabilities. *Research in Developmental Disabilities, 47*, 61–72.

Dackermann, T., Fischer, U., Huber, S., Nuerk, H. C., & Moeller, K. (2016). Training the equidistant principle of number line spacing. *Cognitive Processing, 17*, 243–258.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 626–641.

Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron, 56*, 384–398.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 626–641.

de Hevia, M. D., Vallar, G., & Girelli, L. (2008). Visualizing numbers in the mind's eye: The role of visuo-spatial processes in numerical abilities. *Neuroscience & Biobehavioral Reviews, 32*, 1361–1372.

Fischer, U., Moeller, K., Bientzle, M., Cress, U., & Nuerk, H. C. (2011). Sensori-motor spatial training of number magnitude representation. *Psychonomic Bulletin & Review, 18*, 177–183.

Georges, C., Hoffmann, D., & Schiltz, C. (2017). Mathematical abilities in elementary school: Do they relate to number–space associations? *Journal of Experimental Child Psychology, 161*, 126–147.

Gibson, J. J. (2014). *The ecological approach to visual perception* (Classic Edition). New York: Taylor & Francis.

Gibson, L. C., & Maurer, D. (2016). Development of SNARC and distance effects and their relation to mathematical and visuospatial abilities. *Journal of Experimental Child Psychology, 150*, 301–313.

Glenberg, A. M. (2010). Embodiment as a unifying perspective for psychology. *Wiley Interdisciplinary Reviews: Cognitive Science, 1*, 586–596.

Gracia-Bafalluy, M., & Noël, M. P. (2008). Does finger training increase young children's numerical performance?. *Cortex, 44*, 368–375.

Hoffmann, D., Hornung, C., Martin, R., & Schiltz, C. (2013). Developing number–space associations: SNARC effects using a color discrimination task in 5-year-olds. *Journal of Experimental Child Psychology, 116*, 775–791.

Honoré, N., & Noël, M. P. (2016). Improving preschoolers' arithmetic through number magnitude training: The impact of non-symbolic and symbolic training. *PLoS One, 11*(11) e166685.

Imbo, I., Brauwer, J. D., Fias, W., & Gevers, W. (2012). The development of the SNARC effect: Evidence for early verbal coding. *Journal of Experimental Child Psychology, 111*, 671–680.

Jordan, K. E., & Baker, J. M. (2011). Multisensory information boosts numerical matching in children. *Developmental Science, 14*, 205–213.

Kaufman, E. L., Lord, M. W., Reese, T. W., & Volkmann, J. (1949). The discrimination of visual number. *American Journal of Psychology, 62*, 498–525.

Knops, A., Viarouge, A., & Dehaene, S. (2009). Dynamic representations underlying symbolic and non-symbolic calculation: Evidence from the operational momentum effect. *Attention, Perception, & Psychophysics, 71*, 803–821.

Kucian, K., Grond, U., Rotzer, S., Henzi, B., Schönmann, C., Plangger, F., ... von Aster, M. (2011). Mental number line training in children with developmental dyscalculia. *NeuroImage, 57*, 782–795.

Mandler, G., & Shebo, B. J. (1982). Subitizing: An analysis of its component processes. *Journal of Experimental Psychology: General, 111*, 1–22.

Masson, N., & Pesenti, M. (2014). Attentional bias induced by solving simple and complex addition and subtraction problems. *Quarterly Journal of Experimental Psychology, 67*, 1514–1526.

McCrink, K., Dehaene, S., & Dehaene-Lambertz, G. (2007). Moving along the mental number line: Operational momentum in nonsymbolic arithmetic. *Perception & Psychophysics, 69*, 1324–1333.

McCrink, K., & Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychological Science, 15*, 776–781.

McCrink, K., & Wynn, K. (2009). Operational momentum in large-number addition and subtraction by 9-month-olds. *Journal of Experimental Child Psychology, 103*, 400–408.
Moeller, K., Fischer, U., Link, T., Wasner, M., Huber, S., Cress, U., & Nuerk, H. C. (2012). Learning and development of embodied numerosity. *Cognitive Processing, 13*(Suppl. 1), S271–S274.
Newman, S. D. (2016). Does finger sense predict addition performance?. *Cognitive Processing, 17*, 139–146.
Opfer, J. E., & Furlong, E. E. (2011). How numbers bias preschoolers' spatial search. *Journal of Cross-Cultural Psychology, 42*, 682–695.
Patro, K., & Haman, M. (2012). The spatial–numerical congruity effect in preschoolers. *Journal of Experimental Child Psychology, 111*, 534–542.
Pinet, L., & Gentaz, E. (2008). Evaluation d'entraînements multisensoriels de préparation à la reconnaissance de figures géométriques planes chez les enfants de cinq ans: Étude de la contribution du système haptique manuel. *Revue française de pédagogie, 162*, 29–44.
Pinhas, M., & Fischer, M. (2008). Mental movements without magnitude? A study of spatial biases in symbolic arithmetic. *Cognition, 109*, 408–415.
Ramani, G. B., & Siegler, R. S. (2008). Promoting broad and stable improvements in low-income children's numerical knowledge through playing number board games. *Child Development, 79*, 375–394.
Resnick, L. B. (1989). Developing mathematical knowledge. *American Psychologist, 44*, 162–169.
Shaki, S., Fischer, M. H., & Göbel, S. M. (2012). Direction counts: A comparative study of spatially directional counting biases in cultures with different reading directions. *Journal of Experimental Child Psychology, 112*, 275–281.
Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development, 75*, 428–444.
Siegler, R. S., & Opfer, J. E. (2003). The development of numerical estimation: Evidence for multiple representations of numerical quantity. *Psychological Science, 14*, 237–243.
Siegler, R. S., & Ramani, G. B. (2008). Playing linear numerical board games promotes low-income children's numerical development. *Developmental Science, 11*, 655–661.
Trick, L. M., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Review, 101*, 80–102.
van Galen, M. S., & Reitsma, P. (2008). Developing access to number magnitude: A study of the SNARC effect in 7- to 9-year-olds. *Journal of Experimental Child Psychology, 101*, 99–113.
Van Nieuwenhoven, C., Grégoire, J., & Noël, M.-P. (2001). *Le TEDIMATH: Test diagnostique des compétences de base en mathématiques*. Paris: Etablissement Cinématographique et Photographique des Armées.
Vilette, B., Mawart, C., & Rusinek, S. (2010). L'outil "estimateur", la ligne numérique mentale et les habiletés arithmétiques. *Pratiques psychologiques, 16*, 203–214.
Wasner, M., Nuerk, H. C., Martignon, L., Roesch, S., & Moeller, K. (2016). Finger gnosis predicts a unique but small part of variance in initial arithmetic performance. *Journal of Experimental Child Psychology, 146*, 1–16.
Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*, 625–636.
Yang, T., Chen, C., Zhou, X., Xu, J., Dong, Q., & Chen, C. (2014). Development of spatial representation of numbers: A study of the SNARC effect in Chinese children. *Journal of Experimental Child Psychology, 117*, 1–11.