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

Word count: 6023

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 may therefore be learned and remembered better than the same information presented to only one modality. In the present paper, we wanted to evaluate whether training arithmetic with a multisensory intervention could induce larger learning improvements than a visual intervention alone. Moreover, as 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 and randomly-organized arithmetic training. Five training programs were therefore created and called: (1) multisensory linear; (2) multisensory random; (3) visual linear; (4) visual random; (5) control. Eighty-five preschoolers were randomly assigned to one of these five training conditions. While children were trained to solve simple addition and subtraction operations in the first 4 training conditions, stories understanding was the focus of the control training. Several numerical tasks (arithmetic, number-to-position, number comparison, counting, subitizing) were used as pre- and post-test measures. While the effect of spatial disposition was not significant, results demonstrated that the multisensory training condition led to a significantly larger performance's improvement than did the visual training and the control conditions. This result was specific to the trained ability (arithmetic) and is discussed in light of the multisensory redundancy hypothesis.

Keywords

Multisensory, arithmetic, number processing, training, mathematical development

Introduction

Embodied cognition refers to the idea that human cognition is rooted in the bidirectional perceptual and physical interactions of the body with the 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).

While 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 sensory-motor 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 problems solving (Masson & Pesenti, 2014; McCrink, Dehaene, & Dehaene-Lambertz, 2007). Additions and subtractions indeed involve spatial movements on the mental number line: a rightward displacement for additions and a leftward displacement for subtractions (i.e., the operational momentum effect: Knops, Viarouge, & Dehaene, 2009; Masson & Pesenti, 2014 ; McCrink et al., 2007; McCrink & Wynn, 2004, 2009; Pinhas & Fisher, 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, Grond, Rotzer, Henzi, Schönmann, Plangger, Gälli, Martin, & von Aster, 2011; Vilette, Mawart, & Rusinek, 2010). Spatial processing could therefore provide humans the sensory-motor 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 as most children in our Western cultures use their fingers while learning to count and calculate (Butterworth, 1999). If it has been demonstrated that a finger gnosis training could improve mathematics learning in young children (Gracia Baffaluy & 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 has for example been shown to increase more strongly after a sensori-motor training requiring children to walk on the line than after a 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), children were for example trained to recognize plane geometrical figures using two learning methods which 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 both their visual and haptic modalities in the ''multisensory'' learning one. The ability to recognize the geometrical figures was better after the multisensory method than after the visual one. If this visuo-haptic 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 and Lickliter's, 2000). According to this hypothesis, multisensory stimulation can enhance early perceptual, affective, and cognitive discrimination. Information simultaneously available across two or more modalities is therefore 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 present experiment, we wanted to examine whether a visuo-haptic (multisensory) training of aritmetic could lead to higher improvement in basic numerical understanding as compared to a visual training condition. Moreover, as numerous studies 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 (linear vs. random) of the materials used could affect the effectiveness of our training methods. To meet those aims, 4 arithmetic training methods were developed according to 2 factors : 1) the perceptual modalities involved in processing the arithmetic operations, multisensory vs. visual only, and 2) the spatial disposition of the materials used, linear or left-to-right oriented vs. non-linear or random. In order 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.

As several numerical tasks were used as pre- and post-test measures, we were able to evaluate the respective contributions of sensory and spatial information on the understanding of arithmetic and basic numerical abilities. We expected : 1) a larger improvement of performance after the multisensory training than after the visual and control training, especially in the arithmetic and counting tasks entrained; 2) a larger improvement of performance after the training conditions using a left-to-right number-space mapping compared to a random disposition, especially in the number-to-position and SNARC tasks (as these tasks are assumed to rely on space processing); 3) no improvement of performance in the subitizing task as this ability is assumed to be a stable quantification process (Kaufman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982; Trick & Pylyshyn, 1994); and 4) no improvement of numerical performances in the control group, or just a mere test-retest effect.

Method

Participants

Eighty-six preschool children participated in this study. However, one child was removed from the analyses because his/her scores were 2 standard deviations below the mean of the group in the pre- as well as in the post-test session. The remaining 85 children were recruited from a school in Walloon Brabant (Belgium). All the children were aged between 5 and 6 years old ($M \pm SD$ = 5.26 ± 0.68) (43 girls and 42 boys). Five children were left-handed, one was ambidextrous and all the others (n=79) were right-handed. Testing occurred at the end of the school year (from March to June) on two 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 on 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 minutes and involved small groups of 4 to 5 children.

The numerical training methods used differed according to 2 factors : 1) the perceptual modalities involved in processing the arithmetic operations and 2) the spatial disposition of the materials used to learn. Children indeed 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 4 numerical training conditions: the multisensory linear (ML), the multisensory random (MR), the visual linear (VL) and the visual random (VR) interventions. Children were randomly assigned to a specific training condition (n=17 per training condition; see supplemental table 1 for a repartition of the participants in each training condition).

In each training condition, children had 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 2 sessions by asking children to solve 5 additions and 5 subtractions already trained in the first 2 sessions (see supplemental table 2 for a list of the operations trained). The arithmetic operations were presented visually (by means of magnetized Arabic numbers positionned on a blackboard). Cards with a written arabic digit (from 1 to 10) were placed in front of each child. To give their answers, children had to choose the appropriate number card, position it upside down on an envelope, wait until all the 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.

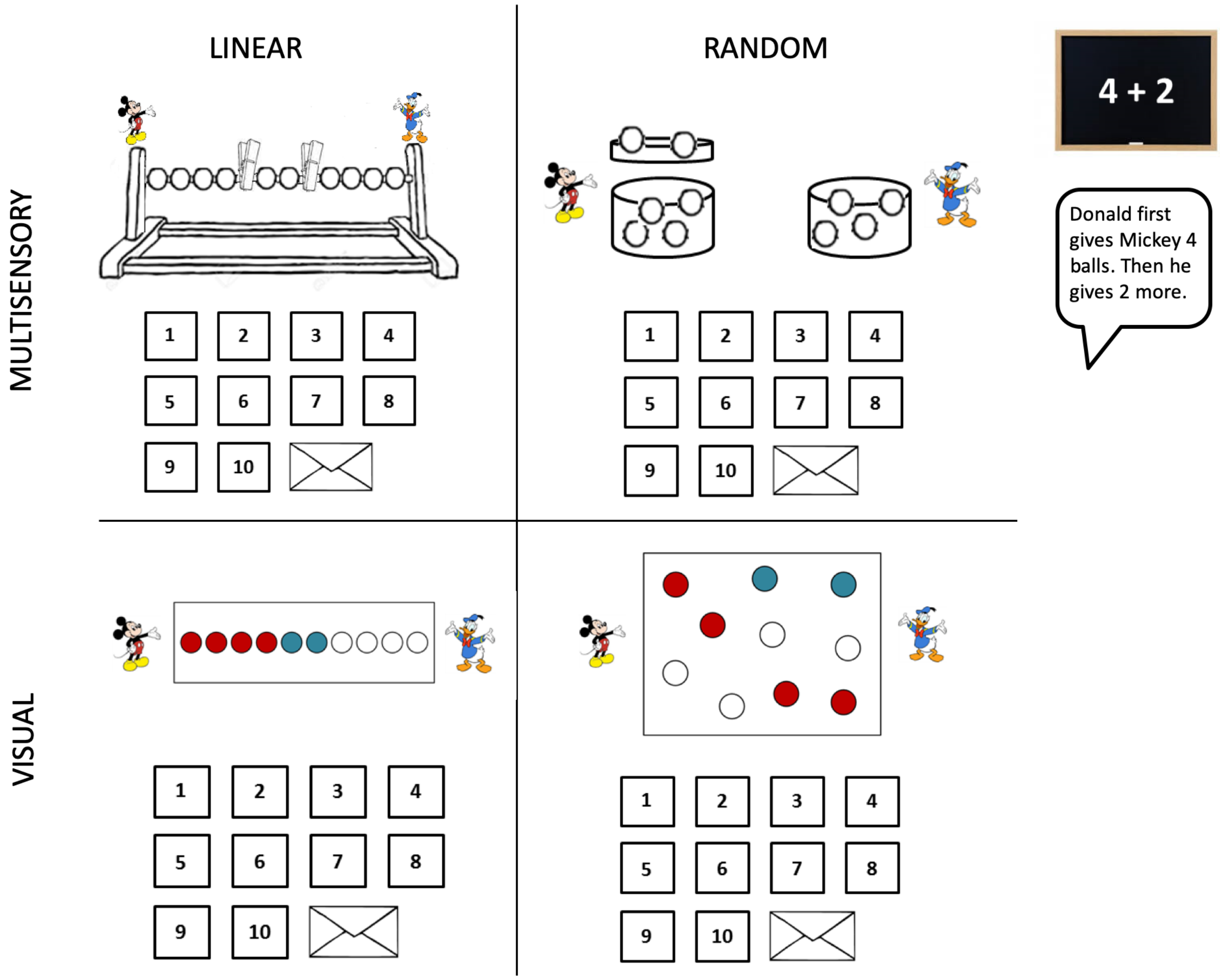


Figure 1. Visual depiction of the four numerical training conditions.

In the ML group, children were place in front of a 10-ball abacus with Mickey located on the left end of the abacus and Donald on the right end (see figure 1, top left). At the beginning of each trial, the 10 balls were positionned on Donald's side. Children were first told that Donald had 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 had 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 2 operands of the arithmetic operation presented.

In the MR group, were presented with 2 small boxes (Mickey's box on their left and Donald's box on their right) (see figure 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 the child had to add or remove balls from Mikey's box. To help children keep track of the operands, the added or removed balls had to be positionned on a lid, next to Mikey's box.

In the VL group, a left-to-right oriented line of 10 white cricles (see Figure 1, bottom left) was positionned in front of the children. For the additions, Mickey and a box of pre-colored red circles were positionned at the left end of the line; Donald and a box of pre-colored blue circles were positionned 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 subtractions, 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 pre-colored 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 visual linear group, except that a random position of 10 circles was used by the experimenter as a basis to perform the arithmetic operations (see Figure 1, bottom right). The location of the circles was pre-established and fixed across training groups.

In the non-numerical control group (CTRL; adapted from Honoré & Noël, 2016), stories of approximately 20 minutes were read to the children (a different story in each of the 3 training sessions). The meaning of 3 difficult words was explained in the context of each story ("dune" (*dune*), "mirage" (*mirage*), "chèche" (*chech*) in the first story; "montagnard" (*moutain-dweller*), "baluchon" (*bundle*), "brise" (*breeze*) in the second story; "picorer" (*to peck*), "miauler" (*to meow*), "avoir la frousse" (expression to say *to be scared*) in the third story).

Pre- and post-training measures

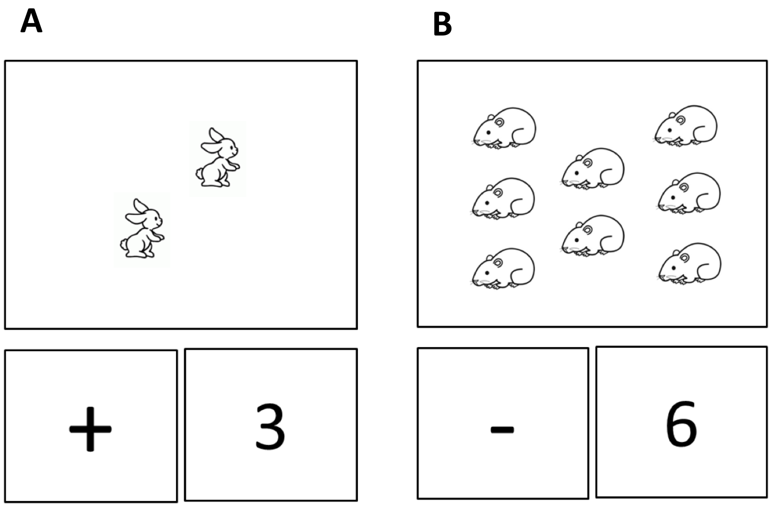
Pre-tests were carried out by 3 different experimenters. As soon as all the pre-tests were done, the three training sessions started. Because we were interested in examining the short-term effect of our different training conditions, the training sessions were held over 3 consecutive days (by the first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

The presentation of the tasks used as well as the result sections are organized in 3 different parts, each one being related to one specific hypothesis. The first part presents the results of the tasks entrained (arithmetic and counting) and intends to examine our first hypothesis : is it possible to observe a larger improvement of performance after the visuo-haptic 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 which corresponds to our control task.

Tasks entrained

Arithmetic operations

Children were required to perform 10 simple additions 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 while the second operand was always represented as a symbolic Arabic number (see Figure 2A et 2B). Half of the operations (5 additions and 5 subtractions) was trained during the training sessions, the other half consisted in untrained opeartions (see Figure 2C). The experimenter gave the following instructions for the additions: “Can you help me count the animals? Look here. There are 2 rabbits. If 3 others arrive, how many will there be?”. Instructions were similar for subtractions : “Look here. There are 8 mice. If 6 mice leave, how many are left?”. Responses were recorded by the experimenter and one point was given for each correct answer, giving a total maximun score of 20. Percentage of correct responses was calculated.



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

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

Counting

To assess the knowledge of the counting word sequence, children were first asked to count orally as far as possible. One point was given when the couting range fell between 1 and 10; 2 points were given for a 11-20 counting range; 3 points for a 21-30 range 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 on 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. One point was given for each correct response. All these items were drawn from the Tedi-Math Battery (Van Nieuwenhoven, Grégoire, & Noël, 2001). The total maximum 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 in length. Each line was labelled “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 paper (21 cm x 30 cm – five lines per page). The sheet was laid in front of the participant’s midline. Children were told that they had 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 the children were not biased by their previous responses. There were no time restriction. Three children (one from the CTRL group, one from the VL and one from the VR group) were unable to perform the task. They did not understand the instructions and were therefore 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 to 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, while the "larger than 5" response was assigned to the right response key. In the second condition (the non-congruent 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 to the appropriate response key (see Crollen & Noël, 2015; 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 4 times in each condition, giving a total of 64 trials [number (8) x presentation (4) x 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 inter-stimuli interval ranged from 800 to 1200 msec. 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 1 to 6 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 grey 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 1 to 6 dots for 250 ms. The collection was then immediately occulted by 2 successive masks of 100 ms. Finally, a screen with a question mark was presented until participants gave their response orally (see supplemental figure 1). A numerical pad was used by the experimenter to type children's responses. The stimuli consisted of 1 to 6 randomly arranged black dots of equal size (6mm in diameter), plotted randomly in the cells of a 6x6 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 6 practice trials.

Results

ANOVA's were conducted to analyse the data. The Greenhouse-Geisser correction was applied when the sphericity assumption was violated. However, for the ease of comprehenison, non-corrected degrees of freedom were reported. As the reaction times in the number comparison task were not normally distributed, they were logarithmically transformed. Analyses were moreover performed on the median reaction times to avoid any contamination of the results by outlier data.

Tasks entrained

Arithmetic

Percent of correct responses was calculated in the arithmetic task and submitted to a repeated measures ANOVA with session (pre-test vs. post-test) as the within-subject variable and modality (multisensory, visual, control) and linearity (linear, random, control) as the between-subject factors. Results demonstrated a significant effect of session, $F(1, 80) = 61{,}05$, $p < .001$, $\eta^2_p = 0.43$. Children's performances were indeed higher in the post-test session (M ± SE= 64.29% ± 2.70) than in the pre-test session (M ± SE= 48.41% ± 2.91). The modality as well as the linearity effects were not significant, respectively $F(1, 80) = 0.06$, $p > .8$, $\eta^2_p = 0.001$ and $F(1, 80) = 0.02$, $p > .8$, $\eta^2_p = 0.001$. However, there was a significant session x modality interaction, $F(1, 80) =$

3.88, $p < .05$, $\eta^2_p = 0.05$. To further examine this session x 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-subject 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 ± SE= 22.35% ± 2.58) as compared to the control (M ± SE= 6.18% ± 5.15, $p = .002$) and visual groups (M ± SE= 14.26% ± 2.78, $p = .05$) (see figure 3A). No other interactions were significant, $F(1, 80) = 1.40$, $p > .2$, $\eta^2_p = 0.01$ for the session x linearity interaction; $F(1, 80) = 0.22$, $p > .6$, $\eta^2_p = .003$ for the session x modality x linearity interaction.

Counting

In the counting task, a 2 (session: pre-test vs. post-test) x 3 (modality: multisensory, visual, control) x 3 (linearity: linear, random, control) ANOVA was performed on the accuracy scores (transformed in percentages). This analysis only showed a significant effect of session, $F(1, 80) = 33.57$, $p < .001$, $\eta^2_p = 0.30$. Children's accuracy scores were larger in the post-test session (M ± SE= 77.84% ± 1.98) than in the pre-test session (M ± SE= 68.72% ± 2.29). There were no effects of modality, $F(1, 80) = 0.15$, $p > .7$, $\eta^2_p = 0.002$, nor linearity, $F(1, 80) = 0.25$, $p > .6$, $\eta^2_p = 0.003$. No interaction was either higlighted, suggesting that the performance improvement was similarly observed in every training condition (see figure 3D).

Spatial tasks

Number-to-position

In the number-to-position task, the absolute deviations to the true number position (absolute deviation score, hereafter called |DS|) were carefully measured as follows: |participant's number estimation – true number|. However, the 2 (session: pre-test vs. post-test) x 3 (modality: multisensory, visual, control) x 3 (linearity: linear, random, control) ANOVA performed on this measure did not higlight any significant main effect (see figure 3B), $F(1, 77) = 0.47$, $p > .4$, $\eta^2_p = 0.006$ for the session effect; $F(1, 80) = 1.72$, $p > .1$, $\eta^2_p = 0.02$ for the modality effect; $F(1, 80) = 0.79$, $p > .3$, $\eta^2_p = 0.01$ for the linearity effect. No interactions were neither highlighted, $F(1, 77) = 0.86$, $p > .3$, $\eta^2_p = 0.01$ for the session x modality interaction; $F(1, 77) = 0.45$, $p > .5$, $\eta^2_p =$

0.006 for the session x linearity interaction; $F(1, 77) = 0.85$, $p > .3$, $\eta^2_p = 0.01$ for the session x modality x linearity interaction.

Number comparison

In the number comparison task, a 2 (session: pre-test vs. post-test) x 3 (modality: multisensory, visual, control) x 3 (linearity: linear, random, control) x 2 (condition: congruent vs. non congruent) ANOVA was first performed on the accuracy scores. This analysis did not highlight any significant effect (see figure 3C). The same 2 (session: pre-test vs. post-test) x 3 (modality: multisensory, visual, control) x 3 (linearity: linear, random, control) x 2 (condition: congruent vs. non congruent) ANOVA was then performed on the logarithm of the median reaction times (for correct responses). For the ease of comprehension, non-transformed values (in ms) are however presented in the text. One child from the VL group was removed from the analysis because he failed to give any correct response in the non-congruent condition of the post-test session. The results demonstrated an effect of session, $F(1, 79) = 18.64$, $p < .001$, $\eta^2_p = 0.19$. Children responded faster in the post-test session (M ± SE= 1263.27 ± 53.09) than in the pre-test session (M ± SE= 1430.07 ± 58.71). This analysis however failed to demonstrate the presence of the SNARC effect. The condition effect was indeed not significant, $F(1, 79) = 1.69$, $p > .1$, $\eta^2_p = 0.02$, suggesting that children were not faster in the congruent (M ± SE= 1328.39 ± 56.98) than in the incongruent condition (M ± SE= 1364.95 ± 53.39). The modality and linearity effects were not highlighted either, $F(1, 79) = 0.01$, $p > .9$, $\eta^2_p = 0.001$ for the modality effect; $F(1, 79) = 0.06$, $p > .8$, $\eta^2_p = 0.001$ for the linearity effect. Only one interaction (condition x linearity) was significant, $F(1, 79) = 9.10$, $p < .01$, $\eta^2_p = 0.10$. To further examine this interaction, the difference between the congruent and non-congruent 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 non-congruent one. This measure was submitted to a one-way ANOVA with the linearity variable as the between-subject 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 ± SE= -160 ± 45.72) were different from the control (M ± SE= -0.62 ± 256.18, $p = .02$) and random groups (M ± SE= 4.31 ± 37.97, $p = .001$). The control and random groups were not different from each other ($p > .6$). The congruence (SNARC) effect was therefore larger in the linear training groups. However, this effect was not related to the training condition as it did not interact with the session variable.

Control task

Subitizing

A 2 (session: pre-test vs. post-test) x 6 (numerosities: 1, 2, 3, 4, 5, 6) x 3 (modality: multisensory, visual, control) x 3 (linearity: linear, random, control) ANOVA was performed on the accuracy scores (transformed in percentages). This analysis did not show any significant session effect, $F(1, 80) = 2.64$, $p > .1$, $\eta^2_p = 0.03$, but demonstrated a main effect of numerosity, $F(5, 400) = 225.91$, $p < .001$, $\eta^2_p = 0.74$. An inspection of Figure 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 $p_s > .1$) while numerosities 4, 5, and 6 were different from all the other numerosities (all $p_s < .001$). There were no main effect of modality, $F(1, 80) = 0.25$, $p > .6$, $\eta^2_p = 0.003$, no main effect of linearity, $F(1, 80) = 0.50$, $p > .4$, $\eta^2_p = 0.06$, and no significant interactions. As expected, arithmetic training did therefore not lead to an enlargment of the subitizing range. This was true in every training group (see figure 3E).

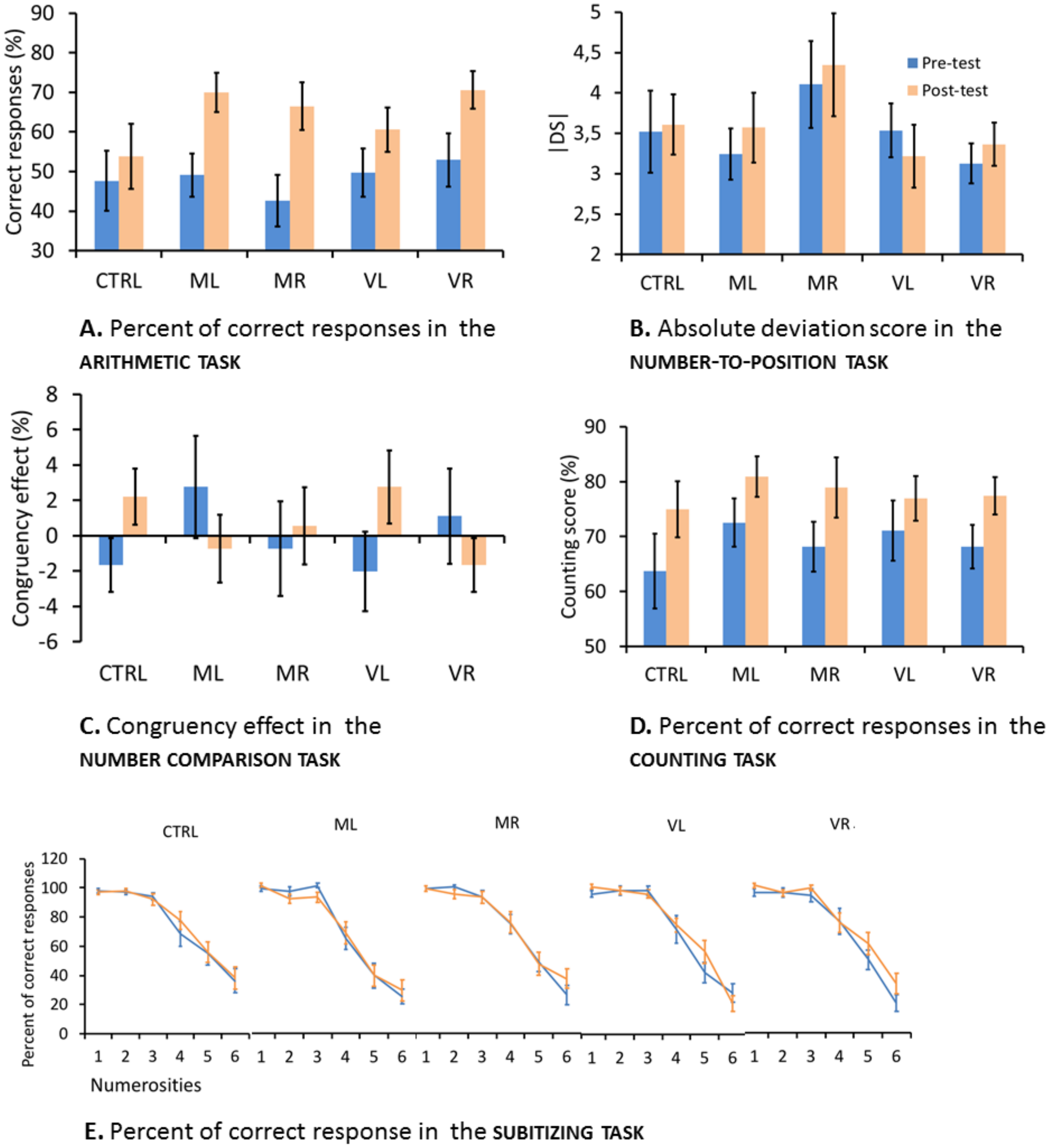


Figure 3. Children's performances in the different numerical tasks before (in blue) and after (in orange) each training condition. Bars represent standard errors of the mean.

Discussion

In this study, we wanted to evaluate the respective contribution of sensory modalities and spatial orientation for basic arithmetic learning. In order 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 figure 2). In order 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 had to listen to stories was finally created in order to test whether the performance improvement was due to the numerical training or to a mere test-retest effect.

Multisensory vs. visual training

Our results demonstrated that the multisensory training induced a larger improvement in arithmetic performance as compared to 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 could therefore improve learning by providing additional cues for representing abstract concepts. We should however acknowledge that participative learning was enhanced in our multisensory training. So, we do not know whether it is the passive vs. active or the multisensory vs. unisensory distinction which is important for education puproses. We do not know neither 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 2 or more sensory modalities. It arises from an interaction between an organism and its environment, makes information highly salient and can therefore direct attention and plays a foundational role in cognitive development (Bahrick & Lickliter, 2002).

As 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 vs. random training

Numerous evidence suggested the existence of a close link between numbers and space (see Crollen, Collignon, & Noël, 2017; de Hevia, Vallar, & Girelli, 2008 for reviews). While additions and subtractions 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 & Fisher, 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 old children when explicit processing of numerical magnitude was required in a magnitude comparison task and in 8–9-year old children 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 present study were 5-6 years old. They were therefore tested before the acquisition of writing and reading and accordingly did not systematically present the SNARC effect. It is therefore 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; Fisher et al., 2001) or did not directly contrast training invovling 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, 2015; Patro & Haman, 2012 for the SNARC-like effect). However, these effects were highlighted with non-symbolic stimuli while symbolic stimuli were included in all the tasks of the present study. With symbolic stimuli, SNARC effects were demonstrated in Chinese kindergardeners (Yang, Chen, Zhou, Xu, Dong, & Chen, 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 have to perform a magnitude judgment task requiring exact number knowledge (like in this paper), the SNARC effect seems to emerge at 5.8 years only. It is linked to proficiency with Arabic digits and emerges from formal or informal schooling (Hoffmann et al., 2013), which is not the case of the 5-year-old children tested in the present paper. Although previous studies demonstrated that number-space mappings were related to arithmetic abilities (Georges, Hoffmann, & Schiltz, 2017; Moeller, Fischer, Link, Wasner, Huber, Cress, & Nuerk, 2012), we therefore failed to conclusively highlight the opposite relation (an influence of arithmetic training on the strenght of number-space mappings). As our study involves a small sample size, it could however be interesting to examine whether such an effect could appear with more participants.

Learning transfer

Performance improvements were observed in 3 different tasks: counting, number comparison and arithmetic. However, the improvements observed in the counting as well as in the number comparison tasks were not specifically due to the numerical training. Increase of performance was observed in the different numerical training conditions but was also observed in the control training. Therefore, we cannot therefore exclude the possibility that this global session effect actually reflects a test-retest effect. In contrast, in the arithmetic task, performance improvements were in contrast larger in the mutlisensory numerical training conditions (as compared to the control training condition). This suggests that the multisensory training had a specific effect on the trained entrained (arithmetic) and did not generalize to other numerical abilities.

Limitations

The present paper 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 the child begins 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 have to deploy other strategies to enable them to find sums or differences. One such strategy is counting. For addition, the procedure which the child typically first uses 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 towards the mature strategy of retrieval is a process of gradual refinement and abandonment of counting with a complementary gradual institution of retrieval. Improving children's counting abilities can therefore lead to arithmetic abilities improvements as well. By asking children to perform, in the third training session, some of the operations already trained in the first 2 sessions, we wanted to accelerate this gradual refinement.

Finally, we cannot exclude the fact that our numerical training actually help children to process continuous dimensions co-varying with number such as density, surface area, etc. Within this context, the multisensory training could be causing children to experience number 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 however not invalidate our conclusion according to which the multisensory training leads to larger performance improvements than the visual training alone.

General conclusions

In this paper, 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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