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The spatial representation of numbers and time follow distinct developmental trajectories: A study in 6- and 10-year-old children

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ABSTRACT

Space-number and space-time associations have been a timely topic in the cognitive sciences for years, but evidence from developmental populations is still scarce. In particular, it remains to be established whether space-number and space-time mappings are anchored onto the same spatial frame of reference across development. To explore this issue, we manipulated visual and proprioceptive feedback in a Number Comparison task (Experiment 1) and a Time Comparison task (Expriment 2), in which 6- and 10-year-old children had to classify numerical and temporal words by means of a lateralised response with or without a blindfold (visual manipulation), and with hands uncrossed or crossed over the body midline (proprioceptive manipulation). Results revealed that 10-year-old children were more efficient in associating smaller numbers and past events with the left key, and larger numbers and future events with the right key, irrespective of the visual and proprioceptive manipulations. On the contrary, younger children did so only in the Time Comparison task, but not in the Number Comparison task. In the latter task, 6-year-olds associated small/large numbers with the left/right side of space only in the presence of visual feedback, but not when blindfolded. Taken together, our findings unveil that in school-aged children the spatial representation of number and time develop on different spatial frames of reference: while space-time associations exclusively rely on external coordinates at age 6, space-number associations shift from mixed internal and external coordinates at age 6 to more adult-like external coordinates by age 10.

1. Introduction

Studies conducted in human adults suggest that numbers are represented in a spatial format, typically along a left-to-right continuum, thus suggesting the existence of a *Mental Number Line* (MNL, for a review see de Hevia, Vallar, & Girelli, 2008). This directional bias is testified by the so-called SNARC effect (Spatial Numerical Association of Response Codes, SNARC; Dehaene, Bossini, & Giraux, 1993), which indexes faster response times to smaller numbers with left keys, and to larger numbers with right keys in tasks in which numerial size is task-irrelevant.

This spatial format of numerical information has been recently reported in non-human animals (Rugani, Vallortigara, Priftis, & Regolin, 2015) and preverbal infants (Bulf, Hevia, & Macchi Cassia, 2016; de Hevia, Addabbo, Girelli, & Macchi Cassia, 2014), suggesting that the coding of numbers into a directional spatial code is likely a developmental default and does not rely on symbolic knowledge or formal education. Nevertheless, various studies have shown that the orientation of the MNL varies according to the

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direction of reading and writing habits (Zebian, 2005), as individuals from Western cultures present a left-to-right MNL, while individuals from cultures in which language proceeds from right to left show a reduced or opposite pattern (Shaki, Fischer, & Petrusic, 2009). Therefore, a potential initial orientation bias for number-space mapping can still be modulated by experience later in life (de Hevia, Girelli & Macchi Cassia, 2012; McCrink & Opfer, 2014; Nuerk et al., 2015).

Interestingly, and similarly to number, temporal information appears to be represented along a spatial continuum, with time typically flowing in a left-to-right direction (i.e., with past/earlier events associated with the left space and future/later events with the right space), thus suggesting the existence of an analogus *Mental Time Line* (MTL, see Bonato, Zorzi, & Umiltà, 2012). Indeed, also time-space mapping is susceptible to the influence of cultural routines, as the MTL has been found to be reversed (i.e., oriented from right-to-left) in cultures adopting right-to-left reading and writing habits (Ouellet, Santiago, Israeli, & Gabay, 2010).

The fact that representation of both number and time appear to possess a spatial organisation is in line with the idea that all magnitude information that can be conceptualized in ordinal (more than/less than) terms would be coded according to a common metric (Feigenson, 2007; Walsh, 2003), and that they are represented through a unitary magnitude system. Indeed, the theory of magnitude (i.e., ATOM model), originally proposed by Walsh (2003; Bueti & Walsh, 2009), claims that there may be one common analog format, in which all quantity information are represented. Numerical magnitude, time, and space would all be represented in a common region of the brain – the parietal lobe –, where the integration of all this information occurs in order to guide action.

However, although a shared spatial format for number and time apparently speaks for a common system operating on these two dimensions, a closer look at studies addressing the spatial frame of rereference of the MNL and the MTL reveals a rather different scenario. Frames of reference refer to coordinate systems that individuals use to code spatial information with respect to the body. Spatial information can be coded as centered on the observer's body (egocentric/body-centered coding) or on external, non-bodily objects (allocentric/object-centered coding). Across development, different sensorimotor experiences contribute to the coding of information on either internal or external frames or reference; for example, tactile perception and localisation are initially mapped on internal/body coordinates, while reading and writing orient attention in the external space (Azañón & Soto-Faraco, 2008).

Studies on blind individuals have recently rekindled the debate on the nature of the spatial frames of reference involved. Indeed, visual experience is known to play a crucial role in shaping the use of internal and external coordinate systems, especially for action control and sensorimotor processing (Crollen, Albouy, Lepore, & Collignon, 2017; Röder, Kusmierek, Spence, & Schicke, 2007). For example, Röder et al. (2007) investigated whether developmental vision induces the default use of external coordinates for action control, by testing congenitally blind, late blind and sighted controls on an auditory-based version of a spatial-compatibility task ('Simon task'), in which participants had to discriminate a low vs. high tone, presented by pressing either a right or left key. When participants performed this task with their arms uncrossed, a compatibility effect, i.e., a response facilitation for stimuli presented on the same side of the hand, even though the stimulus location was task-irrelevant, emerged for all. When participants performed the same task with hands crossed over the body midline, the compatibility effect reversed for the congenitally blind, but not for the late blind and sighted controls. This suggests that late blind and sighted controls used an external frame of reference that made them automatically map their responses to the stimulius position. On the contrary, the congenitally blind used an internal frame of reference that made them automatically map the response to the position of their hands. The authors therefore suggested that (developmental) vision determines whether hand-based/internal or stimulus-based/external frames of reference are automatically used for spatially mapping stimuli/objects.

Accordingly, studies that have investigated whether vision is necessary for the development of a MNL have questioned which frame of reference blind individuals use to represent number along a spatial dimension (Castronovo & Seron, 2007; Cattaneo, Fantino, Tinti, Silvanto, & Vecchi, 2010; Rinaldi, Vecchi, Fantino, Merabet, & Cattaneo, 2015). For example, Crollen, Dormal, Seron, Lepore, and Collignon (2013) compared the performance of three groups of sighted, late blind (i.e., blindness onset after 2 years) and early blind (i.e., blindness onset before 2 years of age) individuals, in a numerical comparison task in which participants were required to respond with their hands either uncrossed or crossed (i.e., left hand in the right visual field, right hand in the left visual field) over the body midline. The hypothesis was that, if participants relied upon an external frame of reference, a SNARC effect should be observed irrespective of hand posture. On the contrary, if participants relied upon an internal frame of reference, their performance was expected to vary as a function of the hands' position with respect to the body midline, thus showing a reversed SNARC effect in the crossed hand condition. Results showed that the SNARC effect was independent of hand posture in the late blind and in the sighted; on the contrary, early blind individuals presented an inverted SNARC effect, suggestive of the adoption of an internal frame of reference for representing numbers. These findings suggest that early visual experience drives the development of an external coordinate system onto which numbers are spatially represented.

Interestingly, research with blind participants have also shown that, contrary to the MNL, the frame of reference onto which the MTL is anchored is not modulate by visual experience accumulated throughout development, nor on hands' posture. Bottini, Crepaldi, Casasanto, Crollen, and Collignon (2015) tested for the presence of a MTL in sighted, early and late blind individuals, and found that all groups responded faster with their left/right hand to words referring to the past/future, irrespective of hand posture (uncrossed vs. crossed). Hence, time seemes to be represented entirely along external coordinates, irrespective of visual experience (for complementary evidence see de la Vega, Eikmeier, Ulrich, & Kaup, 2017).

Taken together, the studies conducted in blind individuals (Bottini et al., 2015; Crollen et al., 2013) suggest that the MNL and the MTL rely upon different spatial frames of reference: while the MNL relies on both internal and external frames of reference (see for a discussion Fischer & Hill, 2004; Müller & Schwarz, 2007; Viarouge, Hubbard, & Dehaene, 2014), the MTL would be anchored exclusively on an external frame of reference. Furthermore, there appears to be a different contribution of vision to the development of the two representations: vision would drive the development of the automatic use of an external frame of reference for number, while it would not play any role in driving the reliance on an external frame of reference for time.

Notwistanding the relevance of research with blind individuals to test for the effects of sensory deprivation at different developmental times, a key limitation of this research is that it doesn't allow to directly specify when in development the external frame of reference would become dominant for representing numbers. A recent study has attempted to do so (Nava, Rinaldi, Bulf, & Macchi Cassia, 2017), by investigating the spatial representation of number and time in 5–6 year-old children under different vision (with vs without blindfold) and hand posture (uncorssed vs crossed) conditions. Results showed that preschool-aged children rely on an external frame of reference when they spatially represent time, but use both an internal and an external frames of reference for representing number onto space. This pattern of results partially corroborates the differences observed between the MTL and the MNL following sensory deprivation. Indeed, the representation of time seems to be anchored onto external coordinates already at age 5. On the contrary, the use of a mixed frame of reference for number-space mapping was dependent upon vision and hand posture. In fact, children's mapping was neither fully consistent with an external frame of reference, as it would have been shown by a consistent association of small/large numbers with the left/right lateralised response keys regardless of hand posture, nor with an internal frame of reference, as it would have been shown by a consistent association of small/large numbers with the left/right hands in the crossed hand posture, corresponding to a reverse SNARC effect. Rather, children showed an adult-like SNARC effect only when their hands were visible, and only when their hands were in an uncrossed position.

Overall, these findings indicate that at 6 years of age children are not yet relying on an external frame of reference for mapping numbers onto space, as adults do. This suggests a developmental pattern whereby the MNL would be initially grounded, at least to some extent, on the child's body, and would then get mapped on an external frame of reference sometime after age 6. Indeed, 9-10-year-old children have been shown to use an external frame of reference for representing numbers, thus resembling the adult pattern, as they exhibit a left-to-right number-space mapping regardless of hand posture (i.e., uncrossed or crossed, see Crollen & Noël, 2015b; Crollen, Vanderclausen, Allaire, Pollaris, & Noël, 2015). Yet, children in these studies were not blindfolded while performing the task, and, as such, the possible contribution of visual feedback in the representation of numbers was not tested. On these grounds, in the present study we investigated whether a prolonged experience with habits that are known to promote the development of both the MNL and MTL (i.e., reading and writing), also stabilises the preferential use of an external frame of reference for mapping number and time onto space.

Children were required to classify number words (Experiment 1) or words referring to time (Experiment 2) by pressing two keys positioned on the left and right side of space. After Nava et al. (2017), proprioceptive feedback was manipulated in both experiments by asking children to perform half of the task with their hands uncrossed, and the other half with their hands crossed over the body midline. The influence of visual feedback was tested by manipulating the possibility for children to see the position of their hands through the request to perform the task either blindfolded or not. In light of the evidence provided by recent studies on blind individuals (Bottini et al., 2015; Crollen et al., 2013; Röder et al., 2007), we reasoned that vision may play a crucial role in modulating the nature of the frame of reference underlying the mapping of number onto space. Thus, while visual feedback may promote the use of an external frame of reference, temporary lack of vision, specifically in younger children, may impair access to such frame of reference. In particular, by manipulating both visual and proprioceptive feedback, we aimed at documenting the alleged transition from a more mixed to an external, adult-like, frame of reference in the spatial representation of numbers. In light of previous studies, we expected number-space associations to undergo a developmental change between 6 and 10 years of age, shifting from a mixed contribution of internal and external frames of reference to a full, adult-like external frame of reference. In particular, we hypothesised that 6-year-old children would show a congruency effect (i.e., small/large numbers responded faster with the left/righ key respectively, compared to the reverse response mapping) only when visual feedback was available and when their hands were uncrossed. On the contrary, 10-year-old children should show a congruency effect irrespective of experimental manipulations. This would testify that the spatial coordinates onto which the MNL is mapped undergo a developmental shift, with the adoption of a purely external frame of reference only from age 10. As for time-space associations, based on earlier demonstration of a mapping on external frames of reference in children within the 5-to-6-year age range (Nava et al., 2017), we expected to observe a congruency effect (i.e., past/future words responded faster with the left/righ key respectively, compared to the reverse response mapping) in both the uncrossed and crossed conditions and irrespective of visual feedback in both 6- and 10-year-olds.

2. Experiment 1

2.1. Participants

The final sample consisted of forty (20 girls) 6-year-old children (mean age = 6.7 years; range = 6.3–7.3) and forty-one (23 girls) 10-year-old children (mean age = 10.6 years; range = 10.1–11.2), recruited from local kindergartens and primary schools, respectively.

An a-priori power analysis conducted using GPower (Faul & Erdfelder, 1992) revealed that about 52 participants would be required to have a 95% chance to observe a significant effect with a four measurements x four groups design, an alpha level of .05, and a medium effect size (.25). Our sample size (N = 81) was larger than the minimum sample size needed as we reasoned that, because children's performance always presents large variability, testing more participants would guarantee a more conservative approach.

Two children in the 6-year-old group were tested but excluded from the final sample because they were uncooperative and/or failed to complete testing. Half of the children in each age group (6-year-olds: N = 20; 10-year-olds, N = 21) performed the task while blindfolded, while the other half performed the same task with vision. All children were right-handed, as assessed by making them write their name on a sheet of paper before starting the experiment, and by asking them about their habits (e.g., "which hand do you use when you brush your teeth?"; "which hand do you use when you throw a ball?"). Written informed consent was obtained from all participants' parents. The protocol was carried out in accordance with the ethical standards of the Declaration of Helsinki (BMJ 1991; 302: 1194), and approved by the Ethics Committee of the University of *** (*blinded for reviewing purposes*).

2.2. Stimuli and procedure

Stimuli and procedure were identical to those used in Nava et al. (2017). Stimuli consisted of 6 audio recordings of a female voice speaking out numbers ranging between 2 and 8 (with the exception of number '5') in *** language (*blinded for reviewing purposes*). The audio stimuli lasted 600 ms each, had identical auditory properties (44,100 Hz, 32 bits, stereo), and an adjustable intensity ranging between 50 and 60 dB. Stimulus presentation and response sampling was done through the software E-Prime2 (Psychology Software Tools, Pittsburgh, PA), running on a portable HP Compaq laptop. Stimuli were presented through headphones.

The children were instructed to decide whether the numbers presented through headphones were smaller or larger than 5 (the reference number) by pressing as quickly and as accurate as possible one of the two response buttons placed in front of them in the left and right hemi-spaces. Each child was told that the instructions referred to the location of the response keys (i.e., and not to the hand). We labelled as "congruent" the condition in which participants were asked to respond to the presented numbers in accord with the left-to-right external orientation of the MNL; that is, when they responded to "smaller" with the left key, and "larger" with the right key. On the contrary, we labelled as "incongruent" the condition in which the key responses were switched, so when children responded to smaller numbers with the right key, and to larger numbers with the left key. Visual feedback (present vs. absent) was manipulated between children, with half of the participants being blindfolded for the entire duration of the task. On the contrary, hand posture (uncrossed vs. crossed) and congruency (congruent vs. incongruent with respect to the orientation of the MNL) were manipulated within participants, with children performing half of the trials with their hand uncrossed and the other hald with their hand crossed over the body midline, and the association between the past-future response and the left-right key counterbalanced across trials.

Each participant completed 4 blocks of trials: half of the children started with uncrossed hands, while the other half started with crossed hands, and that the congruent or incongruent nature of the first block was counterbalanced across participants. Each block comprised 24 trials, for a total of 96 trials. Each stimulus lasted 600 ms, with the inter-stimulus interval fixed at 2500 ms, and participants had 3000 ms to respond. The overall experimental session lasted about 30 min.

2.3. Results

Proportion of correct responses and inverse efficiency scores (IESs) were analysed in two repeated-measures Analyses of Variance (ANOVAs) with Age (6 years, 10 years) and Vision (present, absent) as between-subjects factors, and Hand posture (uncrossed, crossed) and Congruency (congruent, incongruent) as within-subjects factors. Proportion of correct responses was calculated for each participant in each condition, and was analysed in order to provide a general measure of the overall level of performance. IES data were calculated separately for each participant in each condition by dividing mean response time (RT) by proportion of correct responses (Townsend & Ashby, 1978), so that lower values on this measure (expressed in ms) indicate better performance. IES data are typically used to discount possible criterion shifts or speed-accuracy trade-offs in participants' performance (Akhtar & Enns, 1989; Goffaux, Hault, Michel, Vuong, & Rossion, 2005; but see some limitations raised by Bruyer & Brysbaert, 2011). We preferred IES over RT because we reasoned that younger children may tend to respond more rashly, favouring response times over accuracy, whereas older children may respond more cautiously but slowly, favouring accuracy. Significant interactions were followed-up through paired-sample *t*-tests, and Bonferroni correction was applied for multiple comparisons.

2.3.1. Proportion of correct responses

The ANOVA on proportion of correct responses revealed main effects of age, $F(1,77) = 22.24$, $p < .001$, $\eta^2 = 0.22$, and posture, $F(1,77) = 4.31$, $p = .04$, $\eta^2 = 0.05$. Although the performance of children in both age groups was significantlyabove chance, as assessed through one-sample *t*-tests (versus .50) (6-year-olds: $M = 0.86$, $SE = 0.003$, $t(39) = 17.47$, $p < .001$; 10-year-olds: $M = 0.97$, $SE = 0.006$, $t(40) = 77.73$, $p < .001$), 10-year-old children were overall significantly more accurate than the 6-year-olds, and children in both age groups showed overall better performance when they had their hands uncrossed ($M = 0.93$, $SE = 0.01$) than crossed ($M = 0.91$, $SE = 0.01$). There was also a significant Congruency x Vision interaction, $F(1,77) = 4.98$, $p = .03$, $\eta^2 = 0.06$, and, most importantly, a significant triple interaction between congruency, vision and age, $F(1,77) = 7.05$, $p = .01$, $\eta^2 = 0.08$. To follow-up this triple interaction we conducted two separate three-way ANOVAs, one for each age group. These revealed that the interaction was mostly driven by the performance of the younger children, as the ANOVA on the 10-year-olds did not reveal any significant main effect or interaction (all $ps > .11$).

To further test for the presence of a SNARC effect in the older children, we compared participants' performance in the congruent versus non-congruent trials, separately for the two visual feedback conditions (blindfolded and non-blindfolded) and the two hand-posture conditions (crossed and uncrossed), through a series of four dependent samples t-tests (Bonferroni correction). The comparisons did not reveal any significant difference in children's performance (all $p > .10$), confirming that it was not under any testing condition that the accuracy of older children's performance was sensitive to congruency effects.

Unlike older children, the ANOVA on the 6-year-old children revealed a significant Congruency x Vision interaction, $F(1,38) = 7.25$, $p = .01$, $\eta^2 = 0.16$, due to younger children showing a congruency effect in the presence of vision (congruent: $M = .92$, $SE = .03$; incongruent: $M = 0.85$, $SE = 0.03$), $t(19) = 2.65$, $p = .02$, but not in the absence of vision (congruent: $M = 0.82$,

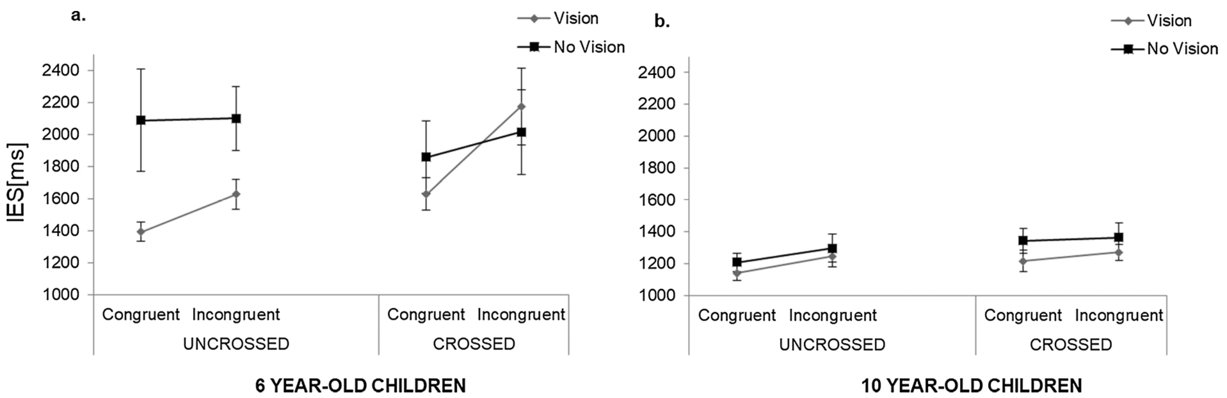

Fig. 1. Results from the Number Comparison Task in Experiment 1, showing mean Inverse Efficiency Scores (IES), separately for the 6-year-old (panel a) and the 10-year-old children (panel b). Performance of the older children was more efficient on congruent than incongruent trials, irrespective of visual feedback (vision vs. no vision) and posture (hand uncrossed vs. crossed). On the contrary, 6-year-old children performed more efficiently on congruent than incongruent trials only in the presence of visual feedback, and, overall, when their hands were uncrossed. Error bars represent standard errors of the means.

SE = 0.04; incongruent: *M* = 0.86, *SE* = 0.04), $t(19) = 1.36$, $p = .36$ (Fig. 1). To exclude the possibility that the absence of a congruency effect in the blindfolded condition was not simply due to an overall greater difficulty of younger children to perform the task while blindfolded than under normal viewing condition, we compared the performance of the blindfolded and the non-blindfolded children across all conditions through independent samples *t*-tests. No significant differences emerged in any of the conditions (all ps > .38), showing that deprivation of vision per se could not explain the absence of a congruency effect when children were blindfolded.

Dependent sample t-tests (Bonferroni correction) confirmed that 6-year-old children exhibited a congruency effect only in the presence of visual feedback (i.e., when not blindfolded) in the uncrossed condition, $t(19) = 3.32$, $p = .01$. In no other condition accuracy performance differed between congruent and incongruent trials (all $p > .18$).

2.3.2. Inverse efficiency scores

The results of the ANOVA performed on IES data mimicked those obtained for the accuracy data. We found main effects of age, $F(1,77) = 22.36$, $p < .001$, $\eta^2 = 0.23$, and posture, $F(1,77) = 9.30$, $p = .003$, $\eta^2 = 0.11$, indicating that 10-year-old children (*M* = 1260, *SE* = 89) performed more efficiently than the 6-year-olds (*M* = 1860, *SE* = 90), and that both the younger and the older children performed more efficiently when their hands were uncrossed (*M* = 1484, *SE* = 67) than crossed (*M* = 1637, *SE* = 69). Furthermore, there was a significant Congruency x Vision interaction, $F(1,77) = 5.15$, $p = .03$, $\eta^2 = 0.06$, which was qualified by a significant Congruency x Vision x Age interaction, $F(1,77) = 7.51$, $p = .008$, $\eta^2 = 0.09$. To further explore this triple interaction we conducted two additional three-way ANOVAs, one for each age group. For the 10-year-old children, the ANOVA revealed a main effect of congruency, $F(1,39) = 4.35$, $p = .04$, $\eta^2 = 0.10$, due to children performing more efficiently in congruent (*M* = 1218, *SE* = 48) than incongruent (*M* = 1294, *SE* = 55) trials, irrespective of visual and proprioceptive feedback (Fig. 1). Indeed, congruency did not interact with any other factor (all *ps* > .31). In contrast, the ANOVA performed on the 6-year-old children showed a significant Congruency x Vision interaction, $F(1,38) = 6.92$, $p = .01$, $\eta^2 = 0.15$, indicating that the congruency effect was apparent in the presence of vision (congruent: *M* = 1510, *SE* = 68; incongruent: *M* = 1901, *SE* = 155), $t(19) = 3.14$, $p = .01$, but not in the absence of vision (congruent: *M* = 2094, *SE* = 227; incongruent: *M* = 1936, *SE* = 230), $t(19) = 0.94$, $p = .70$. A main effect of posture, $F(1, 38) = 6.46$, $p = .01$, $\eta^2 = 0.15$, was also present for the 6-year-olds, as performance was more efficient when the response had to be provided with the hands in an uncrossed (*M* = 1741, *SE* = 114) than in a crossed position (*M* = 1979, *SE* = 119) (Fig. 1). That is, congruency effects were found in both hand postures, although IES scores were overall lower when children performed the task with their hand uncrossed.

Finally, a within-subjects split-half reliability analysis was performed by calculating Spearman-Brown coefficient on even-odd trials for each condition (age x vision x posture x congruency). For both the 6-year-old children and the 10-year-olds, this resulted in high levels of reliability for both the crossed and uncrossed conditions in both the blindfolded (6-year-olds: rs > 0.96; 10-year-olds: *rs* = 0.91) and the non-blinfolded (6-year-olds: *rs* > 0.96; 10-year-olds: *rs* > 0.93) group, thus indicating that children's overall performance (i.e., irrespective of visual and proprioceptive feedback) in the task is indeed reliable for both age groups.

Together, the results of Experiment 1 showed that 10-year-old children presented a typical, adult-like SNARC effect irrespective of visual and proprioceptive feedbacks. On the contrary, 6-year-olds exhibited the SNARC effect only when visual feedback was available, and were overall affected by the position of their hands, suggesting that, ulike older children, children in this younger age group do not fully map numbers onto external spatial coordinates.

3. Experiment 2

3.1. Participants

The final sample consisted of forty-two (23 girls) 6-year-old children (mean age = 6.6 yeras; range = 6.1–7.5) and forty-two (21 girls) 10-year-old children (mean age = 10.7 years; range = 10.2–10.8), recruited from local kindergartens and primary schools, respectively.

An a-priori power analysis using the same parameters as in Experiment 1 estimated an appropriate sample size of N = 52. Like in Experiment 1, in this study too a larger number of participants were tested (N = 84) to accomodate for the ample variability in children's performance.

Seven 6-year-old and three 10-year-old children were tested but excluded from the sample because they failed to complete testing. None of them participated in Experiment 1. Like in Experiment 1, half of the children in each age group (6-year-olds: N = 21; 10-year-olds: N = 21) performed the task while blindfolded, while the other half performed the same task with vision. All children were right-handed, with hand dominance being assessed in the same way as in Experiment 1. Written informed consent was obtained from all participants' parents. The protocol was carried out in accordance with the ethical standards of the Declaration of Helsinki (BMJ 1991; 302: 1194), and approved by the Ethics Committee of the University of *** (*blinded for reviewing purposes*).

3.2. Stimuli and procedure

The Time Comparison task mimicked the Number Comparison Task used in Experiment 1 in all characteristics, with the only exception of the stimuli, which consisted of audio recordings of a female voice speaking out words referring to past events ("before", "yesterday", "past") and future events ("after", "tomorrow", "future"). All stimuli were presented through headphones (after Nava et al., 2017).

Children were asked to respond as accurately and quickly as possible to the words presented through headphones by pressing one of the two response buttons placed in front of them in the left and right hemi-spaces. Like in Experiment 1, children were told that the instructons referred to the locations of the response keys (i.e., not the hands). Children had to decide whether the heard word referred to an event that had already happened (past event) or that still had to happen (future event) with reference to "now". Similarly to Experiment 1, we labelled as "congruent" the condition in which participants responded to the presented words in accord with the left-to-right external orientation of the MTL; that is, when children responded to past events with the left key, and to future events with the right key. On the contrary, we labelled as "incongruent" the condition in which the key responses were switched, so that children responded to past events with the right key, and to future with the left key.

Like in Experiment 1, visual feedback (present vs. absent) was manipulated between participants by blindfolding half of the children, while hand posture (uncrossed vs. crossed), and congruency (congruent vs. incongruent with respect to orientation of the MTL) were manipulated within participants. Each participant completed 4 blocks of trials: half of the children started with uncrossed hands, while the other half started with crossed hands, and that the congruent or incongruent nature of the first block was counterbalanced across participants. Each block comprised 24 trials, for a total of 96 trials. Each stimulus lasted 600 ms, with the inter-stimulus interval fixed at 2500 ms, and participants had 3000 ms to respond. The overall experimental session lasted about 30 min.

3.3. Results

The dependent variables and the statistical analyses mimicked those of Experiment 1: proportion of correct responses and inverse efficiency scores (IESs) were analysed in two repeated-measures Analyses of Variance (ANOVAs) with age (6 years, 10 years) and visual feedback (present, absent) as between-subjects factors, and hand posture (uncrossed, crossed) and congruency (congruent, incongruent) as within-subjects factors. Significant interactions were followed-up through paired-sample *t*-tests with Bonferroni correction for multiple comparisons.

3.3.1. Proportion of correct responses

The ANOVA on proportion of correct responses revealed main effects of age, $F(1, 80) = 105.38$, $p < .001$, $\eta^2 = 0.57$, and congruency, $F(1,80) = 26.23$, $p < .001$, $\eta^2 = 0.25$. Despite the performance of children in both age groups was significantly above chance, as assessed through one-sample *t*-tests (versus .50) (6-year-olds: $M = 0.57$, $SE = 0.02$, $t(41) = 3.45$, $p < .001$; 10-year-olds: $M = 0.96$, $SE = 0.001$, $t(41) = 16.35$, $p < .001$), 10-year-old children were overall significantly more accurate than the 6-year-olds. Irrespective of this overall difference in performance, the congruency main effect indicated that all children were more accurate in responding to past-related words with the left key and to future-related words with the right key (congruent condition: $M = 0.77$, $SE = 0.03$) than the reverse (incongruent condition: $M = 0.69$, $SE = 0.03$), irrespective of posture and vision (Congruency x Posture and Congruency x Vision interactions, $ps > .50$) (Fig. 2).

3.3.2. Inverse efficiency scores

The ANOVA performed on the IES data revealed a pattern of results that mimicked those obtained for the accuracy data. A Congruency main effect, $F(1,80) = 32.11$, $p < .001$, $\eta^2 = 0.29$, showed that both 6-year-old and 10-year-old children responded more efficiently to past-related words with the left key and to future-related words with the right key than the reverse, irrespective of posture and vision (Congruency x Posture and Congruency x Vision interactions, $ps > .34$) (Fig. 2). An Age main effect, *F*

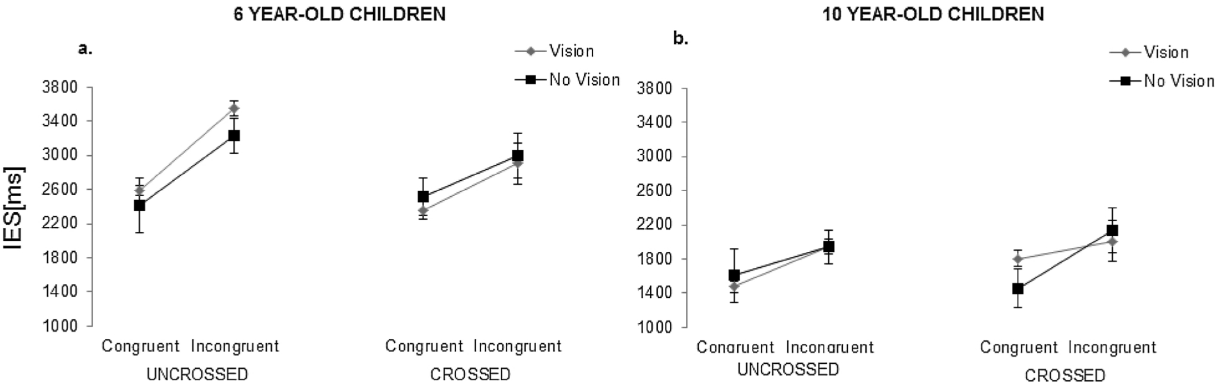

Fig. 2. Results from the Time Comparison Task in Experiment 2, showing mean Inverse Efficiency Scores (IES), separately for the 6-year-old (panel a) and the 10-year-old-children (panel b). Although older children performed overall more efficiently than the younger ones, responses of children in both age groups were faster on congruent than incongruent trials, irrespective of visual feedback (vision vs. no vision) and posture (hand uncrossed vs. crossed). Error bars represent standard errors of the means.

(1,80) = 31.07, $p < .001$, $\eta^2 = 0.28$, showed that older children ($M = 1796$, $SE = 130$) performed overall more efficiently than the younger ones ($M = 2820$, $SE = 130$). No interactions involving age attained significance (all $ps > .09$).

As in Experiment 1, split-half reliability using Spearman-Brown coefficients were performed using the odd-even method for each single condition. Contrary to Experiment 1, reliability measures in both the crossed and uncrossed conditions were overall higher for the 10-year-old children in both the blindfolded ($rs > 0.93$) and no-blindfolded group ($rs > 0.76$), compared to the 6-year-olds, whose performance in the crossed and uncrossed conditions showed modest reliability, particularly for the blindfolded group (blindfolded: $rs > 0.38$; non-blindfolded: $rs > 0.51$).

Together, the results of Experiment 2 showed that both 6- and 10-year-old children were more accurate and efficient in responding to past-related words with the left key and to future-related words with the right key than the reverse, indicating that they mapped temporal information onto a left-to-right oriented continuum. Children's performance was not affected by visual or proprioceptive feedback, suggesting that, contrary to numerical concepts, time concepts are mapped onto space using an external frame of reference already by age 6. However, low reliability measures for the 6-year-old children suggest that the lack of significant differences between the visual and/or posture conditions in the magnitude of the congruency effect for these younger children should be taken with caution.

4. Discussion

In the present study we explored the development of the spatial attributes of the mental representation of number and time, and the contribution of vision and proprioception in building the spatial frame of reference onto which these two domains are mapped.

In particular, by manipulating both visual and proprioceptive feedback within a number and time classification task in which spatially lateralized responses were required, we aimed at investigating whether, within the 6- to 10-years age range, representation of number and time are built on shared spatial reference frames – as predicted by observing that both magnitude dimensions are mapped onto either an external or internal frame of reference – or whether the spatial frames of reference underlying representation of the two dimensions evolve following different developmental trajectories. Our findings appear to support the latter view, suggesting that it is only by age 10 years that both number and time are automatically mapped onto external frames of reference. Indeed, while 10-year-old children appeared to map both number and time onto an external frame of reference, younger children only did so for time. In particular, results of Experiment 1 showed that, in the case of number, a typical SNARC effect (i.e., small/large numbers associated with the left/right side of space) emerged in 6-year-old children only when they performed the number classification task in the presence of visual feedback, but not when they were blindfolfded. This result suggests that having visual control over their hands boosted the mapping of numbers onto an external reference frame, possibly by dampening the saliency of the tactile and proprioceptive feedback on the hands' position in peripersonal space.

Importantly, the absence of a SNARC effect when visual feedback was not available was not driven by the 6-year-olds finding the task particularly challenging under temporarily visual deprivation per se, as in no condition blindfolded children performed more poorly than non-blindfolded children. Instead, 6-year-olds' performance was significantly lower when children responded with their hands crossed over their body midline, albeit hand posture did not interact with congruency. Unlike 6-year-old children, and in line with previous studies (Crollen & Noël, 2015b; Crollen et al., 2015), 10-year-olds fully mapped numbers onto an external frame of reference. In this case, indeed, neither visual feedback nor hand posture modulated the SNARC effect, i.e., small/large numbers were associated with the left/right side of the external space. It should be noted though that this conclusion can only be applied to the IES results, as 10-year-old children did not manifest any SNARC effect when accuracy was taken into account. This was probably due to ceiling effects, as mean performance was above 93% in all conditions for these children. Nonetheless, the fact that reaction times proved sensitive to congruency effects irrespective of postural and visual feedback in these older children resonates well with adults' data (Dehaene et al., 1993; Wood, Nuerk, & Willmes, 2006), and is in line with the conclusion that, by 10 years of age, number-space mapping is fully established.

The fact that vision modulated the congruency effect in 6-year-old children is in line with a recent study carried out by Nava et al. (Nava et al., 2017), in which 5- to 6-year-old children exhibited a SNARC effect in the presence of vision, but not when they were blindfolded. It should be noted, nevertheless, that hand posture also modulated performance in these younger children, as the SNARC effect was apparent only when children performed the number classification task with their hands uncrossed. We suggest that, when considered together, these earlier findings and those from the current study depict a developmental pattern in which the frames of reference onto which numbers are spatially mapped progressively shift from bodily-centered to external coordinates, with the age of 6 years as a time of transition. This notion finds support in studies showing that a similar transition from body-centered to object-centered frames of reference occurs at around this same age in other perceptual domains as well. For example, in a study measuring tactile localisation, Pagel, Heed, and Röder (2009) asked children to verbally indicate which hand was stimulated first in a typical temporal order judgment task (TOJ), with children performin the task with their hands uncrossed or crossed over the body midline. Results showed that while the performance of children older than 6 years was significantly impacted by hand posture, the performance of children younger than 6 was not, indicating that the use of an external frame of reference for tactile localization emerges between 5 and 6 years of age. Importantly, the notion that it is right between the ages of 4 and 6 years that vision progressively becomes the dominant sense between (e.g., in comparison to audition, see Robinson & Sloutsky, 2004; Nava & Pavani, 2013), suggests that vision might have a critical role in mediating the transition from bodily-centered to external frames of reference.

Indeed, the possibility that this transition is promoted by visual experience is also substantiated by studies conducted with congenitally blind individuals (Crollen et al., 2013; Röder et al., 2007), who, unlike late blind and sighted controls, use a bodily-centered frame of reference to control their actions when responding to number words. This evidence corroborates the view that vision is critical in prompting a default use of an external reference frame in auditory-manual control. Of course, in our study visual feedback was only modulated temporarily, as blindfolding was limited to the task at hand. Critically, despite its short duration, the deprivation of visual feedback was able to affect the way children mapped numbers onto space.

Furthermore, previous studies has shown that there is flexibility in the nature of the spatial frames of reference onto which adults anchor their responses in the task at hand, as contextual factors can contribute to see the dominance of one spatial frame of reference over the other (e.g., Viarouge et al., 2014; Wood et al., 2006). For instance, when Viarouge et al. (2014) explicitely asked participants to focus on their hands, they only showed a SNARC effect under the crossed-hand condition, but not in the uncrossed condition. This means that the SNARC effect is not univocally linked to a specific (i.e., external) frame of reference in adults, but can be flexibly readjusted to accommodate the instructions given to perform the task at hand. On these grounds, future studies may address whether instructing 6- and 10-year-old children to focus on their hands'position, for example, may induce the emergence of a reversed SNARC effect.

As already noted, the finding that, in striking contrast to younger children, 10-year-olds showed a left-to-right MNL fully anchored onto external coordinates with no effect of hand posture, replicates previous evidence with children of this age (Crollen & Noël, 2015b; Crollen et al., 2015) and adults (Crollen et al., 2013; Dehaene et al., 1993; Viarouge et al., 2014). An exclusive use of external coordinates to map numbers during primary school years may be prompted by directional visuomotor experience linked to literacy acquisition, such as reading and writing (Nuerk et al., 2015). In this sense, 10-year-old children, tested here at the end of the fifth grade, are certainly more expert readers and writers than 6-year-old children, whose mastery of literacy is still quite poor.

The results of Experiment 2 on time-space mapping are particularly interesting not only because they fully replicate the findings of Nava et al. (2017) with a new sample of young children (i.e., 6-year-olds), but also extend these findings to older children (i.e., 10-year-olds). To the best of our knowledge, with the only exception of the work by Nava et al. (2017), no studies have addressed time-space associations in childhood, and, particularly, the spatial frame of reference onto which this association relies on in developmental populations. Our finding that the congruency effect was not modulated by vision nor by posture in both 6- and 10-year-old children suggests that children at both ages robustly map time onto an external spatial frame of reference. While our results cannot exclude the possibility that other changes in the spatial frames of reference for time may occur in sighted children before age 5, it is interesting to note that even early blind individuals use an external frame of reference for time-space mapping (Bottini et al., 2015), suggesting that vision modulates the development of number-space, but not time-space mapping.

To possibly account for the dissociation between the spatial coordinates onto which the representations of number and time are anchored, we note that, because we often learn to count using our own body (e.g., hands and fingers), our representational space for numbers is also partially built around bodily coordinates (e.g., Di Luca, Granà, Semenza, Seron, & Pesenti, 2006; Fischer & Brugger, 2011), and this is especially true during chidlhood. Accordingly, the direction of finger counting routines has been shown to influence the orientation of the MNL and, more generally, to impact numerical processing (Di Luca et al., 2006; Fischer, 2008; Riello & Rusconi, 2011; Rinaldi, Di Luca, Henik, & Girelli, 2016), particularly in childhood (Crollen & Noël, 2015a; Rinaldi, Gallucci, & Girelli, 2016). When it comes to time, on the contrary, body-centered coordinates appear much less relevant, as we do not count time using our body, and tend to adopt an "external" perspective of horizontal time series (Bender & Beller, 2014; Núñez & Cooperrider, 2013).

Reliability measures obtained in Experiment 2, specifically for the 6-year-old children, deserve attention though. As a matter of fact, performance of this group showed low reliability, especially in the no-vision condition, thus questioning the stability of the observed congruency effect across conditions. In light of the main effect of age observed in both accuracy and IES data for this task, it is reasonable to assume that the time comparison task proved particularly challenging for the younger children. This may have increased noise in their performance, and, as a consequence, may have hindered possible differences across visual and/or posture conditions in the magnitude of the congruency effect. Thus, the presence of a different developmental trajectory for the spatial representation of number and time in young children needs to be substantiated by further research.

Finally, it should also be noted that the idea that number could be dissociated from other dimensions that can be still spatially represented is not new. For example, Holmes & Lourenco (2011) found that when presented with facial emotion expressions varying in intensity (e.g., neutral-to-extremely happy), participants aligned the emotional content along a left-to-right orientation, just like they do for increasing numerical magnitudes. However, the strength of the spatial orientation for emotion intensity and numerical magnitude were not correlated. This suggests that different domains may be represented spatially, without necessarily sharing the same representational format. Our results add to this evidence, by showing that even number and time – two domains that are apparently strictly intertwined- do not share across development the same spatial frames of reference.

In conclusion, our findings suggest that the reference frames underlying representations of number and time follow different developmental trajectories in childhood. While the MTL appears to rely upon external coordinates by the age of 6 years (or even 5 years, see Nava et al., 2017), at this same age the MNL relies on both body-centered and external frames of reference. Overall, our study contributes to the ongoing debate as to whether number, time, and other quantities are coded through a single metric and represented through a shared format (see Walsh, 2003), by suggesting that sensorimotor experience during childhood may lead number and time to be merged into a common representation format later in life.

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References

Akhtar, N., & Enns, J. T. (1989). Relations between convert orienting and filtering in the development of visual attention. *Journal of Experimental Child Psychology, 48*, 315–334.
Azañón, E., & Soto-Faraco, S. (2008). Changing reference frames during the encoding of tactile events. *Current Biology, 18*(14), 1044–1049.
Bender, A., & Beller, S. (2014). Mapping spatial frames of reference onto time: A review of theoretical accounts and empirical findings. *Cognition, 132*, 342–382.
Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: Evidence for a mental time line. *Neuroscience and Biobehavioral Review, 36*, 2257–2273.
Bottini, R., Crepaldi, D., Casasanto, D., Crollen, V., & Collignon, O. (2015). Space and time in the sighted and blind. *Cognition, 141*, 67–72.
Bruyer, R., & Brysbaert, M. (2011). Combining speed and accuracy in cognitive psychology: Is the inverse efficiency score (IES) a better dependent variable than the mean reaction time (RT) and the percentage of errors (PE)? *Psychologica Belgica, 51*, 5–13.
Bueti, D., & Walsh, V. (2009). The parietal cortex and the representation of time, space, number and other magnitudes. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 364*(1525), 1831–1840.
Bulf, H., 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.
Castronovo, J., & Seron, X. (2007). Semantic numerical representation in blind subjects: The role of vision in the spatial format of the mental number line. *The Quarterly Journal of Experimental Psychology, 60*, 101–119.
Cattaneo, Z., Fantino, M., Tinti, C., Silvanto, J., & Vecchi, T. (2010). Crossmodal interaction between the mental number line and peripersonal haptic space representation in sighted and blind individuals. *Attention, Perception & Psychophysics, 72*, 885–890.
Crollen, V., & Noël, M. P. (2015a). The role of fingers in the development of counting and arithmetic skills. *Acta Psychologica, 156*, 37–44.
Crollen, V., & Noël, M. P. (2015b). Spatial and numerical processing in children with high and low visuo-spatial abilities. *Journal of Experimental Child Psychology, 132*, 84–98.
Crollen, V., Dormal, G., Seron, X., Lepore, F., & Collignon, O. (2013). Embodied numbers: The role of vision in the development of number-space interactions. *Cortex, 49*, 276–283.
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.
Crollen, V., Albouy, G., Lepore, F., & Collignon, O. (2017). How visual experience impacts the internal and external spatial mapping of sensorimotor functions. *Scientific Reports, 7*, 1022.
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 and Biobehavioral Reviews, 32*, 1361–1372.
de Hevia, M. D., Girelli, L., & Macchi Cassia, V. (2012). Minds without language represent number through space: origins of the mental number line. *Frontiers in Psychology, 3*, 466.
de Hevia, M. D., Girelli, L., Addabbo, M., & Cassia, V. M. (2014). Human infants' preference for left-to-right oriented increasing numerical sequences. *PloS one, 9*(5), e96412.
de la Vega, I., Eikmeier, V., Ulrich, R., & Kaup, B. (2017). The mental timeline in a crossed-hands paradigm. *Experimental Psychology, 63*, 326–332.
Dehaene, S., Bossini, S., & Giraux, S. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology General, 122*, 371–396.
Di Luca, S., Granà, A., Semenza, C., Seron, X., & Pesenti, M. (2006). Finger-digit compatibility in Arabic numerical processing. *The Quarterly Journal of Experimental Psychology, 59*, 1648–1663.
Feigenson, L. (2007). The equality of quantity. *Trends in Cognitive Sciences, 11*, 185–187.
Fischer, M. H. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex, 44*, 386–392.
Fischer, M. H., & Hill, R. (2004). A SNARC in the dark: Input modality affects number representation. January *Poster Presented at the 22nd European Workshop of Cognitive Neuropsychology*.
Fischer, M. H., & Brugger, P. (2011). When digits help digits: spatial–numerical associations point to finger counting as prime example of embodied cognition. *Frontiers in Psychology, 2*, 260.
Goffaux, V., Hault, B., Michel, C., Vuong, Q. C., & Rossion, B. (2005). The respective role of low and high spatial frequencies in supporting configural and featural processing of faces. *Perception, 34*, 77–86.
Holmes, K. J., & Lourenco, S. F. (2011). Common spatial organization of number and emotional expression: A mental magnitude line. *Brain and Cognition, 77*(2), 315–323.
McCrink, K., & Opfer, J. E. (2014). Development of spatial-numerical associations. *Current Directions in Psychological Science, 23*, 439–445.
Müller, D., & Schwarz, W. (2007). Is there an internal association of numbers to hands? The task set influences the nature of the SNARC effect. *Memory & Cognition, 35*, 1151–1161.
Nava, E., & Pavani, F. (2013). Changes in sensory dominance during childhood: Converging evidence from the Colavita effect and the sound-induced flash illusion. *Child Development, 84*, 604–616.
Nava, E., Rinaldi, L., Bulf, H., & Macchi Cassia, V. (2017). Visual and proprioceptive feedback differently modulate the spatial representation of number and time in children. *Journal of Experimental Child Psychology, 161*, 161–177.
Nuerk, H. C., Patro, K., Cress, U., Schild, U., Friedrich, C. K., & Göbel, S. M. (2015). How space-number associations may be created in preliterate children: Six distinct

mechanisms. *Frontiers in Psychology, 6*, 215.
Núñez, R., & Cooperrider, K. (2013). The tangle of space and time in human cognition. *Trends in Cognitive Sciences, 17*, 220–229.
Ouellet, M., Santiago, J., Israeli, Z., & Gabay, S. (2010). Is the future the right time? *Experimental Psychology, 57*, 308–314.
Pagel, B., Heed, T., & Röder, B. (2009). Change of reference frame for tactile localization during child development. *Developmental Science, 12*, 929–937.
Riello, M., & Rusconi, E. (2011). Unimanual SNARC effect: Hand matters. *Frontiers in Psychology, 2*, 372.
Rinaldi, L., Vecchi, T., Fantino, M., Merabet, L. B., & Cattaneo, Z. (2015). The effect of hand movements on numerical bisection judgments in early blind and sighted individuals. *Cortex, 71*, 76–84.
Rinaldi, L., Di Luca, S., Henik, A., & Girelli, L. (2016). A helping hand putting in order: Visuomotor routines organize numerical and non-numerical sequences in space. *Cognition, 152*, 40–52.
Rinaldi, L., Gallucci, M., & Girelli, L. (2016). Spatial-numerical consistency impacts on preschoolers' numerical representation: Children can count on both peri-personal and personal space. *Cognitive Development, 37*, 9–17.
Robinson, C. W., & Sloutsky, V. M. (2004). Auditory dominance and its change in the course of development. *Child Development, 75*, 1387–1401.
Röder, B., Kusmierek, A., Spence, C., & Schicke, T. (2007). Developmental vision determines the reference frame for the multisensory control of action. *Proceedings of the National Academy of Sciences, 104*, 4753–4758.
Rugani, R., Vallortigara, G., Priftis, K., & Regolin, L. (2015). Number-space mapping in the newborn chick resembles humans' mental number line. *Science, 347*, 534–536.
Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review, 16*, 328–331.
Townsend, J. T., & Ashby, F. G. (1978). Methods of modeling capacity in simple processing systems. *Cognitive Theory, 3*, 200–239.
Viarouge, A., Hubbard, E. M., & Dehaene, S. (2014). The organization of spatial reference frames involved in the SNARC effect. *The Quarterly Journal of Experimental Psychology, 67*, 1484–1499.
Wood, G., Nuerk, H. C., & Willmes, K. (2006). Crossed hands and the SNARC effect: A failure to replicate Dehaene, Bossini, and Giraux (1993). *Cortex, 42*, 1069–1107.
Zebian, S. (2005). Linkages between number concepts, spatial thinking, and directionality of writing: The SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. *Journal of Cognition and Culture, 5*, 165–190.