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Visual and proprioceptive feedback differently modulate the spatial representation of number and time in children

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ABSTRACT

There has been compelling evidence favoring the idea that human adults similarly represent number and time along a horizontal mental number line (MNL) and mental time line (MTL), respectively. Yet, analogies drawn between the MNL and MTL have been challenged by recent studies suggesting that adults' representations of number and time arise from different spatial frames of reference; whereas the MNL relies on both hand-centered and object-centered coordinates, the MTL appears to be exclusively anchored on object-centered coordinates. To directly test this possibility, here we explored the extent to which visual feedback and proprioceptive feedback affect children's performance in a Number Comparison task (Experiment 1) and a Time Comparison task (Experiment 2), in which participants needed to associate a lateralized key with numerical and temporal words, respectively. Children (5- and 6-year-olds) performed the task with their hands either uncrossed or crossed over the body midline (i.e., manipulation of proprioceptive feedback) and with either visual control over their hands allowed or precluded under blindfolds (i.e., manipulation of visual feedback). Results showed that children were facilitated in associating smaller/larger numbers with the left/right side of the external space, but only when hands were uncrossed and visual feedback was available. On the contrary, blindfolding and crossing their hands over the midline did not affect spatial time mapping, with 6-year-olds showing facilitation in associating words referring to the past/future with the left/right side of the external space irrespective of visual and proprioceptive feedback.

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This same effect was also present in 5-year-olds despite their difficulty in performing the Time Comparison task. Together, these findings show, for the first time, that—just like adults—young children (a) map temporal events onto space in a rightward direction as they do for numbers and (b) anchor their spatial representation of time and numbers to different spatial frames of reference.

Introduction

Over the past two decades, studies have converged over the idea that human adults conceptualize numbers in terms of space by translating them into corresponding spatial extensions and positions along a horizontal continuum, that is, the so-called mental number line (MNL; de Hevia, Vallar, & Girelli, 2008; Dehaene, Bossini, & Giraux, 1993; Hubbard, Piazza, Pinel, & Dehaene, 2005). This phenomenon, commonly referred to as number–space mapping, occurs automatically and accounts for various systematic behavioral effects in numerical and visuospatial tasks (for a review, see Fischer & Shaki, 2014). For example, processing of numerical magnitude influences the deployment of overt visuospatial attention, with small numbers speeding up leftward relative to rightward attentional orienting and the converse for larger numbers (Bulf, Macchi Cassia, & de Hevia, 2014; Myachykov, Cangelosi, Ellis, & Fischer, 2015; see also Loetscher, Bockisch, Nicholls, & Brugger, 2010).

The classical finding supporting the existence of an internal, spatially oriented continuum onto which numbers are represented is the SNARC (spatial–numerical association of response codes) effect, whereby judgments about small numbers are typically faster with a left response key and judgments about large numbers are faster with a right response key, suggesting a compatibility effect between the left and right sides of external space and a left-to-right-oriented numerical representation (Dehaene, 1992; Dehaene et al., 1993). Critically, this effect appears when numbers are presented both as Arabic digits and as written words (Fias & Fischer, 2005) and occurs even when numerical magnitude is irrelevant to the task and without semantic processing of the numbers at all (Fias, Lauwereyns, & Lammertyn, 2001). Together, these findings have led researchers to conclude that adults automatically access spatial representations when processing numbers.

Evidence that preverbal infants (Bulf, de Hevia, & Macchi Cassia, 2016; de Hevia, Girelli, Addabbo, & Macchi Cassia, 2014; de Hevia & Spelke, 2010), animals phylogenetically very divergent from humans (e.g., chicks; Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010; Rugani, Vallortigara, Priftis, & Regolin, 2015), and humans in remote cultures (Dehaene, Izard, Spelke, & Pica, 2008; but see Núñez, 2011) all spontaneously associate numerical magnitude with space supports the view that the number–space mapping is a fundamental spontaneous trait of human, and possibly nonhuman, cognition that is likely rooted in innate or early developing characteristics of the brain (see reviews by de Hevia, Girelli, & Macchi Cassia, 2012, and Nuerk et al., 2015). Although there may be a predisposition for such mapping, its strength and/or orientation are modulated by exposure to directional cultural routines during the course of development. Indeed, several studies have documented that the SNARC effect is influenced by reading and writing practices (e.g., Berch, Foley, Hill, & Ryan, 1999; Dehaene et al., 1993), so that a left-to-right spatial mapping with small-to-large numbers is common in adults from Western cultures, whereas the association is frequently weaker or reversed in right-to-left readers (e.g., Arabic). These findings have been taken as evidence that the specific spatial frame of reference that adults access when they process numbers derives from scanning habits acquired mainly through reading and writing experience. Spatial frames of reference, in general, refer to coordinate systems that individuals use to code spatial information with respect to the body. Spatial information can be coded/centered on the observer's body (egocentric/body-centered coding) or on external nonbodily objects (allocentric/object-centered coding).

Because reading and writing practices orient visuo-spatial attention in the external space (see Rinaldi, Di Luca, Henik, & Girelli, 2014), spatial–numerical associations have often been described within an object-centered frame of reference. However, findings supporting this view are quite mixed. For example, Dehaene et al. (1993) explored the contribution of object-centered and hand-centered reference frames to the emergence of the SNARC effect by asking left-to-right readers to perform a parity judgment task with their hands uncrossed or crossed over the body midline. The hypothesis was that if the left-to-right-oriented spatial representation activated by numerical magnitudes is centered on the hands, a reversed SNARC effect would occur (i.e., small numbers would respond faster with the right key and large numbers would respond faster with the left key) when the hands are crossed over the body midline. On the contrary, if the direction of the SNARC effect arises from object-centered coordinates, no effect of posture would be found, so that faster responses to small numbers with the left key and faster responses for large numbers with the right key would still persist even when the hands are crossed. Results of Dehaene et al. (1993) study showed that spatial–numerical compatibility depended on the relative external position of the hands rather than on the responding hand itself, arguing against the role of a hand-centered reference frame in number–space mapping. Nevertheless, in a subsequent study, Wood, Nuerk, and Willmes (2006; see also Fischer & Hill, 2004) showed that the SNARC effect was significantly reduced in the crossed-hands condition, suggesting a relevant contribution of hand-centered coordinates (for a discussion, see Viarouge, Hubbard, & Dehaene, 2014).

The question of which reference frames are involved in the association of numbers with spatial codes has been recently resumed by studies investigating the role of vision in numerical processing (e.g., Crollen, Dormal, Seron, Lepore, & Collignon, 2013; Rinaldi, Vecchi, Fantino, Merabet, & Cattaneo, 2015). It has been shown that individuals who become blind during the earliest stages of development present a typical SNARC effect (Castronovo & Seron, 2007; Rinaldi, Brugger, Bockisch, Bertolini, & Girelli, 2015; Rinaldi, Vecchi, et al., 2015; Szücs & Csèpe, 2005) when their hands are uncrossed. However, the direction of the effect reverses when they cross their hands over the midline, indicating the use of hand-centered coordinates in these individuals (Crollen et al., 2013). These findings suggest that early visual experience drives the development of an external frame of reference onto which numbers are represented and contributes to the development of an adult-like SNARC effect. Indeed, visual control over the hands has been proposed to be one of the critical factors influencing the direction of the SNARC effect in a crossed-hands posture (Wood et al., 2006; see also Fischer & Hill, 2004). Seeing the hands in a crossed or uncrossed posture affects the saliency of spatial information gathered from the visual modality, and, thus, would influence the activation of the corresponding frame of reference onto which numbers are mapped (for a discussion, see Viarouge et al., 2014).

The idea that numerical magnitudes are internally represented along an oriented spatial layout has prompted researchers to hypothesize that representations of all types of intrinsically ordered information (e.g., time) may similarly exploit space. In fact, ordinal meaning is not unique to numbers given that it is shared by other concepts that can be described in terms of their relative position in a series or sequence (e.g., Gevers, Reynvoet, & Fias, 2003). For example, adults not only talk but also think about time spatially (for reviews, see Bonato, Zorzi, & Umiltà, 2012, and Núñez & Cooperrider, 2013). Spatial compatibility effects similar to those arising for numbers have been reported in the classification of temporal events, with time flowing from one extremity toward the other along a horizontal spatial continuum that, in adults from Western cultures, is oriented from left to right (see Bonato et al., 2012). Along this continuum, not only short durations (Ishihara, Keller, Rossetti, & Prinz, 2008; Vallesi, Binns, & Shallice, 2008) but also earlier events (Santiago, Román, Ouellet, Rodríguez, & Pérez-Azor, 2010) and past events (Santiago, Lupiáñez, Pérez, & Funes, 2007; Torralbo, Santiago, & Lupiáñez, 2006) are represented on the left side, whereas longer durations and future events are represented on the right side. Furthermore, as in number–space mapping, overt visuospatial attention mediates the processing of temporal information, with eyes deviating rightward when thinking about the future and leftward when thinking about the past (Hartmann, Martarelli, Mast, & Stocker, 2014; Rinaldi, Brugger, et al., 2015). These findings have led to the hypothesis that humans represent time along a mental time line (MTL), which shows striking similarities with the MNL (Bonato et al., 2012).

Indeed, like the MNL (e.g., Dehaene et al., 1993), the MTL also shows cross-cultural variations in its orientation as a function of reading and writing habits (Boroditsky, Fuhrman, & McCormick, 2011;

Ouellet, Santiago, Israeli, & Gabay, 2010), suggesting the involvement of an external spatial frame of reference for time representation. However, unlike number–space associations (Crollen et al., 2013), time–space associations are not influenced by hands' posture. In a study with blind individuals, Bottini, Crepaldi, Casasanto, Crollen, and Collignon (2015) asked participants to associate a left or right key with temporarily characterized (i.e., past or future) words while keeping their hands either uncrossed or crossed. Results showed that all participants, regardless of visual experience and hand position, responded faster to past events with the left key and to future events with the right key. This indicates that, unlike number–space mapping (Crollen et al., 2013), time–space mapping relies on the relative left–right position of the effectors in external space rather than on their absolute position with reference to the participant's body.

Therefore, available evidence seems to suggest that adults' spatial representation of numbers and time may rely on different spatial frames of reference given that they are differently influenced by proprioceptive (i.e., hand position) and visual (i.e., sight of the hand position) feedback (for a discussion, see Hendricks & Boroditsky, 2015). Whereas the MNL relies on both hand-centered and object-centered coordinates (for a discussion, see Viarouge et al., 2014), the MTL seems to be exclusively anchored on an external spatial frame of reference.

The idea that the representation of numbers and time may arise from different spatial frames of reference has so far received very little attention and, more critically, has not been directly investigated in developmental populations. The lack of developmental research on this topic seems very unfortunate given that testing children, particularly preschool-aged children, would provide a unique opportunity to understand the role of proprioceptive and visual cues in modulating spatial representations of numbers and time. In fact, a progressive shift from a hand-centered frame of reference to an object-centered one has been documented for sensory localization between 5 and 10 years of age (Pagel, Heed, & Röder, 2009). Moreover, vision becomes more dominant in manual spatial localization during childhood, especially between 5 and 7 years of age (Bremner, Hill, Pratt, Rigato, & Spence, 2013). Therefore, testing children within this age range, when they equally rely on object-centered and hand-centered coordinates, would provide an ideal tool to explore the contribution of different spatial frames of reference to the representation of number and time.

To date, associations between number and space have been repeatedly documented in preschool- and school-aged children (McCrink, Shaki, & Berkowitz, 2014; Opfer, Thompson, & Furlong, 2010; Patro & Haman, 2012; Rinaldi, Gallucci, & Girelli, 2016). These studies, however, did not include any manipulation of hand posture and/or visual input and, thus, did not allow testing for the impact of proprioceptive and/or visual cues on children's number–space mapping. To the best of our knowledge, there are only two studies, both involving 10-year-olds, that have investigated the impact of proprioceptive cues on spatial–numerical associations in nonadult individuals by manipulating hand posture (Crollen & Noël, 2015b; Crollen, Vanderclausen, Allaire, Pollaris, & Noël, 2015). In these studies, children's responses reflected the use of an object-centered frame of reference for representing numbers that was not influenced by hand posture, resembling the adult pattern. However, because the children tested were 10 years old, it might well be that they had already remapped their representation in external coordinates as a result of schooling and consequent massive experience with formal reading and writing practices (Pagel et al., 2009). Albeit nonexistent, studies manipulating proprioceptive and/or visual feedback in younger children may prove to be useful in shedding light on the default use of an external or internal frame of reference for mapping numbers onto space and whether this changes with age and/or schooling experience.

When it comes to the representation of time, it has still to be determined whether children automatically access spatial representations when processing temporarily characterized items in response-side classification tasks. The only existing evidence on the topic comes from the analysis of spontaneous graphic productions (arrangement of transparencies: Tversky, Kugelmass, & Winter, 1991; drawing sequences of events: Dobel, Diesendruck, & Bölte, 2007) of preschool-aged children (i.e., 3–6 years). Although these reports suggest that by the time children enter school their spatial ordering of temporal relations starts to be influenced by reading and writing direction (Tversky et al., 1991), they do not provide any information concerning the spatial frame of reference from which such spatial ordering of temporal information arises. The lack of studies on time–space mapping during the early stages of life may be due to the common opinion that it is difficult to draw strong conclusions about children's ability to differentiate the past and the future when children need to spontaneously produce words referring to past and future events (see Friedman, 1986, 2003, for reviews on the topic). However, children have been shown to be aware that the past can be known and that the future can be changed, indicating that by 4 or 5 years of age they possess a quite complex representation of time and can discriminate between the past and the future.

In the current study, we attempted to fill these gaps by exploring the spatial representation of numbers (Experiment 1) and time (Experiment 2) in 5- and 6-year-old children as a function of hand posture and visual feedback. Children were tested in a modified version of the Number Comparison task (Crollen et al., 2013), in which stimuli were auditorily presented with number words (i.e., 2–8) or words referring to time (e.g., "yesterday", "tomorrow") and participants responded by pressing two keys positioned on the left and right side of space. To assess the role of the spatial frames of reference involved, proprioceptive feedback was manipulated 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. Moreover, to explore the contribution of vision, we manipulated the possibility for children to see the position of their hands by requiring them to perform the task either blindfolded or not. The stimuli and study design were modeled after those used in previous studies with adults (Bottini et al., 2015; Crollen et al., 2013), with the aim of drawing possible parallels between results obtained with children and those obtained with adults.

The study included 5- and 6-year-old children to explore the impact that formal education and learning of reading and writing routines, which are mainly grounded on external coordinates, may have on the organization of spatial representation of number and time. To this end, in addition to the response-side classification task, which provided an implicit measure of spatial associations by anchoring children's response to specific spatial locations (i.e., the left or right key and/or hand), at the end of the testing session we also assessed children's explicit mapping of number and time onto space by asking them to count a set of objects (Experiment 1) or to reorganize a set of cards depicting a story (Experiment 2). These tasks explicitly require children to associate numerical and temporal information with space and, therefore, may provide a more sensitive measure of the influence of formal schooling (for a discussion, see Nuerk et al., 2015).

We hypothesized that if numbers and time are grounded on different spatial frames of reference already at 5 or 6 years of age, the effects of proprioceptive and visual feedback should dissociate between Experiment 1 and Experiment 2. In particular, if the representation of numbers relies, at least to some extent, on hand-centered coordinates, we should observe a stronger response-side compatibility effect when children perform the task in the uncrossed hand posture. In the same vein, the effect should mainly emerge when children have access to the sight of their hands' position in the peripersonal space because they are not blindfolded, whereas the absence of vision in blindfolded children should prevent the spatial–numerical mapping to occur. We also reasoned that if the representation of time is already grounded on object-centered coordinates by 5 or 6 years of age, as it is during adulthood (Bottini et al., 2015), manipulating hand posture and sight of the hands should not affect the establishment of the space–time mapping.

Experiment 1

Method

Participants

The final sample consisted of 45 5-year-old children (mean age = 5.5 years; 25 girls) and 43 6-year-old children (mean age = 6.7 years; 22 girls) recruited from local kindergartens and primary schools. An additional 3 children in the 5-year-old group and 3 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 (5-year-olds: $n = 23$; 6-year-olds: $n = 20$) performed the Number Comparison task while blindfolded, and 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?"). All children were Italian, all came from urban communities, and all had Caucasian origins. The kindergartens and primary schools from which the children were recruited are mostly attended by families from middle socioeconomic status.

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 Milan–Bicocca.

Apparatus, stimuli, and procedure

Participants were tested individually in a quiet room while seated in front of a table. All children performed three tasks administered in a fixed order: (1) Give a Number task, (2) Number Comparison task, and (3) Chip Counting task.

In the Give a Number task (see Opfer et al., 2010), we assessed children's representation of numbers. In this task, children were verbally asked to give the experimenter 3 and 8 chips, respectively, from their set of 12 chips. The experimenter was seated in front of the children, and the chips were placed in a small box at reaching distance.

The task started with a practice trial (e.g., give 2 chips) illustrated by the experimenter, and subsequently the children were asked to give 3 and 8 chips, respectively, for a total of two trials. The experimenter recorded the number of chips provided by the children on each trial. This task was considered as a mandatory criterion to proceed to the next task (i.e., only children able to give the correct number of chips in both trials were included in the experimental sample).

In the Number Comparison task, children were instructed to respond as accurately and quickly as possible to auditory numbers presented through headphones by pressing one of two response buttons placed on the table in front of them in the left and right hemi-spaces at a distance of about 20–30 cm from each other (adjusted to children's body size). The software E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA, USA), run on a portable HP Compaq laptop computer, was used for stimulus presentation and response sampling. Stimuli consisted of six audio recordings of a female voice speaking aloud numbers ranging between 2 and 8 (with the exception of number 5) in Italian language (see Crollen et al., 2013, for a similar procedure). The audio stimuli lasted 600 ms each, had identical auditory properties (44,100 Hz, 32 bits, stereo), and had an adjustable intensity ranging between 50 and 60 dB. They were presented through headphones. Participants were instructed to decide as accurately and quickly as possible whether numbers were smaller or larger than a reference number (5), and they had 3000 ms to respond. To make sure that children understood the task, the experimenter provided them with different examples; each child was presented with a variable number of trials before the actual experiment started, depending on the child's full understanding of the task. The task followed a 2 (Age) $\times$ 2 (Vision) $\times$ 2 (Hand Posture) $\times$ 2 (Congruency) design; each age group (i.e., 5- or 6-year-olds) was split into two subgroups, with one group being blindfolded (i.e., no visual control over the hands) throughout the whole experiment and the other one being allowed to see their hands (i.e., visual control over the hands). All participants performed four blocks of trials; in two of the blocks they had their arms crossed over the midline, and in the other two blocks they had their arms in a canonical position (see Fig. 1). Congruency was the other factor we manipulated. In two of the blocks, the children were asked to associate the response keys with the "smaller than" and "larger than" response congruently with respect to the left-to-right object-centered orientation of the MNL. In the other two blocks, the responses were incongruent with respect to the left-to-right object-centered orientation of the MNL. In sum, visual feedback was manipulated between participants, whereas hand posture and congruency were manipulated within participants. All children completed the two crossed or uncrossed trial blocks before proceeding to the other condition, whereas congruency was alternated between blocks; the condition tested in the first block was counterbalanced across participants in each age group. Participants completed one block of 24 trials per each condition for a total of 96 trials. The overall experimental session lasted about 30 min.

The Chip Counting task was administered as the last task to assess the children's tendency to spontaneously map number to space according to a specific direction. Children were asked to count nine poker chips shown on a magnetic board (60 $\times$ 20 cm) in a linear array centered on their midline by

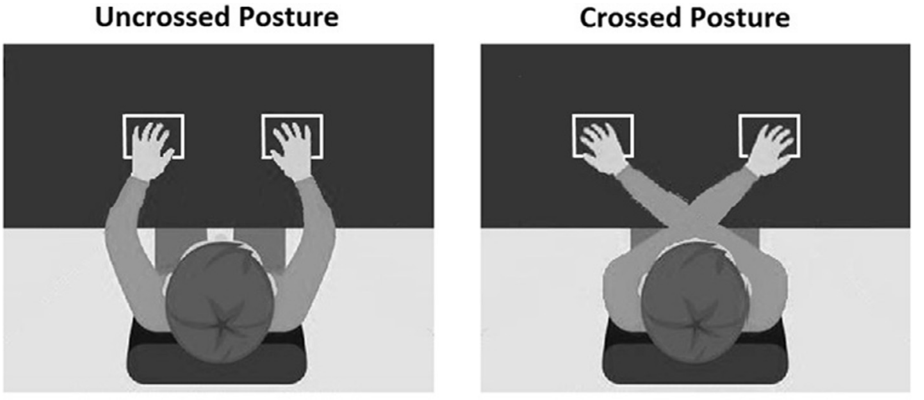

Fig. 1. The experimental setting used to test children in the Number Comparison task of Experiment 1 and in the Time Comparison task of Experiment 2. Participants were seated in front of a table and were required to perform the tasks in two different postures: an uncrossed posture (left panel), and a crossed posture (right panel).

pointing at them one by one. The experimenter recorded the direction the children used to count the chips.

Results

Give a number task

For each child, we attributed 1 point to each correct response for each of the two trials. All children scored 2 because they correctly gave 3 and 8 chips, respectively, and so matched the criterion to be included in the final sample.

Number comparison task

Proportion of correct responses and inverse efficiency scores (IESs) were analyzed in three repeated-measures analyses of variance (ANOVAs) with age (5 or 6 years) and vision (present or absent) as between-participants factors and with hand posture (crossed or uncrossed) and congruency (congruent or incongruent) as within-participants factors. Proportion of correct responses was calculated for each participant in each condition and was analyzed in order to provide a general measure of the overall level of performance. IES data were calculated separately for each participant's performance 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 milliseconds) 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). Due to the age range of participants in this experiment and the variability with which children attending preschool and those attending primary school may favor either RTs or accuracy in performing the task (i.e., younger children may tend to respond more rashly, favoring RTs over accuracy, whereas older children may respond more cautiously but slowly, favoring accuracy over RTs), we reasoned that IESs would fit our analyses best.

Proportion of correct responses. The ANOVA on proportion of correct responses revealed main effects of age, $F(1, 84) = 15.40$, $p < .001$, $\eta^2 = .15$, congruency, $F(1, 84) = 13.11$, $p = .001$, $\eta^2 = .14$, posture, $F(1, 84) = 4.17$, $p = .04$, $\eta^2 = .05$, and vision, $F(1, 84) = 6.70$, $p = .01$, $\eta^2 = .07$. The 6-year-old children ($M = 0.87$, $SD = 0.16$) were overall more accurate than the 5-year-olds ($M = 0.77$, $SD = 0.20$), with both groups performing well above chance level (one-sample t tests against .50, all $ps < .001$). Children in both age groups performed more accurately on congruent trials ($M = 0.85$, $SD = 0.16$) compared with incongruent trials ($M = 0.79$, $SD = 0.20$), on uncrossed trials ($M = 0.84$, $SD = 0.18$) compared with crossed trials ($M = 0.81$, $SD = 0.18$), and when visual feedback was present ($M = 0.86$, $SD = 0.16$) compared with when it was absent ($M = 0.79$, $SD = 0.22$). The analysis also showed a significant Congruency × Vision interaction, $F(1, 84) = 5.78$, $p = .02$, $\eta^2 = .06$. Post hoc comparisons (Bonferroni correction) revealed that in the presence of visual feedback, children performed more accurately in the congruent trials ($M = 0.91$, $SD = 0.19$) than in the incongruent trials ($M = 0.80$, $SD = 0.18$), $p < .001$. On the contrary, blindfolded children did not show any congruency effect (congruent: $M = 0.79$, $SD = 0.21$; incongruent: $M = 0.77$, $SD = 0.23$), $p = .99$.

Inverse efficiency scores. Fig. 2 summarizes the main results obtained. The ANOVA revealed a main effect of congruency, $F(1, 84) = 16.70$, $p < .001$, $\eta^2 = .17$, indicating that children were faster in responding to "smaller than 5" with the left key and "larger than 5" with the right key than the reverse. Crucially, the Congruency × Visual Feedback interaction, $F(1, 84) = 9.99$, $p = .002$, $\eta^2 = .11$, and the Congruency × Posture interaction, $F(1, 84) = 4.86$, $p = .030$, $\eta^2 = .06$, were also significant. Post hoc comparisons showed that responses provided in the congruent trials were significantly faster than those provided in the incongruent trials when children could see their hands ($p < .001$) but not when they were blindfolded ($p > .99$). Moreover, the advantage for congruent trials over incongruent trials was apparent in the uncrossed-hand condition ($p < .001$) but not in the crossed-hand condition ($p > .86$).

Chip counting task

To assess the direction of counting in this task, we split the responses of the children into two categories: the left-to-right responses and the right-to-left responses. We compared the scores of the 5- and 6-year-old children by entering the two categories of responses into a chi-square test, which revealed a significant difference between age groups, $\chi^2(1) = 9.8$, $p < .005$, with 100% of older children counting from left to right as opposed to 79.5% of younger children showing such a tendency. However, and most important, for both the 5-year-olds, $\chi^2(1) = 6.1$, $p = .01$, and the 6-year-olds, $\chi^2(1)$

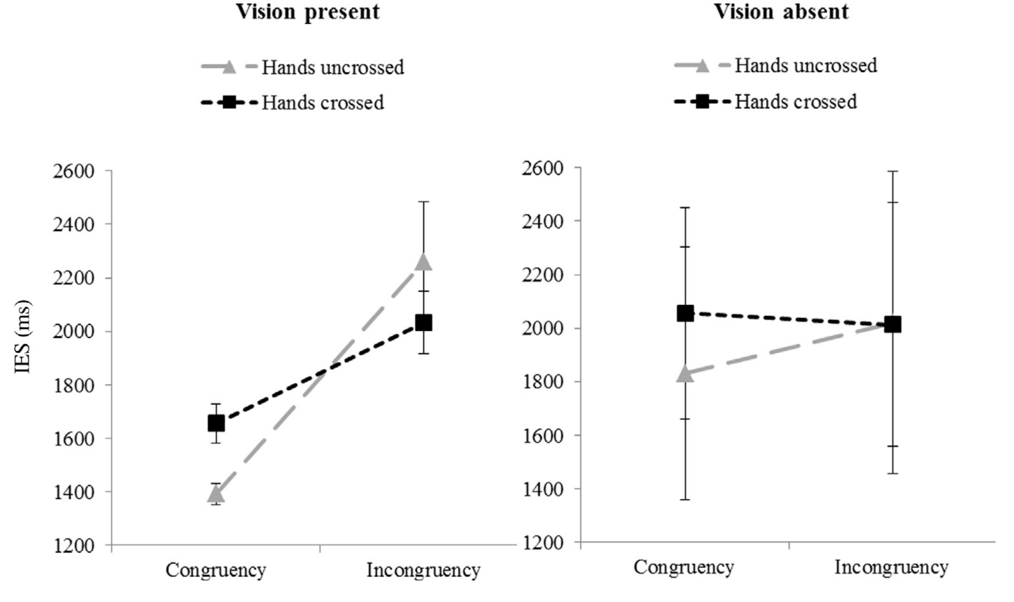

Fig. 2. Results of the Number Comparison task in Experiment 1 showing mean inverse efficiency scores (IESs) collapsed across age groups separately for type of visual condition (present: left panel; absent: right panel). Children's responses were faster on congruent trials than on incongruent trials, but the congruence advantage was modulated both by visual feedback (i.e., present only when vision was available) and by posture (i.e., present only in the uncrossed condition). Error bars represent standard errors of the means.

= 41.0, $p < .001$, most of the children spontaneously counted the chips from left to right rather than from right to left.

Discussion

The results of Experiment 1 yielded a series of important findings. Indeed, we showed that both 5- and 6-year-old children exhibited a SNARC effect given that they were more accurate and faster in associating smaller/larger numbers with the left/right side of the external space. However, and critically, this association was modulated by visual feedback and by hand posture given that the SNARC effect was observed only when hands were uncrossed and visual feedback was present. Together, these findings indicate that an object-centered coordinate system is still not (fully) adult-like by 6 years of age. Rather, by this age there is still a combined activation of object-centered and hand-centered coordinates to represent numbers. Indeed, the fact that crossing the hands over the body midline precluded the SNARC effect, without reversing it, indicates that 5- and 6-year-olds do not rely entirely on either a hand-centered or object-centered reference frame when representing number.

To investigate whether visual feedback and proprioceptive feedback similarly influence the spatial representation of time in young children, we ran a second experiment with a new sample of 5- and 6-year-olds, using the same experimental design of Experiment 1 but with temporal concepts as stimuli.

Experiment 2

Method

Participants

The final sample consisted of 38 5-year-old children (mean age = 5.6 years; 22 girls) and 48 6-year-old children (mean age = 6.8 years; 23 girls). None of them participated in Experiment 1. An additional 3 children in the 5-year-old group and 2 children in the 6-year-old group were tested but excluded from the sample because they were uncooperative and failed to conclude testing. Half of the children in each age group (5-year-olds: $n = 19$; 6-year-olds: $n = 24$) performed the Time Comparison task while blindfolded, and the other half performed the same task while having access to the sight of their hands. All children had similar characteristics than those involved in Experiment 1. Indeed, all children were Italian, Caucasian, and recruited from kindergartens and primary schools mostly attended by families with middle socioeconomic status.

Apparatus, stimuli, and procedure

Like in Experiment 1, all children performed three tasks administered in a fixed order: (1) Give an Order task, (2) Time Comparison task, and (3) Cards Reorganization task.

In the Give an Order task, we assessed whether children had an overall concept of time. In this task, children were presented with two sets of three cards, each describing a temporal sequence, and were verbally asked to provide the cards to the experimenter sequentially (i.e., one by one) by putting them in a box. The first set of cards depicted a pig entering a kitchen and seeing a cake on the table (Card 1), eating most of the cake (Card 2), and getting his face all dirty (Card 3). The second set of cards depicted a rabbit under a snowfall (Card 1) and getting covered more and more by the snow (Card 2) until he is completely covered (Card 3). The experimenter was seated in front of the children, and the cards (6×8 cm) were randomly placed on the table at the children's reaching distance.

The task started with a practice trial that included the experimenter's feedback, followed by two test trials with no feedback. For each trial, the experimenter recorded whether the children put the three cards in the correct order. This task was considered as a mandatory criterion to proceed to the next task (i.e., only children able to give the cards in the correct order in both trials were included in the experimental sample). The response was considered as correct if the children put the card in the right order, with response directionality that could not be assessed. This was done on purpose to not trigger children's directional preferences and to not influence the performance of the subsequent categorization task (i.e., Time Comparison task). Spontaneous directional preferences were then tested at the end of the session in the Cards Reorganization task.

The Time Comparison task mimicked the Number Comparison task in all characteristics except the stimuli, which consisted of audio recordings of a female voice speaking aloud Italian words referring to past ("before", "yesterday", and "past") and future ("after", "tomorrow", and "future"). These temporal terms are similar to those adopted in previous studies on adults' spatial representation of time (Bottini et al., 2015) and are commonly used by children during preschool years (Busby Grant & Suddendorf, 2011). As in Experiment 1, the audio stimuli lasted 600 ms each with the interstimulus interval fixed at 2500 ms, had identical auditory properties (44,100 Hz, 32 bits, stereo), had an adjustable intensity ranging between 50 and 60 dB, and were delivered to participants through headphones. 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, and they had 3000 ms to provide their response. Their task was to decide whether the heard word referred to an event that had already happened (past event) or that had not yet happened (future event) with reference to "now". As in the Number Comparison task, the experimenter presented each child with a variable number of trials to make sure that he or she understood the task before starting the experiment.

Visual feedback (blindfolded or not blindfolded) was manipulated between participants, and hand posture (crossed or uncrossed) and congruency (congruent or incongruent with respect to the left-to-right object-centered orientation of the MTL) were manipulated within participants. Each participant completed the two crossed or uncrossed trial blocks before proceeding to the other condition, whereas congruency was alternated between blocks; the condition tested in the first block was counterbalanced across participants in each age group. There were 24 trials per block for a total of 96 trials; the overall experimental session lasted about 30 min.

The Cards Reorganization task mimicked the Chip Counting task in that it assessed children's tendency to spontaneously map time onto space without the requirement of using a specific frame of reference to do so. Children were shown four cards (6×8 cm) randomly placed in front of them on a table. The cards depicted a flower (Card 1) that progressively loses all of its petals (Cards 2 and 3) until it is withered and without petals (Card 4). The experimenter recorded the accuracy of the cards reorganization and the direction the children used to organize them in the horizontal space.

Results

Give an order task

For each child, we attributed 1 point to each correct response for each of the two trials. All children scored 2 because they correctly displayed the cards from the two sets and, thus, matched the criterion to be included in the final sample.

Time Comparison task

Analyses mimicked those performed for the Number Comparison task, thereby considering proportion of correct responses and IESs.

Proportion of correct responses. The analysis on proportion of correct responses revealed main effects of age, $F(1, 82) = 10.52$, $p = .002$, $\eta^2 = .11$, and congruency, $F(1, 82) = 8.62$, $p = .004$, $\eta^2 = .10$. The 6-year-old children ($M = 0.58$, $SD = 0.19$) were overall more accurate than the 5-year-old children ($M = 0.50$, $SD = 0.13$), and all children, irrespective of age, showed overall greater accuracy on congruent trials ($M = 0.57$, $SD = 0.16$) than on incongruent trials ($M = 0.52$, $SD = 0.17$). There were no interactions involving the factor visual feedback ($p > .75$) or posture ($p > .97$).

One-sample t tests (vs. .50) showed that older children performed significantly above chance, $t(48) = 3.81$, $p < .001$, whereas younger children did not, $t(38) = -0.28$, $p = .78$. Moreover, performance across ages differed from chance level on congruent trials, $t(86) = 4.17$, $p < .001$, but not on incongruent trials, $t(86) = 1.06$, $p = .29$.

Inverse efficiency scores. The ANOVA performed on the IES data revealed a main effect of congruency, $F(1, 82) = 9.23$, $p = .003$, $\eta^2 = .10$, showing that all children were faster in responding to past-related words with the left key and to future-related words with the right key than the reverse, irrespective of hand position and availability of visual feedback (Fig. 3). There were no significant interactions involving the factors age (*p*s > .78), vision (*p*s > .81), and posture (*p*s > .99). However, in light of the age effect observed for accuracy rates, we performed a separate ANOVA for each age group. These analyses confirmed the presence of a main effect of congruency for both 5-year-olds, $F(1, 36) = 4.67$, $p = .03$, $\eta^2 = .12$, and 6-year-olds, $F(1, 46) = 5.14$, $p = .03$, $\eta^2 = .10$ (Fig. 3).

Cards reorganization task

All children were able to display the cards in each sequence in the correct order irrespective of age. As in the Chip Counting task of Experiment 1, to assess the direction of the children's temporal organization of the events, we scored each response as belonging to one of two categories: left-to-right responses or right-to-left responses. We compared the scores of the 5-year-olds and the 6-year-olds by entering the two categories of responses into a chi-square test, which revealed a significant difference between age groups, $\chi^2(1) = 9.1$, $p < .005$, with 93.8% of older children ordering cards from left to right as opposed to 69.2% of younger children showing such a tendency. By comparing the responses within each age group, we found that, for both the 5-year-olds, $\chi^2(1) = 5.0$, $p = .03$, and the 6-year-olds, $\chi^2(1) = 36.7$, $p < .001$, most of the children spontaneously arranged the cards from left to right rather than from right to left.

General discussion

The current study investigated the existence of space–number and space–time mappings in 5- and 6-year-old children and the nature of the spatial frame(s) of reference onto which such mapping is anchored. Results revealed that, at both ages, space–number mapping was influenced by visual feedback as well as by hand posture (Experiment 1). On the contrary, neither visual feedback nor propri-

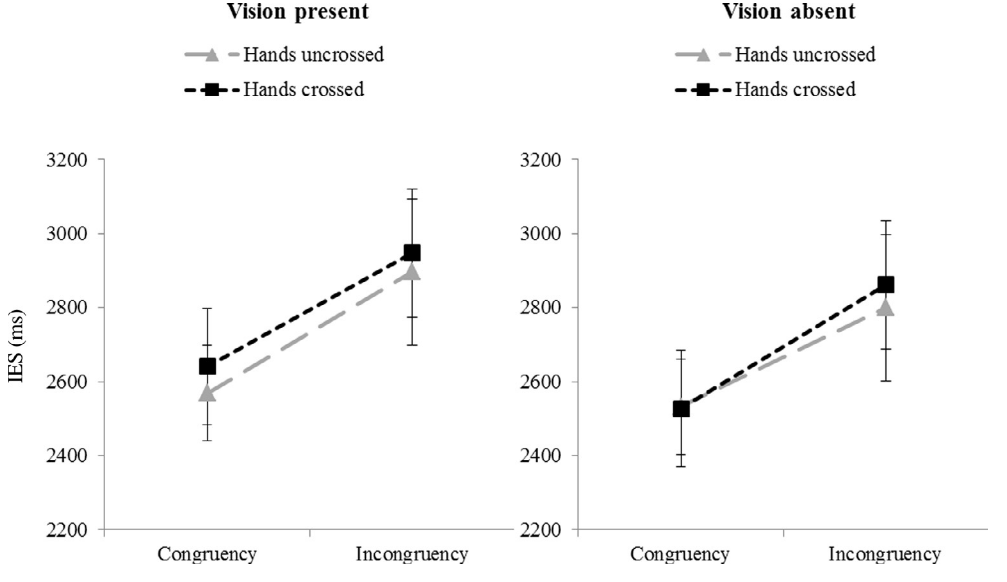

Fig. 3. Results of the Time Comparison task in Experiment 2 showing mean inverse efficiency scores (IESs) collapsed across age groups separately for type of visual condition (present: left panel; absent: right panel). Children's responses were faster on congruent trials than on incongruent trials irrespective of visual feedback (present vs. absent) and posture (hands uncrossed vs. crossed). Error bars represent standard errors of the means.

oceptive feedback concerning the position of the hands affected children's mapping of time onto space (Experiment 2). Together, these findings indicate that the spatial representation of numbers and time arise from different spatial frames of reference, with the MNL being partially anchored on both the body and the space away from the body and the MTL being exclusively anchored on the external space. Importantly, these differences were accompanied by similar performances in tasks that assess the spontaneous organization of numerical and temporal information on space without anchoring children's responses to specific spatial locations (i.e., the left or right key and/or hand). Indeed, when children were explicitly required to count a series of spatially dislocated items (i.e., Chip Counting task) and to spatially organize a series of cards based on temporal order (i.e., Cards Reorganization task), they all displayed a rightward directional bias, which was enhanced by formal education and learning of reading and writing routines given that it was stronger in 6-year-olds compared with 5-year-olds.

In Experiment 1, both 5- and 6-year-old children showed a SNARC effect given that they were more accurate and faster in associating smaller/larger numbers with the left/right side of the external space. However, and most crucially, results showed that this response-side compatibility effect was confined to the condition in which hands were uncrossed and visual feedback concerning hand position was available, indicating that children of this age do not rely entirely on either a hand-centered or object-centered reference frame when representing number. These findings are at odds with earlier demonstrations that, in sighted adults and 10-year-old children (Crollen & Noël, 2015b; Crollen et al., 2015; Dehaene et al., 1993), the SNARC effect is present irrespective of hand posture, that is, even when hands are crossed. This may indicate that the default use of an object-centered coordinate system develops only at older ages, likely following consolidation of reading and writing practices, which may anchor numerical concepts onto external space. In line with this hypothesis, there is evidence of a transition from hand-centered to object-centered reference frames between 5 and 10 years of age for tactile localization (Pagel et al., 2009). It is also worth considering that, along with evidence favoring an object-centered mapping of numbers to space (Crollen & Noël, 2015b; Crollen et al., 2015; Dehaene et al., 1993), other studies found a non-negligible contribution of hand-centered coordinates to the SNARC effect in adult participants (e.g., Viarouge et al., 2014; Wood et al., 2006). These studies suggest that, even in adults, numbers can be flexibly mapped onto different reference frames whose influence depends on the saliency put on the sides of either the body (i.e., hands) or the external space (i.e., response keys) by the task at hand (for a discussion, see Viarouge et al., 2014). Our findings add to this evidence, suggesting that spatial–numerical associations can be conceived during development as the weighted sum of the activation of both object-centered and hand-centered coordinates.

Critically, results of Experiment 1 also yielded a significant effect of visual feedback on number–space associations. In particular, the absence of visual feedback eliminated the SNARC effect, suggesting that the typical left–right orientation of the MNL in young children heavily relies on visual experience. Indeed, although here vision was prevented only temporarily (i.e., during task execution), our findings converge with those obtained with early blind individuals (Crollen et al., 2013). Crollen et al. (2013) reported that crossing the hands reversed the typical SNARC effect in early blind individuals, but not in late blind and sighted individuals, during a numerical comparison task. These findings indicate that participants who experienced visual deprivation during the earliest stages of development adopt a hand-centered reference frame when processing numbers, whereas participants who were deprived of vision later in development rely on an external frame. Therefore, these findings were interpreted as evidence that early visual experience plays an important role in the development of a spatial representation of numbers anchored onto external coordinates. Our findings add to this earlier demonstration suggesting that 6 years of visual experience is not sufficient to establish a default use of an external reference system for number representation.

At the same time, it is worth noting that previous studies on sighted adults reported a SNARC effect in the crossed-hands condition when participants were blindfolded but not when they had access to their hands' sight (e.g., indirect comparison between findings of Crollen et al., 2013, and those of Wood et al., 2006; but see Fischer & Hill, 2004), suggesting that the absence of visual control over the hands may reduce the competition between body-centered and object-centered frames of reference generated by posture manipulations in adult participants. This pattern of results partially contrasts with that obtained with children in the current study, where the competition between object-centered and hand-centered frames of reference was stronger when participants could not see their hands' position. The opposite pattern observed in adults and children may derive from the different impact of visual (vs. proprioceptive) feedback on perceived hand position, which increases during development, making children progressively more dependent on vision in spatial localization tasks (Bremner et al., 2013).

With regard to children's representation of time, results from Experiment 2 revealed, for the first time in a response-side classification task, that 5- and 6-year-old children map temporal events onto space in a rightward direction. So far, young children's use of spatial codes to represent temporal events has been documented only by scattered evidence on spontaneous graphic productions (Tversky et al., 1991) and temporal/spatial judgments (Bottini & Casasanto, 2013). Hence, our findings complement available evidence indicating that humans possess an MTL that keeps track of the subjective time flow from early stages of development.

It is worth noting that children of both ages showed overall worse performance in the Time Comparison task than in the Number Comparison task (Experiment 1). Differences in performance between the two tasks were also evident in the distribution of individual data. Although a significant spatial compatibility effect emerged in the Time Comparison Task for both the 5- and 6-year-olds, the number of children showing the effect was overall smaller in Experiment 2 than in Experiment 1 (56% vs. 62%), and this was especially true for the younger children (54% vs. 63%). These differences are in line with evidence indicating that children's mastery of temporal concepts undergoes a protracted developmental trajectory (for a discussion, see Busby Grant & Suddendorf, 2011). In fact, although understanding of the words "yesterday" and "tomorrow", and terms like "before" and "after", emerges between 3 and 5 years of age (Busby Grant & Suddendorf, 2011; Stevenson & Pollitt, 1987; Suddendorf, 2010), it is only during the first years of primary school that these terms, as well as past and future tenses, are included in children's vocabulary (Harner, 1980; see also Busby Grant & Suddendorf, 2011; for a review, see Friedman, 2003). Yet, despite these difficulties in mastering temporal concepts, the younger children did not differ from the older children in the extent to which their performance was modulated by spatial congruency given that congruency did not interact with age. In striking contrast to the domain of time, a symbolic system for representing numbers develops early during the preschool years (Sarnecka & Gelman, 2004), with 5-year-olds being capable of assigning number words to specific cardinal values even when they fall beyond the counting range (Lipton & Spelke, 2006).

Yet, the fact that 5- and 6-year-old children associate the past with the left side of external space and the future with the right side of external space does not prove that time–space associations are a developmental default. Rather, our findings show that time–space mappings occur before extensive exposure to formal education and, thus, before learning of writing and reading. As in the case of number–space mapping, the source of the observed left or right preference for mapping past or future events, respectively, may be found in passive exposure and/or active experience with cultural-based directional routines such as watching parents or caregivers in joint book reading and pretend reading and writing, activities that would consolidate the mapping of time (i.e., earlier/later) along the direction (i.e., left/right in Western countries) exploited by the native language system (see de Hevia et al., 2012; Nuerk et al., 2015). Indeed, spatial–numerical associations have been repeatedly reported before schooling (for a review, see McCrink & Opfer, 2014) and even during the first year of life (de Hevia et al., 2014), indicating an early sensitivity to the cultural environment in which preliterate children are immersed (for a discussion, see Patro, Nuerk, & Cress, 2016). Another critical aspect of the results from Experiment 2 is that children's representation of time was not influenced by visual feedback or hand posture, suggesting that, like during adulthood (Bottini et al., 2015), already during early childhood the spatial representation of time is strongly anchored to external, object-centered spatial coordinates.

Overall, results on children's number–space associations (Experiment 1) and those on children's time–space associations (Experiment 2) diverge in two main aspects, which deserve further consideration.

First, children's representation of number is anchored on both hand-centered and object-centered coordinates, whereas their spatial representation of time appears to be exclusively anchored on the external space. The idea that representation of number and time may arise from different spatial frames of reference is also supported by studies with blind individuals (Bottini et al., 2015; for a discussion, see Hendricks & Boroditsky, 2015). But how can this dissociation be explained? One could claim that because we often learn to count using our hands and fingers, our representational space for numbers is also partially built around the hand space (Di Luca, Granà, Semenza, Seron, & Pesenti, 2006; Fischer & Brugger, 2011). Accordingly, associations between numbers and space in adults can build on direction of finger counting routines (Di Luca et al., 2006; Rinaldi, Di Luca, et al., 2016 or, at least, can be modulated by them (Fischer, 2008; Riello & Rusconi, 2011). The impact of finger counting routines on number–space mapping would be particularly prominent during childhood, when fingers are an embodied tool through which children keep track of numerical information (Crollen & Noël, 2015a; Rinaldi, Gallucci, et al., 2016). In fact, it has been shown that hand movements interfere with children's performance in counting and addition problem solving, whereas foot movements do not (Crollen & Noël, 2015a). Moreover, early blind individuals, who were deprived of visual input from at least 2 years of age and do not use finger counting strategies (Crollen, Mahe, Collignon, & Seron, 2011), are "stuck" in an anatomically anchored reference system for representing number (Crollen et al., 2013). Yet, it is worth noting that despite limited use of finger counting in early blind individuals (Crollen et al., 2011, 2014), these individuals still rely on hand-centered coordinates when representing numbers (Crollen et al., 2013). In this sense, other factors other than finger counting routines may be responsible for the adoption of hand-centered coordinates in both the sighted and the blind. When it comes to time, on the contrary, body-centered space appears to be much less relevant given that we do not count time on our fingers and tend to adopt an "external" perspective on horizontal time series (Bender & Beller, 2014; Núñez & Cooperrider, 2013). This is particularly true when the experimental task itself encourages viewing of the time series from the outside as in tasks involving left/right arranged response locations (for a discussion, see Núñez & Cooperrider, 2013; see also Rinaldi, Di Luca, et al., 2016).

A second aspect that differentiates number–space associations and time–space associations in the current study is that visual feedback had different impacts on children's MNL and on their MTL; for numbers a response-side compatibility effect was found only in the presence of visual feedback, whereas for time a compatibility effect emerged also when vision was prevented. A similar dissociation was recently inferred (Hendricks & Boroditsky, 2015) from the comparison between available evidence on the spatial representation of numbers (Crollen et al., 2013) and time (Bottini et al., 2015) in blind individuals. To account for this dissociation, Bottini et al. (2015) hypothesized that the MTL relies more on the orthographic experience of reading—irrespective of whether this is achieved through the eyes (in sighted individuals) or through the hands (in blind individuals)—than does the MNL, which would be influenced also by other bodily practices like finger counting. Yet, because the children we tested might not have accumulated extensive reading experience and consequently might not have acquired stable scanning habits, and because we did not find any age-related effect in the results, our findings remain neutral to the role of formal reading practice in such a dissociation between the effects of vision on number–space and time–space mapping.

The finding that the congruency effect in our data was not modulated by participants' age may appear surprising, given that reading and writing habits have modulating effects on both the MNL and the MTL in adult individuals (e.g., Shaki, Fischer, & Petrusic, 2009). Indeed, although writing and reading skills did not modulate children's performance in our implicit tasks (i.e., the Number Comparison and Time Comparison tasks), they did influence the direction onto which numbers and time are spontaneously represented, as assessed through explicit tasks. In particular, our results in the Chip Counting and Cards Reorganization tasks show that both 5- and 6-year-old children align numbers and temporal events in a left-to-right fashion, but this directional bias is more evident in 6-year-olds than in 5-year-olds. This suggests that being systematically exposed to and required to learn culturally based directional reading/writing practices increases the strength of an already existing spontaneous bias, at least when the task explicitly requires associating number with space or associating time with space (i.e., starting to count/order cards from one point in space) (for a discussion, see Nuerk et al., 2015). Future studies should ideally involve children across a wider age range and with highly different writing and reading skills in response-side classification tasks to test whether the impact of formal education practices may differently emerge in tasks involving explicit and implicit measures of spatial associations.

In conclusion, the current study provides the first evidence for an oriented spatial representation of time in young children and shows for the first time that the MNL and the MTL in children are anchored to different spatial frames of reference. Although parallels have often been drawn in the way that humans represent numbers and time in space (Bonato et al., 2012; Walsh, 2003), here we showed that sources of these two mappings can be sought in dissociable mechanisms that are functional during early childhood. In particular, whereas space–time mappings appear to be strongly anchored on the space outside a child's body, space–number mappings are anchored on both the space outside the body and the child's body space itself.

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