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PAPER

Small on the left, large on the right: numbers orient visual attention onto space in preverbal infants

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Abstract

Numbers are represented as ordered magnitudes along a spatially oriented number line. While culture and formal education modulate the direction of this number–space mapping, it is a matter of debate whether its emergence is entirely driven by cultural experience. By registering 8–9-month-old infants' eye movements, this study shows that numerical cues are critical in orienting infants' visual attention towards a peripheral region of space that is congruent with the number's relative position on a left-to-right oriented representational continuum. This finding provides the first direct evidence that, in humans, the association between numbers and oriented spatial codes occurs before the acquisition of symbols or exposure to formal education, suggesting that the number line is not merely a product of human invention.

Research highlights

- This work addresses the origins of the link between numbers and oriented spatial codes, as hypothesized under the 'mental number line' model of numerical representation.
- Using a Posner-like task, we found that numerical, but not non-numerical, cues orient infants' visual attention towards a peripheral region of space that is congruent with the number's relative position on a left-to-right oriented representational continuum.
- This evidence sheds light on the developmental origins of the oriented number-space mapping observed in adults, showing that a predisposition to relate numerical ordering and a left-to-right oriented axis emerges early in life, before humans learn to read, write or count on their hands, and before acquisition of symbolic knowledge.

Introduction

Research on adults' numerical abilities suggests that numbers and space are intimately related in the human mind in the form of an oriented mental number line (Dehaene, 1992; Dehaene, Piazza, Pinel & Cohen, 2003). However, the developmental origins of the relation between numbers and spatial codes, as well as the directionality of this relation, remain controversial. Is the relation between numbers and oriented spatial codes merely a product of cultural experience and exposure to symbolic knowledge and formal education, or is it present in early infancy, before those factors have an impact on the representation of numbers? To address this question, in the current study we examined whether perceiving numerical and non-numerical magnitudes causes lateralized shifts of visual attention in preverbal infants, at an age when no exposure to formal symbolic or mathematical instruction has yet occurred, and when

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the modulating effects of culturally shaped scanning routines are minimized.

In adults, numerical primes boost attention orientation towards the left or right sides of space, depending on their magnitude (Bulf, Macchi Cassia & de Hevia, 2014; Fischer, Castel, Dodd & Pratt, 2003). This finding is consistent with the SNARC (Spatial-Numerical Association of Response Codes effect) effect whereby Western adults respond faster to small numbers with their left, and to large numbers with their right hand (Dehaene, 1992; Dehaene, Bossini & Giraux, 1993). These phenomena reflect a mapping of numbers onto oriented space, where numbers correspond to different spatial extensions along a horizontal left-to-right oriented continuum. Consistent with the existence of such a representation is evidence from right-brain damaged neglect patients, who exhibit deficits in numerical tasks that tap onto an oriented spatial representation of number (Vuilleumier, Ortigue & Brugger, 2004; Zorzi, Priftis & Umiltà, 2002). Neuroimaging studies also support the existence of this phenomenon, showing that partially overlapping regions in the parietal cortex are engaged in both numerical and visuo-spatial tasks (Dehaene *et al.*, 2003, Fias, Lammertyn, Reynvoet, Dupont & Orban, 2003; Hubbard, Piazza, Pinel & Dehaene, 2005), and cortical areas associated to saccadic movements are recruited during arithmetical performance (Knops, Thirion, Hubbard, Michel & Dehaene, 2009), suggesting that numerical processing drives participants' shifts of attention along a representational space (Loetscher, Bockisch, Nicholls & Brugger, 2010).

The prevailing view on the origins of the oriented number-space mapping accentuates the role of culture, with reading, writing and counting routines determining the association between numbers and spatial positions (e.g. Dehaene *et al.*, 1993; Goebel, Shaki & Fischer, 2011; Opfer, Thompson & Furlong, 2010; Zebian, 2005). In fact, languages with opposite reading/writing directions, such as Western vs. Arabic, exhibit an opposite SNARC effect (Dehaene *et al.*, 1993; Zebian, 2005; Shaki & Fischer, 2008), and early attempts to trace the development of the SNARC effect described its emergence in schooled 9-year-old children (Berch, Foley, Hill & Ryan, 1999).

Recently, studies using non-symbolic number and non-chronometric tasks have shown a spontaneous number-space mapping in preschool-aged children, with no formal education. Patro and Haman (2012) found that Western 4-year-olds judge small non-symbolic numbers faster when presented on the left compared to the right side of space, and the opposite for large numbers. Accordingly, Opfer *et al.* (2010) reported that Western 3- and 4-year-old children tend to exhibit a left-to-right bias in tasks such as subtraction and addition of tokens and counting objects (e.g. counting from the left and proceeding rightwards). Moreover, numbers bias spatial search according to the reading directionality of the surrounding culture in 4-year-old English-speaking children (Opfer & Furlong, 2011). Although these findings show that well-established reading/writing abilities are not essential for the establishment of a mental association between numbers and an oriented spatial representation, they are compatible with a modulating effect of culturally shaped routines, such as counting or 'reading' illustrated books, on the specific orientation of children's number-space mapping (McCrink, Shaki & Berkowitz, 2014).

Insights into an unlearned association between numbers and spatial positions along a left-to-right oriented axis come from studies on non-human populations. Newly hatched chicks, adult nutcrackers (Rugani, Kelly, Szelest, Regolin & Vallortigara, 2010), and trained monkeys (Drucker & Brannon, 2014) show a leftward bias when required to locate an object in a series of identical objects on the basis of its ordinal position. In birds, these findings are interpreted as originating from right hemispheric dominance, resulting in the left visual hemifield controlling the birds' visuo-spatial performance. More recently, it has been shown that both chimpanzees (Adachi, 2014) and chicks (Rugani, Vallortigara, Priftis & Regolin, 2015) associate smaller numbers with the left space and larger numbers with the right space, providing evidence for a left-to-right oriented representation of numbers in non-human, non-linguistic species.

More critical to the origins of the number-space mapping in human development would be evidence from studies with preverbal infants, who lack symbolic tools and have limited experience with culturally shaped routines. One recent study showed that 7-month-old infants manifest a spontaneous preference for a specific coupling between numerical order and oriented spatial codes, by preferring increasing over decreasing numerical displays when they appear sequentially along a left-to-right orientation, but not when they are right-to-left oriented (de Hevia, Girelli, Addabbo & Macchi Cassia, 2014). This evidence raises the possibility that the relation between number and oriented spatial codes in humans precedes any symbolic knowledge or formal education.

In the current study we investigated the early, prelinguistic origins of the mapping between numbers and oriented spatial codes by assessing whether perceiving numerosities causes lateralized shifts of visual attention in 8- to 9-month-old infants. This study differs from earlier research on number-space mapping in infants (de

Hevia *et al.*, 2014) in two important respects: it focuses on visuo-spatial performance, rather than learning, and includes number as a task-irrelevant, rather than relevant, feature. We tested whether numbers induce the automatic activation of a spatial representation where 'less' is linked to left and 'more' to right, and whether such spatial representation produces the corresponding shifts of attention within the visual field. To this end, we used a Posner-like cuing visual detection task (Posner, 1980) previously used with adults (Bulf *et al.*, 2014), in which we presented non-symbolic magnitudes to act as cues that might shift visual attention to either the right or left visual field depending on their magnitude, i.e. small vs. large non-symbolic numbers.

We extended the investigation of the effects of numerical cues on infants' allocation of spatial attention within the visual field to the continuous dimension of physical size (i.e. small- vs. large-sized shape). Research on adults has reported SNARC-like effects to non-numerical magnitudes, like size (Bulf *et al.*, 2014; Ren, Nicholls, Ma & Chen, 2011). These findings support the ATOM (i.e. A Theory Of Magnitude) theory (Walsh, 2003) that posits that all ordered magnitudes would be represented in the brain according to a common metric that is inherently spatial in nature (Cantlon, Platt & Brannon, 2009). Studies investigating mappings between magnitudes (i.e. size, number, brightness) suggest that, although 8- to 9-month-old infants (de Hevia & Spelke, 2010; Lourenco & Longo, 2010; Srinivasan & Carey, 2010) and newborns (de Hevia, Izard, Coubart, Spelke & Streri, 2014) spontaneously link representations of number, physical size and time, number and physical size share privileged links with respect to other dimensions (de Hevia & Spelke, 2010, 2013). It is therefore possible that the mapping of magnitudes onto an oriented spatial continuum is specific to number in the earliest stages of development and generalizes to non-numerical continuous dimensions at later ages. Another possibility is that quantitative dimensions other than number, like size, map equally onto each other from infancy, and therefore effects of magnitude on visuo-spatial processing might be present for other continuous dimensions. Studies with infants can provide a crucial contribution to disentangling these two possibilities.

In the present study infants' eye movements were recorded using an eye-tracker apparatus while participants performed a Posner-like attentional task (Posner, 1980): a visual target appeared either on the left or the right side of a screen right after the onset of a centered small-magnitude or large-magnitude cue (Figure 1A). The cue was either a set of dots that varied in numerosity (i.e. 2 or 9) or a shape that varied in physical size (i.e. small or large) (Figure 1B). The recording of infants' eye movements allowed us to measure the time to target fixation under free looking conditions, which has recently proved to be a suitable tool to assess visual attention mechanisms in 8-month-old infants (Bulf & Valenza, 2013; Ronconi, Facoetti, Bulf, Franchin, Bettoni *et al.*, 2014). If magnitudes are associated with different spatial codes at preverbal ages and are represented on a left-to-right spatially oriented number line, then infants would be faster at detecting (i.e. orienting towards) targets when the cue–target relation is congruent with a left-to-right orientation of the number line (i.e. targets on the left cued by a small-magnitude cue and targets on the right cued by a large-magnitude cue), relative to an incongruent cue–target relation (i.e. targets on the left cued by a large-magnitude cue and targets on the right cued by a small-magnitude cue).

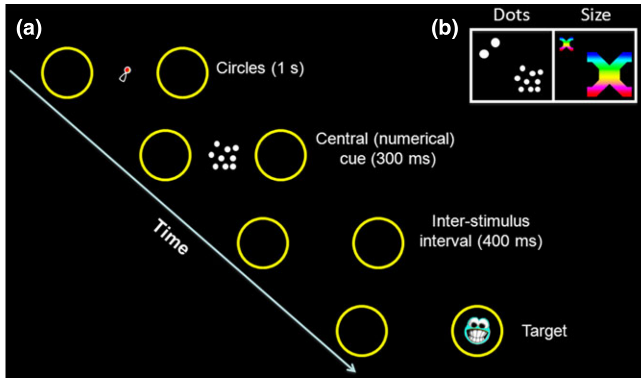

Figure 1 *Trial events and stimuli. (A) Schematic representation of a congruent trial in the dots condition. (B) Dots and size stimuli presented as numerical and non-numerical cues.*

Methods

Participants

The sample included 36 infants (age: $M = 256$ days, SEM = 1.34, range = 237–274). Half of the infants were randomly assigned to the numerical condition, and half to the size condition. Twelve additional infants were tested but not included in the final sample due to a position bias (selecting one lateral position more than 85%, irrespective of the target location; $n = 6$), fussiness ($n = 4$), or non-interpretable data resulting from poor calibration of the point of gaze ($n = 2$). All infants were full-term and were tested after parents had given their written informed consent. Participants were recruited via a written invitation that was sent to parents based on birth records provided by neighboring cities. 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 Milano-Bicocca.

Stimuli, apparatus and procedure

Infants were placed in a car seat 60 cm from the stimulus monitor. Before beginning the experimental trials, the eye tracker was calibrated presenting animated cartoons at three different locations on the stimulus monitor. Subsequent eye movement data were calculated from these calibration values.

Each experimental trial began with the presentation, in the center of the screen, of an attention getter (animated cartoon) appearing on a black background. As soon as the infant looked at the attention getter for 300 ms, two colored circles (6°) were automatically presented peripherally (11° of eccentricity, with the two edges of the circles separated by 16°), one at the left and one at the right side of the central attention getter (Figure 1A). Circles of three different colors (red, yellow and blue) and three different types of attention getters were randomly presented across the experimental trials. The central attention getter remained on the screen until when, 1000 ms after the appearance of the circles, a numerical or a size cue appeared at the center of the screen. The cue remained on the screen for 300 ms, and, after an Inter-Stimulus Interval (ISI) of 400 ms, a target consisting of a flickering schematic face (3.2°) appeared within one of the two peripheral circles. The target disappeared as soon as the infant looked at it for at least 100 ms, or after a maximum of 2 seconds. This terminated the trial, and another trial began with the appearance of the central attention getter. On each trial, one of three different target types was randomly presented within either the left or the right circle. Both the numerical (i.e. array of dots) and the size cues consisted of a small magnitude (e.g. 2 dots) or a large magnitude (e.g. 9 dots) (Figure 1B). The 2-dot and the 9-dot arrays were controlled for overall area, and the virtual square occupied by the dot arrays was 3.5° by 3.5°. Two 2-dot arrays (one oriented leftwards, and one oriented rightwards) and four 9-dot arrays were used. The size cues consisted of two rainbow-colored shapes varying in their physical size according to a 1:4.5 ratio (i.e. an X-shaped figure and an equilateral cross with four arms bent at 90°; range = 2.77 cm^2 to 12.5 cm^2).

Infants in each experimental condition (numerical vs. size) received 60 trials divided into three blocks. Each block consisted of 16 experimental trials and 4 catch trials, for a total of 48 experimental trials (2 cue magnitude × 2 target position × 12 repetition) and 12 catch trials. Catch trials were introduced to prevent anticipatory responses, and did not include the target. The magnitude of the cue (small or large) and the position of the target (left or right) were randomized across trials. Trials in which targets appearing on the left were cued by a small-magnitude cue or targets appearing on the right were cued by a large-magnitude cue were defined as congruent trials (with respect to a left-to-right oriented mental number line); all the other experimental trials were defined as incongruent trials.

The stimuli were presented with E-Prime 2.0 software on a 24″ monitor with a resolution of 1600 × 1200 pixels, and eye movements were recorded using an ASL6 remote eye-tracking system at a frequency of 120 Hz (Applied Science Laboratory, Bedford, MA). To coordinate the eye movement data with the respective stimulus displays, the stimulus-generating computer sent unique, time-stamped numerical codes via a parallel port to the ASL computer, indicating the onset and type of stimulus display. In turn, the ASL computer sent the coordinates of the eye movements continuously to the stimulus-generating computer that computed the coordinates of the eye movements using E-Prime 2.0.

Data analysis

The display was virtually divided into three areas of interest (AOI), one surrounding the position of the central attention getter, and the other two corresponding to the two peripheral circles where the targets appeared. Each AOI measured approximately 12.6° in width and 7.6° in height. Accuracy and time to target fixation (TTF) were measured and considered as the dependent variables. Accuracy refers to the percentage of trials in which infants orient toward the target AOI on the total number of the trials included in the analysis. TTF refers to the time difference between the target onset and the time the participant's gaze entered the target AOI, provided that the AOI was fixated for at least 100 ms.

In each condition, analyses were performed on the 48 experimental trials. Catch trials were not included in the analyses. Infants performed an average of 45.8 experimental trials (SEM = 0.8) in the numerical condition, and 45.4 trials (SEM = 1.3) in the size condition. An average of 15.3 trials (SEM = 0.9) in the numerical condition, and 15.4 trials (SEM = 1.4) in the size condition were excluded from the statistical analyses for the following reasons: (i) the participant did not look at the central AOI at the onset of the peripheral circles, the cue and/or the target; (ii) the participant did not enter any of the two lateral AOIs; (iii) the signal of the eye tracker was lost during stimulus presentation. The average number of trials included in the analyses was 30.45 (SEM = 1.12) and 30 (SEM = 1.62) for each participant in the numerical and size conditions, respectively.

Results

Accuracy to select the target and time to target fixation (TTF) were submitted to two repeated-measures ANOVAs with cue–target congruency (congruent vs. incongruent) as within-subjects factor, and cue type (dots vs. size) as between-subjects factor. Infants were more accurate at detecting the target in the dots condition ($M \pm SEM = 73 \pm 3\%$) than in the size condition ($M \pm SEM = 61 \pm 3\%$), $F(1, 34) = 8.55$, $p = .006$, $\eta_p^2 = 0.2$, all other effects being non-significant, $F(1, 34) < 0.2$, $p > .6$. More crucially, analysis on the TTF revealed a significant interaction between cue–target congruency and cue type, $F(1, 34) = 4.32$, $p = .045$, $\eta_p^2 = 0.11$ (Figure 2). When the cue varied in numerosity, infants were faster at orienting towards the left target when the cue numerosity was small and towards the right target when the cue numerosity was large ($M \pm SEM = 232.2 \pm 12.6$ ms) compared to when the opposite, incongruent cue–target relation occurred ($M \pm SEM = 260.0 \pm 14.8$ ms), $t(17) = 2.62$, $p = .018$, paired t-test. In contrast, when the cue varied in physical size, it took equally long for infants to orient toward the target when its left–right position was congruent ($M \pm SEM = 258.4 \pm 17.1$ ms) or incongruent ($M \pm SEM = 241.4 \pm 14.3$ ms) with the cue size, $t(17) = 0.9$, $p = .38$, paired t-test. Examination of the data for individual participants through binomial tests confirmed the results of the analysis on TTF, revealing that 13 out of 18 participants who were cued by non-symbolic numbers showed faster visual response times to the target in the congruent trials than in the incongruent ones (binomial test, $p = .049$), whereas only 8 out of 18 participants who were cued by size showed faster visual response times to the target in the congruent trials than in the incongruent ones (binomial test, $p = .82$). The difference between dots and size in driving infants' visual attention does not seem to be due to a timing difference between numerical vs. non-numerical magnitude in allocating visual attention onto space as infants' time to orient towards the target across the two cue type conditions (dots vs. size) was virtually identical ($M \pm SEM = 226.0 \pm 12.66$ ms vs. $M \pm SEM = 229.9 \pm 12.63$ ms), $F(1, 34) = 0.045$, $p = .83$, $\eta_p^2 = 0.001$.

Discussion

Recent studies on non-human animals (e.g. Adachi, 2014; Drucker & Brannon, 2014; Rugani *et al.*, 2015) and preverbal infants (de Hevia *et al.*, 2014) have provided evidence for an association between numerical magnitude and oriented spatial codes in non-verbal populations who lack symbolic tools. Using a Posner-like attentional task (Posner, 1980) akin to those used in adults (Bulf *et al.*, 2014; Fischer *et al.*, 2003), we investigated whether a numerical cue and a size cue drive the allocation of visual attention in 8- to 9-month-old infants in the same way as they do in adults. Infants were faster at detecting targets appearing on the right when cued by large numbers, and targets appearing on the left when cued by small numbers, indicating that, as in adults (Bulf *et al.*, 2014), non-symbolic numbers induce attentional shifts towards a peripheral region of space that is congruent with the numbers' relative position along a left-to-right oriented mental number line already during the first year of life.

This evidence sheds light on the developmental origins of the oriented number-space mapping observed in adults, showing that a predisposition to relate numerical ordering and a left-to-right oriented axis emerges early in life, before humans learn to read, write or count on their

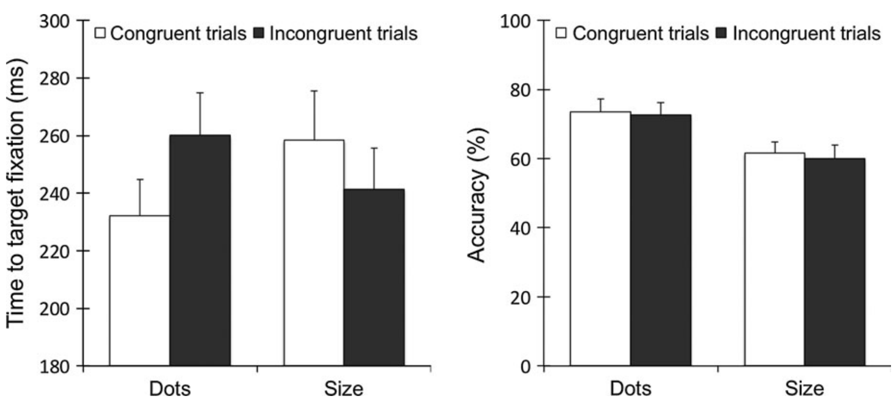

Figure 2 *Mean times to target fixation and accuracy on congruent and incongruent trials for the dots and size conditions. Error bars represent standard error of the means.*

hands, and before acquisition of symbolic knowledge. These findings provide the first direct evidence for a left-to-right oriented number-space mapping at early stages of human development, where small numbers are associated to the left and large numbers to the right side of space. As in adults, this association appears to be automatic in infants, with numerical information producing spontaneous shifts of visual attention towards specific regions of space, depending upon the numerical magnitude.

It should be noted that, since our non-symbolic numerical stimuli were controlled for surface area but not for contour length and density, it might be possible that the congruency effect observed in the numerical condition was partially driven by the quantitative information provided by these two continuous dimensions that covaried with numbers. However, we know that in adults the same dot arrays used in the present study lead to the same congruency effect as Arabic digits, which supports the idea that non-symbolic and symbolic numbers share a common numerical code (Bulf *et al.*, 2014). Moreover, in the present study we found that variations in size, another form of non-numerical magnitude information, did not exert the same congruency effect as number on the allocation of infants' visual attention, suggesting that number must have played a crucial role in driving visual attention in the numerical condition.

The absence of a congruency effect in the size cue condition suggests that, in the first months of life, the relation between magnitudes and oriented spatial codes is number specific. This raises the possibility that the privileged link between numbers and oriented space might generalize to other non-numerical quantitative dimensions during development, likely as a result of experience accumulated with various sources of magnitude information. In fact, although it is still unclear whether in adults the number-space mapping extends to all continuous dimensions, there is evidence that physical size is linked to directional spatial codes (Ren *et al.*, 2011), and induces interference effects in Stroop-like tasks, as measured in the parietal cortex, not dissimilar to those induced by number (Pinel, Piazza, Le Bihan & Dehaene, 2004).

However, the finding that variations in size did not exert the same congruency effect as number on the allocation of infants' visual attention might be a byproduct of differences in perceptual salience between the size and numerical cues and/or in discriminability of magnitude information (small versus large) across the size and numerical conditions. The high perceptual salience of the colored shapes in the size condition might have interfered with the automatic attentional response triggered by the peripheral target, masking a possible effect of shape size on the deployment of visual attention. Indeed, infants were less accurate in detecting the target when this was cued by a size cue than by a numerical cue. However, this was not accompanied by any timing difference between the two conditions, as infants' time to orient towards the target across size and dots conditions was virtually identical. Therefore, although it is known that there are specific temporal windows at which the effect of numerical magnitude onto spatial attention is functional in adults (Fischer *et al.*, 2003), timing differences cannot explain infants' differential performance for size and numerical cues. As for the discriminability of small and large cues in the size versus numerical conditions, the available evidence suggests that the acuity for non-symbolic number and size is comparable in 6-month-old infants, who can easily discriminate magnitude contrasts at a 1:2 ratio (see Cordes & Brannon, 2008), which is much harder than the one provided in this task (i.e. 1:4.5). Moreover, it has been shown that the acuity for size discrimination is higher than that for non-symbolic numerical discrimination in adults and children (Odic, Libertus, Feigenson & Halberda, 2013). Altogether, in light of this evidence, it seems unlikely that the absence of a spatial lateralized effect in the size condition is due to poor discrimination between the small and large magnitudes. Nonetheless, future research should establish whether factors inherent to the perceptual salience or acuity are enough to cancel out the automatic deployment of lateralized spatial attention when variations in size are used as non-numerical cues.

Although we cannot exclude that continuous variables other than number have contributed to infants' shifting of visual attention in the dots condition, our results indicate that number is critical in orienting infants' visual attention. By showing that the association between numbers and oriented spatial codes occurs before the acquisition of symbols or exposure to formal education, results provide support to existing demonstrations in non-human animals to suggest that the number line is not merely a product of human invention. As recently proposed by de Hevia, Girelli and Macchi Cassia (2012), the tendency to associate numbers with spatial positions might be an emerging property of early biases present in the processing of magnitude information, whether spatial or numerical. Optimal candidates for these biases might be a biologically determined advantage for processing the left hemispace (Rosen, Galaburda & Sherman, 1987), and an advantage in the processing of increasing order, which has been recently reported in 4-month-old infants (Macchi Cassia, Picozzi, Girelli & de Hevia, 2012). As suggested by evidence of cross-cultural differences in the way numbers are spatially represented (Goebel *et al.*, 2011), these early biases are modulated and refined during development through exposure to cultural conventions. Indeed, it is even possible that the directional association between number and space found in the present study was influenced by cultural factors engendered by 7 months of interaction with adult caregivers who are likely to structure the environment for their children in many different ways, thus influencing the direction in which infants explore external space. Only studies with newborn infants might disentangle the role of early experience and biological endowment in shaping the way infants represent number and space.

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