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ORIGINAL ARTICLE

Operational momentum and size ordering in preverbal infants

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Abstract Recent evidence has shown that, like adults and children, 9-month-old infants manifest an operational momentum (OM) effect during non-symbolic arithmetic, whereby they overestimate the outcomes to addition problems, and underestimate the outcomes to subtraction problems. Here we provide the first evidence that OM occurs for transformations of non-numerical magnitudes (i.e., spatial extent) during ordering operations. Twelve-month-old infants were tested in an ordinal task in which they detected and represented ascension or descension in physical size, and then responded to ordinal sequences that exhibited greater or lesser sizes. Infants displayed longer looking time to the size change whose direction violated the operational momentum experienced during habituation (i.e., the smaller sequence in the ascension condition and the larger sequence in the descension condition). The presence of momentum for ordering size during infancy suggests that continuous quantities are represented spatially during the first year of life.

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Introduction

The use of spatial metaphors to describe abstract concepts like time, value, or number, is a key feature of adults' mental life. Psychological research has shown that adults not only talk about abstract concepts using spatial language, but they also think about these concepts using spatial representations (e.g., Casasanto, 2010; Srinivasan & Carey, 2010). Moreover, evidence suggests that this spatial representation is often organized along a horizontal continuum, which, at least in Western cultures, is oriented from left to right.

For example, the use of an internal, oriented, spatial continuum to represent number was demonstrated by showing that judgments about small numbers are faster when performed with the left hand, and judgments about large numbers are faster when performed with the right hand—the so-called SNARC effect (Spatial-Numerical Association of Response Codes; Dehaene, Bossini, & Giraux, 1993), and the processing of numerical magnitude influences the deployment of visual attention in space, with small numbers speeding up leftward relative to rightward orienting and the converse for larger numbers (e.g., Myachykov, Ellis, Changelosi, & Fischer, 2016). Similar spatial biases have been reported in the classification of such varied stimuli as visual shapes (e.g., Ren, Nicholls, Ma, & Chen, 2011), temporal events (e.g., Vallesi, Binns, & Shallice, 2008), pitches of sounds (e.g., Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006), months of the year or days of the week (e.g., Gevers, Reynvoet, & Fias, 2003), letters of the alphabet (e.g., Gevers et al., 2003), and even elements in a learned list of unrelated words (e.g., Previtali, de Hevia, & Girelli, 2010; Van Opstal, Fias, Peigneux, & Verguts, 2009).

Overall, these findings have been taken as suggestive of an oriented spatial representation as adults' privileged way of mentally organizing serially ordered information. Today, a critical question is where this spontaneous mapping of order onto space comes from, and—more specifically—how much of this mapping is based on innate or early-developing characteristics of the human brain relative to experiential and cultural factors (for a review see Nuerk et al., 2015). To address this question, the current study used preverbal infants' ability to appreciate ordinal changes in size (i.e., spatial extent) to explore whether a tendency to represent ordered information along an internal oriented spatial continuum is apparent, before the acquisition of symbolic knowledge or exposure to formal education.

Culture has a relevant role in modulating specific aspects of the internal spatial representation of ordered dimensions; the spatial frame of references (e.g., horizontal vs. vertical) for time representation is culturally-specific (e.g., Boroditsky, Fuhrman, & McCormick, 2011; Fedden & Boroditsky, 2012) and the direction (left-to-right vs. right-to-left vs. no direction) of the number-space link is modulated by reading and writing habits (e.g., Dehaene et al., 1993; Goebel, Shaki, & Fischer, 2011; Opfer, Thompson, & Furlong, 2010; Zebian, 2005). Nevertheless, behavioral research on learning biases in preverbal infants has documented the presence of a spontaneous mapping of ordered temporal (Lourenco & Longo 2010; Srinivasan & Carey, 2010) and numerical (de Hevia & Spelke 2010; de Hevia, Izard, Coubart, Spelke, & Streri, 2014b; Lourenco & Longo 2010) information to spatial extent.

For example, Srinivasan and Carey (2010) showed that 9-month-old infants, like adults, successfully learn and generalize an ordinal rule that establishes a positive relationship between sound duration and spatial length (increasing duration paired with increasing length), while they fail with the inverse relationship (increasing duration paired with decreasing length). Of note, evidence of a spontaneous tendency to relate numerical and spatial dimensions has recently been documented in newborns, who relate auditory numerosity and line length when these dimensions vary in the same direction (e.g., an increase in numerosity is accompanied by an increase in line length) but not when they vary in opposite directions (e.g., an increase in numerosity is accompanied by a decrease in line length: de Hevia et al., 2014b). Overall, although infants do not map all ordered dimensions equally to space (see Srinivasan & Carey, 2010 for 9-month-olds' failure to relate loudness and spatial extent), they appear to represent at least numerical and temporal order within a spatial frame of references, just like adults do, at an age when they lack symbolic tools and have not accumulated extensive perceptuo-motor experience with the natural correlations between these dimensions.

In addition, results from two recent studies suggest that infants not only relate numerical magnitudes to spatial extent, but they also link these spatial extents to a particular spatial direction (Bulf, de Hevia, & Macchi Cassia, 2015; de Hevia, Girelli, Addabbo, & Macchi Cassia, 2014a). Seven-month-old infants succeeded at discriminating inversion in the direction of numerical order when habituated to spatiotemporal sequences of increasing numerical arrays displayed along a left-to-right orientation but failed with decreasing order, and showed a preference for increasing over decreasing left-to-right oriented numerical sequences (de Hevia et al., 2014a). Moreover, 8- to 9-month-olds' eye movements in visuo-spatial tasks are modulated by numerical information (Bulf et al., 2015a) in the same way as in adults (Bulf, Macchi Cassia, & de Hevia, 2014; Fischer, Castel, Dodd, & Pratt, 2003; Fischer, Warlop, Hill, & Fias, 2004). Infants are faster at detecting targets appearing on the right when cued by a large non-symbolic number, and targets appearing on the left when cued by a small number, indicating that non-symbolic numerical cues induce spontaneous shifts of visual attention towards a peripheral region of space congruent with the number's relative position on a left-to-right oriented representational continuum. Looking at eye movements is generally a helpful way to investigate the processing of magnitude information, even outside the developmental area (Mock, Huber, Klein, & Moeller, 2016). However, a critical aspect of this last set of findings is that, unlike adults (Bulf et al., 2014), infants do not show an attentional congruency effect when the peripheral target is cued by visual shapes varying in physical size. That is, a single object that is small does not result in faster detection of the left side of space, relative to a single object that is large. This seems to suggest that in infancy the mapping of ordered dimensions to an internal, oriented spatial representation is number-specific, and raises the possibility that the privileged link between numbers and oriented space undergoes a gradual generalization to non-numerical quantitative dimensions during development. By the time children become adults, 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).

In light of this evidence, the aim of the current study was to test whether infants utilize an oriented spatial code to represent size when they are asked to process ordinal changes in this dimension. In fact, it is possible that the act of ordering, which was absent in Bulf et al.'s (2015a) cueing task, may boost infants' mapping of size onto a spatial continuum. Indeed, in adults it is not only number, but ordinal information in general, that triggers the use of an internal, oriented, spatial continuum (e.g., Gevers et al., 2003; Previtali et al., 2010). To test this hypothesis we explored whether size ordering in infants generates momentum-like effects similar to those generated by numerical transformation (i.e., addition or subtraction; McCrink & Wynn, 2009).

Momentum effects are biases in participants' responses which reflect future expectations concerning the displacement of a stimulus or stimulus transformation within a physical or representational spatial coordinate system (see Hubbard, 2014, for a review). For example, in the classic 'representational momentum' effect the anticipated final location of a perceived moving target is displaced forward in the direction of target motion (Freyd, 1987; Freyd & Finke, 1984; Hubbard, 2014). The perceived displacement is influenced by expectations for target behavior that the observer either develops while viewing the target or brings to the experimental setting (as reviewed in Hubbard, 2005), and fMRI results suggest that the prefrontal cortex may be involved in the effect (Rao et al., 2004). On this basis, it is argued that representational momentum reflects cognitive processes that mediate dynamic transformations in representation: it arises whenever transformation of a target or execution of a process could be mapped onto a transformation across a spatial representational continuum.

Momentum effects similar to those generated by physical transformation of a target arise for numerical transformation generated during mental calculation, a phenomenon known as operational momentum (hereafter OM; McCrink, Dehaene, & Dehaene-Lambertz, 2007). In OM, adult subjects systematically overestimate the outcomes to approximate addition and multiplication problems involving both symbolic and non-symbolic numbers (Katz & Knops, 2014; Knops, Viarouge, & Dehaene, 2009b; McCrink et al., 2007; Pinhas & Fischer, 2008), and underestimate the outcomes to approximate subtraction and division problems. At the root of this bias is proposed to be a forward displacement of the implied direction of the operation along a mental number line (to greater amounts for addition, and lesser amounts for subtraction), an explanation supported by shifted motor movements during arithmetic (Pinhas & Fischer, 2008; Yu, Liu, Li, Cui, & Zhou, 2015) and neural links to the visual attention network which supports directional saccadic eye movements (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009a).

Operational momentum has also been found during infancy (McCrink & Wynn, 2009) and childhood, where it is linked to the maturation of visual attention (Knops, Zitzmann, & McCrink, 2013). For example, McCrink and Wynn (2009) have shown that 9-month-old infants' performance in addition and subtraction problems over large non-symbolic numbers (i.e., 6 + 4 and 14 − 4) is prone to momentum effects. Similar to earlier investigations on non-symbolic arithmetic with preverbal infants (e.g., Wynn, 1992), infants were shown videos of addition or subtraction events, and subsequently presented with three different types of outcomes: correct, too large, and too small. Infants tested in the addition condition (6 + 4) looked longer at the too-small outcome (5) than at the correct outcome (10), whereas those tested in the subtraction condition (14 − 4) looked significantly longer at the too-large outcome (20) than the correct and the too-small outcomes. These findings were taken as evidence that infants' formulations of the addition outcome were slightly larger than correct, and their formulated subtraction outcomes slightly smaller than correct.

Insofar as OM is underlain by a mapping of numerical transformation onto a spatially organized mental representation of numerical magnitude, the observation of OM for numerical computations in infancy, prior to exposure to culture-specific representations of numbers, points towards an unlearned, inherent spatial-numerical link. On the same ground, we reasoned that the observation of OM for size ordering would imply infants' reliance on an oriented spatial code to represent monotonic (e.g., uniformly increasing or decreasing) changes in this dimension. If OM reflects anticipation of a target feature consistent with expected transformations across spatial representation, the effect should be bolstered by the operation of ordering, in which expected transformations are anticipated based on prior monotonic transformations. Moreover, sequential information is critical to the occurrence of momentum-like effects, and in order to successfully appreciate sequential information one has to process ordinal relationships between the stimuli.

Infant research indicates that the ability to process size order is apparent at 9 months (Brannon, 2002), and even earlier (i.e., 4 months) when size changes involve ascending relations (Macchi Cassia, Picozzi, Girelli, & de Hevia, 2012). In relevant studies, infants were habituated to three sets of repeated dynamic sequences of a single shape varying in size according to ascending or descending order, and the ability to detect a reversal of ordinal direction was implied by infants' longer looking at the novel sequence that illustrated a reversed order with respect to the one presented in habituation. In the current study we adopted a similar method to test 12-month-old infants' proneness to experience momentum-like effects while processing monotonic changes of spatial extent. We predicted that, if the transformation of spatial extent during ordering operation is mapped onto a transformation across an internal spatial continuum, then a mental spatial shift, whose direction would depend on the represented ordinal direction (i.e., ascending or descending), would take place.

Infants were presented with repeated, dynamic, tripartite sequences in which a single shape either doubled or halved in size according to a 1:2 ratio, and were tested with two different sequences in which a new shape displayed the familiar order—but new absolute size. The average size of each test sequence was either larger or smaller than the average size of the habituation sets, with the difference corresponding in both cases to a ratio of 1:2. All infants received two test trials: a with-momentum test sequence (i.e., the large-sized sequence for infants habituated to ascending order, and the small-sized sequence for infants habituated to descending order) and an against-momentum test sequence (i.e., the small-sized sequence for infants habituated to ascending order and the large-sized sequence for infants habituated to descending order). Although the two sequences were equated in terms of how much they differed from the range of physical sizes to which infants were exposed in habituation, we hypothesized that, if infants are prone to OM while performing the ordering operation, they should exhibit longer looking time to the against-momentum test trial than to the with-momentum test trial. The infants who viewed ascending sequences at habituation should prefer the smaller-sized test sequence, because they had been biased into representing larger sizes during the ordering operation, and would therefore be habituated to them. The opposite pattern for descension should be observed, with the infants preferring the larger-sized test sequence because they had become familiarized to representations of smaller sizes as a result of their OM bias.

Infants were tested at 12 months to ensure they exhibit other types of momentum-like effects, after McCrink and Wynn's (2009) demonstration of OM in non-symbolic arithmetic at 9 months, as well as overall ordering prowess, after earlier demonstrations of ordinal abilities for continuous amount at 4 (Macchi Cassia et al., 2012) and 9 months (Brannon, 2002). Twelve-month-olds were tested with a 1:2 ratio difference to ensure they could discriminate size changes both within and between habituation and test sequences, after earlier demonstration that this ratio is sufficient to allow size discrimination and ordering in infants as young as 4 months (Macchi Cassia et al., 2012).

Methods

Participants

Participants were 40 12-month-old infants (16 female, mean age = 12 months 7 days, range = 11 months 17 days to 12 months 26 days). Data from an additional 18 infants were discarded due to fussiness resulting in failure to complete all testing trials ($n = 10$) or looking time in at least one test trial shorter than 1.5 s ($n = 8$). Infants were recruited via a written invitation that was sent to parents based on birth records provided by neighbouring 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. Parents gave their written informed consent before testing began.

Stimuli

Stimuli were single colored shapes varying in area by a 1:2 ratio (range 5.5–84 cm^2) and were presented on a white background in the center of the computer monitor. There were five sets of stimuli: three for the habituation phase and two for the test phase, each set being composed of a different shape displaying a unique color. The three habituation sets contained blue circles, green triangles, and red diamonds that were, respectively, 9, 18, 36; 11, 22, 44; and 13, 26, 52 cm^2. The two test sets contained three rainbow-colored bars that expanded/contracted along the horizontal axis and whose sizes were different in each set, with an overall area of 5.5, 11, 22 cm^2 in the smaller set and 21, 42, 84 cm^2 in the larger one (Fig. 1). The average shape size of the smaller and larger test set differed from the average habituation set by a 1:2 ratio. Bars were used at test to preclude any approaching (looming) or retracting (zooming) percepts (after Macchi Cassia et al., 2012), and rainbow-color was used to increase stimulus saliency (after Brannon, 2002).

Design

Infants were habituated to ascending or descending sequences of blue circles, red diamonds, and green triangles, and were then tested with ascending or descending sequences containing newly-sized bars (Fig. 1). Half of the infants were randomly assigned to the ascending habituation condition. Within each habituation condition, the three different stimulus sets were cycled in a fixed order until infants met the habituation criterion: from the smallest to the largest shape for the ascending condition (i.e., 9-18-36, 11-22-44, 13-26-52 cm^2) and from the largest to the smallest shape for the descending condition (i.e., 52-26-13, 44-22-11, 36-18-9 cm^2). The use of a consistent fixed order of presentation of the sets across trials for each of the two habituation conditions provided infants with redundant cues to ordinality between, as well as within, trials (see Macchi Cassia et al., 2012). Following habituation, all infants were given two test trials alternating the with-momentum and the against-momentum sequences of rainbow-colored bars (i.e., 5.5-11-22, 21-42-84 cm^2), with the order of presentation counterbalanced across participants. For infants in the ascending habituation condition the with-momentum test sequence comprised bars measuring 21, 42, 84 cm^2, and the against-momentum test sequence

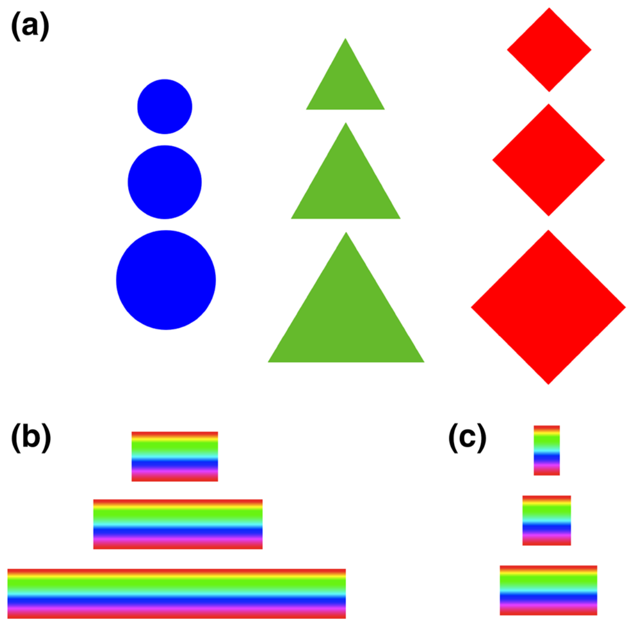

Fig. 1 The four sets of colored shapes presented to infants in the ascending habituation and test condition (*blue circles*, *green triangles*, *red diamonds*, and *rainbow-colored bars*). The sets of shapes showed in **a** were presented in a fixed order during habituation, and the *bars* showed in **b** and **c** were presented, respectively, during the with-OM and the against-OM test trial, with presentation order counterbalanced across participants. The same shapes were presented in reversed, descending, order to infants in the descending habituation condition. For those infants, the sets of shapes shown in **a** were presented in a fixed descending order starting from the *red diamonds* and proceeding to the *blue circles*, and the *bars* showed in **b** and **c** were presented, respectively, in the against-OM and the with-OM test trial (color figure online)

comprised bars measuring 5.5, 11, 22 cm^2; the opposite was true for infants in the descending habituation condition. For both conditions, both test trials exhibited an order (ascension, or descension) that was identical to that displayed in habituation.

Apparatus

Each infant was tested while sitting in an infant seat approximately 60 cm from the monitor where the stimuli were presented (24″ screen size, 1920 × 1200 pixel resolution, refresh rate of 60 Hz) in a dimly lit room. A video camera was positioned just above the stimulus presentation monitor and was directed to the infant's face. The live image of the infant's face was displayed on a television monitor to allow the online coding of the infant's looking times through the E-Prime 1.0 program by the experimenter, who was blind to the habituation condition to which the infant was assigned and the order of test trials. The image of the infant's face was also recorded via a Mini-DV digital recorder, and for half of the infants in the sample ($n = 20$) data were subsequently coded offline. Intercoder agreement (Pearson correlation) between the two observers who coded the data live or from digital recording, as computed on total fixation times on each of the two test trials, was $r = 0.997$.

Procedure

A cartoon animated image associated with varying sounds served as an attention catcher before the trial began. When the infant looked at the animated fixation point, the experimenter started the trial. Each trial consisted of a repeating cycle (6500 ms in total) that began with a black screen (500 ms) followed by the three shapes. Each shape appeared for 1750 ms on a white background, and was preceded by a 250 ms white inter-stimulus interval (ISI) to reduce the impact of looming/zooming cues. Each trial continued until the infant looked continuously for a minimum of 500 ms and ended when the infant looked away continuously for 2 s or looked for a maximum of 60 s. The three habituation stimulus sets were presented in a fixed order and repeated until the infant saw a maximum of 12 trials or met the habituation criterion, which was defined as a 50 % decline in looking time on three consecutive trials, relative to the looking time on the first three trials. Following the habituation phase, infants were given two test trials, a with-momentum sequence and an against-momentum sequence, with half of the infants seeing the with-momentum sequence first.

Results

The average number of trials received during habituation did not differ for infants in the ascending and descending habituation conditions ($M = 9.30$, SEM = 0.54 vs. $M = 7.95$, SEM = 0.49), $t(38) = 1.846$, $p > 0.07$. A two-way analysis of variance (ANOVA) on mean habituation looking times with habituation condition (ascending vs. descending) as the between-participants factor and habituation trials (first three vs. last three) as the within-participants factor confirmed the presence of a significant overall decrease from the first three ($M = 14.20$ s, SEM = 1.07) to the last three habituation trials ($M = 6.90$ s, SEM = 0.77), $F(1, 38) = 51.59$, MSe = 1065.45, $p < 0.001$, $\eta_p^2 = 0.58$, with no main effect or interaction involving the factor habituation condition ($ps > 0.2$) (Fig. 2).

To determine whether at test infants looked longer to the ordered sequence that violated the momentum effect, as generated by the abstraction of the ordinal rule during habituation, mean looking times to novel and familiar test trials were entered into a three-way ANOVA with habituation condition (ascending vs. descending) and test order

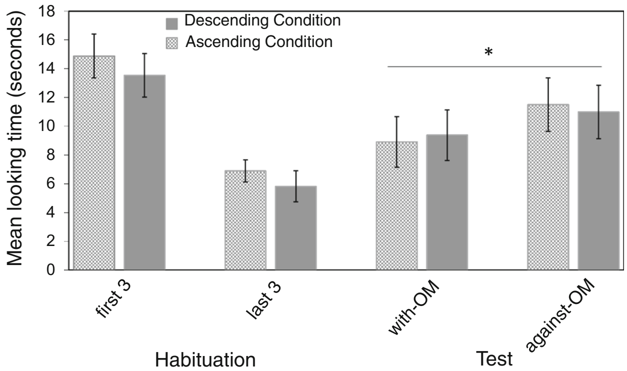

Fig. 2 Overall mean total looking time (±SEM) to the first three and last three habituation trials, and to the with-OM and against-OM test trials displayed by infants in the ascending and descending condition. Infants showed overall longer looking times to the against-OM sequence than to the with-OM sequence. $^{**}p < 0.005$

(with-OM first vs. against-OM first) as between-participants factors and test trial type (with-OM vs. against-OM) as within-participants factor. The analysis revealed a significant main effect of test trial type, $F(1, 36) = 9.57$, MSe = 87.87, $p = 0.004$, $\eta_p^2 = 0.21$, with infants looking longer to the against-OM sequence ($M = 11.24$ s, SEM = 1.27) than to the with-OM sequence ($M = 9.14$ s, SEM = 1.20) (Fig. 2). Neither the Test trial type × Habituation condition interaction, $F(1, 36) = 0.53$, MSe = 4.84, $p = 0.473$, nor other main effects or interaction were significant (ps > 0.06). Paired-sample t tests showed that, for infants in the ascending condition, looking times for the against-OM test trial ($M = 11.50$ s, SEM = 2.03) were significantly longer than those for last three habituation trials ($M = 7.98$ s, SEM = 1.34), $t(19) = 3.05$, $p = 0.007$, but this was not the case for the with-OM test trial ($M = 9.91$ s, SEM = 1.71), $t(19) = 1.18$, $p = 0.25$, indicating that infants dishabituated to the ordered sequence that violated the momentum effect but not to the one that followed momentum. For the descending condition, recovery of attention was still larger for the against-OM sequence than for the with-OM sequence, but infants' shorter looking times during the last three habituation trials ($M = 5.83$ s, SEM = 0.73) induced a generalized dishabituation effect that was significant for both test trials [against-OM: $M = 10.98$ s, SEM = 1.57, $t(19) = 3.58$, $p = 0.002$; with-OM: $M = 9.38$ s, SEM = 1.72, $t(19) = 3.46$, $p = 0.003$].

Finally, examination of the data for individual infants through binomial tests confirmed the results of the analysis on mean looking times, revealing that 27 out of 40 infants looked longer to the against-OM test trial compared to the with-OM one (27 vs. 13, $p = 0.038$, two-tailed), with a similar number of infants showing the pattern in the ascending and descending habituation condition (13 vs. 14, n.s.).

Discussion

The current study investigated whether operational momentum, similar to that observed during non-symbolic addition and subtraction (McCrink & Wynn, 2009), occurs when infants perform the operation of size ordering. Infants were tested in an ordinal task in which they had to detect, abstract and represent ascension or descension in physical size, and then respond to sequences that exhibited greater or lesser sizes. We predicted that infants would differ in their ability to discriminate variations in absolute size as a function of the previously viewed sequences.

Indeed, we observed the following results: infants looked significantly longer to the against-momentum test trials, in which the presented sizes were opposite to those that would have been represented if infants experienced operational momentum when encoding order during habituation. In fact, although the ratio of the change in the average shape size was equated across the two test sequences (i.e., 1:2), infants displayed longer looking time for the change whose direction violated the expected transformation on an OM account. This finding is not driven by a preference for a certain type of absolute size; infants in the ascending condition looked longer to the overall smaller sequence at test, while infants in the descending condition looked longer to the overall larger sequence. This demonstrates that infants' reaction to size changes in test was neither driven by the physical extent of those changes, nor by the physical size of the shapes exhibiting the changes, but rather by the extent to which the change was anticipated (versus unexpected) as a consequence of the momentum experienced during habituation.

The current results extend available evidence on OM in adults (McCrink et al., 2007), children (Knops et al., 2013) and preverbal infants (McCrink & Wynn, 2009), by providing the first evidence that, at least in infants, momentum effects can occur during magnitude transformation involving a non-numerical dimension like spatial extent. Earlier demonstrations of OM in arithmetic calculation have been interpreted as evidence that numbers are represented spatially and that such a spatial representation is oriented as increasing from left to right along the horizontal axis, consistent with the notion of an oriented mental number line (Dehaene et al., 1993; Moyer & Landauer, 1967). In adults, the link between OM and oriented spatial codes is based on cortical parallels in the parietal lobes between circuits for eye movements and those for mental arithmetic (Hubbard, Piazza, Pinel, & Dehaene, 2005; Knops et al., 2009a), as attention displacement along the internal representation of number would be analogous to leftward and rightward displacement of attention to external space (e.g., Hartmann, Mast, & Fischer, 2015; Ranzini, Lisi, & Zorzi, 2016). In children, the amount of OM bias during addition and subtraction is linked to the child's propensity to exhibit adult-like patterns when disengaging oriented spatial attention (Knops et al., 2013).

In this context, the presence of operational momentum when ordering size in 12-month-old infants provides indirect support for the notion that size is internally represented along an oriented spatial continuum. Of note, this conclusion is at odds with earlier demonstration that, unlike numerical cues, size cues fail to drive the allocation of visual attention in younger infants (8–9-month-olds) tested in a Posner-like spatial cueing task (Bulf et al., 2015a). It is possible that difference in participants' age underlies the discrepancy in the results of the previous and current investigation. Indeed, future studies may test this possibility by investigating whether the current demonstration of OM effects during size ordering operations generalizes to younger infants. However, another possibility, which we favour, is that the discrepancy in the results is driven by ordinal information, which was absent in Bulf et al.'s study but present in the current experiment. In fact, in the same way as SNARC effects in adults occur for overlearned ordinal series (Gevers et al., 2003; Previtali et al., 2010), recent evidence suggests that 7-month-old infants spontaneously map order and left-to-right oriented spatial codes: the extraction and generalization of abstract rules (i.e., ABA or ABB) conveyed by the ordinal position of geometrical shapes within tripartite sequences is possible only when the sequences are presented from left to right (Bulf, Gariboldi, de Hevia, & Macchi Cassia, 2015b). These findings seem to suggest that infants, like adults, have a spontaneous bias to mentally organize serially ordered information through an oriented spatial representation. Future investigations shall provide a direct test for the hypothesis that the ordering operation was the critical feature here that triggered infants' representation of size along an oriented spatial continuum, by examining whether the different types of size ordering operations (i.e., ascension, descension) orient infants' attention to opposite locations on a spatial continuum in a spatial cueing task similar to the one used by Bulf et al. (2015b).

The current demonstration that, in infants, OM occurs for transformations of size in the same way as it occurs for numerical transformations (Mc Crinck & Wynn, 2009) has relevant implications for our understanding of the nature of infants' magnitude representation. Insofar as momentum phenomena are thought to reflect properties of spatial representation of a given magnitude continuum, the presence of momentum for transformations of number and size in the same populations (9-month-olds for number, 12-month-olds for size) supports the existence of shared representational resources and similar functional properties in infancy for any magnitude information that can be conceptualized ordinally (more than/less than; de Hevia & Spelke, 2010; Feigenson, 2007; Lourenco & Longo, 2010; Walsh, 2003).

To conclude, in light of these findings, and other work with non-human animals and populations with no formal education (see de Hevia, Girelli, & Macchi Cassia, 2012; McCrink & Opfer, 2014, and Nuerk et al., 2015 for reviews), our results suggest that there is an intuitive and early-developing bias to link ordered information to an internal oriented spatial continuum that is not wholly driven by extensive enculturation or formal instruction.

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