Journal of Numerical Cognition
jnc.psychopen.eu | 2363-8761

PsychOpen publishing psychology

Research Reports

Operational Momentum During Ordering Operations for Size and Number in 4-Month-Old Infants

Viola Macchi Cassia*[ab], Hermann Bulf[ab], Koleen McCrink[c], Maria Dolores de Hevia[de]

[a] Department of Psychology, University of Milano-Bicocca, Milan, Italy. **[b]** NeuroMi, Milan Center for Neuroscience, Milan, Italy. **[c]** Department of Psychology, Barnard College, Columbia University, New York, USA. **[d]** Université Paris Descartes, Sorbonne Paris Cité, Paris, France. **[e]** CNRS UMR 8242, Laboratoire Psychologie de la Perception, Paris, France.

Abstract

An Operational Momentum (OM) effect is shown by 9-month-old infants during non-symbolic arithmetic, whereby they overestimate the outcomes to addition problems, and underestimate the outcomes to subtraction problems. Recent evidence has shown that this effect extends to ordering operations for size-based sequences in 12-month-olds. Here we provide evidence that OM occurs for ordering operations involving numerical sequences containing multiple quantity cues, but not size-based sequences, already at 4 months of age. Infants were tested in an ordinal task in which they detected and represented increasing or decreasing variations in physical and/or numerical size, and then responded to ordinal sequences that exhibited greater or lesser sizes/numerosities, thus following or violating the OM generated during habituation. Results showed that OM was absent during size ordering (Experiment 1), but was present when infants ordered arrays of discrete elements varying on numerical and non-numerical dimensions, if both number and continuous magnitudes were available cues to discriminate between with-OM and against-OM sequences during test trials (Experiments 2 vs. 3). The presence of momentum for ordering number only when provided with multiple cues of magnitude changes suggests that OM is a complex phenomenon that blends multiple representations of magnitude early in infancy.

Keywords: Operational Momentum, ordering operations, size, number, infants, number-space mapping

Journal of Numerical Cognition, 2017, Vol. 3(2), 270–287, doi:10.5964/jnc.v3i2.67

Received: 2016-06-16. Accepted: 2017-04-24. Published (VoR): 2017-12-22.

Handling Editors: Silke Goebel, University of York, York, United Kingdom; André Knops, Humboldt-Universität Berlin, Berlin, Germany; Hans-Christoph Nuerk, Universität Tübingen, Tübingen, Germany

*Corresponding author at: Department of Psychology, University of Milano-Bicocca, p.za Ateneo Nuovo 1, 20126 Milan, Italy. E-mail: viola.macchicassia@unimib.it

Number is a basic property of the environment to which human and non-human animals are spontaneously attuned (Dehaene, 1997; Gallistel & Gelman, 1992). Developmental research has shown that preverbal infants extract numerical information from the environment and represent such information in an abstract form, which holds across sensory modalities (Coubart, Streri, de Hevia, & Izard, 2015; Feigenson, Dehaene, & Spelke, 2004; Jordan & Brannon, 2006; Turati, Gava, Valenza, & Ghirardi, 2013). For instance, newborn infants who hear a sequence of sounds look longer to a visual image containing the same numerosity than to a visual image with a different numerosity (differing by a 1:3 ratio) (Izard, Sann, Spelke, & Streri, 2009). Infants not only detect and represent numerical information, but also operate on such representations to perform numerical transformations. For instance, they perform simple computations, such as addition, subtraction, and ordering. McCrink and Wynn (2004) showed that 9-month-olds look longer to an outcome of 5 than to an outcome of 10 after familiarization to computerized displays of a 5 + 5 addition event, and longer to an outcome of 10 than to an outcome of 5 after familiarization to a 10 - 5 subtraction event. Picozzi and colleagues (Picozzi, de Hevia, Girelli, & Macchi Cassia, 2010) found that 7-month-old infants discriminate changes in the ordinal direction of numerical relations, and do so in the absence of corresponding variations in other non-numerical quantities such as surface area, density, and contour length. After habituation to sequences of three displays whose numerical values increased or decreased by a 1:2 ratio, infants looked longer at subsequent numerical sequences of a reversed ordinal direction; for example, infants who viewed increasing sequences of 6, 12, and then 24 objects during habituation looked longer to a decreasing sequence of 16, 8, and then 4 objects at test.

In adult numerical cognition, it is widely accepted that numerical representations take the form of a ‘mental number line’. This model posits that numerosities are spatially represented along a continuum, such that (in Western cultures) small numbers are associated to the left side and large numbers to the right side of space, first evidenced by the so-called SNARC (Spatial-Numerical Association of Response Codes) effect (Dehaene, Bossini, & Giraux, 1993). As the cultural direction of writing and reading exerts an influence on the specific orientation, it has been argued that numerical-spatial associations derive from overlearned scanning habits acquired mainly through reading and writing experience well into the schooled childhood years (Berch, Foley, Hill, & Ryan, 1999; Göbel, Shaki, & Fischer, 2011). However, the last few years have overturned this view, as recent research has shown that infants in their first year of life exhibit a variety of spatial-numerical associations. By 8 months, infants establish a correspondence between number and spatial extent (‘more numerous is mapped onto more extent’, de Hevia & Spelke, 2010; Lourenco & Longo, 2010), and associate different numerosities to different lateralized spatial positions (Bulf, de Hevia, & Macchi Cassia, 2016). In particular, Bulf and colleagues (Bulf et al., 2016) found that 8-month-old infants orient faster towards a left-sided cue when previously primed by a central small numerosity, and they orient faster to a right-sided cue when previously primed by a central large numerosity. This evidence suggests that numerical representations have an inherent spatial component, which points to the existence of a spatially oriented numerical representation that is functional in the first year of life.

A recent subfield that helps to unravel the developmental origins of the spatial-numerical associations is the Operational Momentum (OM) effect in arithmetic. The OM effect arises when participants systematically overestimate the outcomes of addition problems and underestimate those of subtraction problems (Knops, Viarouge, & Dehaene, 2009; McCrink, Dehaene, & Dehaene-Lambertz, 2007). This phenomenon has been documented in infancy; when infants are shown videos of addition or subtraction events, and are then presented with three different types of outcomes -one correct, one too large, and one too small-, they look longer to the too small when tested with addition and to the too large when tested with subtraction (McCrink & Wynn, 2009). Overall, OM effects in adults, children and infants have been interpreted by borrowing the original account given in the interpretation of the representational momentum (Freyd & Finke, 1984), in which the anticipated final location of a moving target is displaced forward in the direction of target motion (see review in Hubbard, 2014). Therefore, the OM in arithmetic has been interpreted as arising from the displacement of the anticipated outcome along the spatial numerical representation onto which the numerical transformation is mapped: Toward the left (smaller) for subtraction and toward the right (larger) for addition (McCrink et al., 2007).

Recently, the OM effect has been extended to ordering operations, as it arises even when 12-month-old infants represent increasing/decreasing relations among continuous magnitudes (i.e., size of a single object). In particular, when infants are habituated to an object that progressively increases or decreases in size, and are subsequently presented at test with ordinal sequences that exhibit greater or lesser size, they look longer to size changes whose direction violate the operational momentum experienced during habituation (i.e., the smaller sequence in the increasing condition and the larger sequence in the decreasing condition) (Macchi Cassia, McCrink, de Hevia, Gariboldi, & Bulf, 2016). This evidence indicates that not only numerical information, but also non-numerical quantities - such as size - might be represented as well along a spatially oriented representational continuum in the first year of life.

These findings are at odds with earlier evidence suggesting that the dimension of size does not lead to SNARC-like effects. In fact, Bulf et al. (2016) found that, unlike non-symbolic numerical cues, size cues are not capable to orient spatial attention towards peripheral regions of space in 8-month-old infants. In discussing the discrepancy between the presence of OM for the dimension of size in 12-month-olds and the absence of a size cueing effect in 8-month-olds, Macchi Cassia and colleagues (2016) argued that the phenomenon of mentally spatialize information may emerge first for numerical information and later be extended, possibly by analogy, to other dimensions, such as size. A more intriguing possibility raised by the authors is that the explicit processing of ordinal information, which was present in the Macchi Cassia et al.'s (2016) OM task with 12-month-olds, but absent in the Bulf et al.'s (2016) cueing paradigm with 8-month-olds, might have boosted infants' reliance on spatial codes to represent quantity information.

Indeed, there is mounting evidence that, in adults, the coding of serially ordered information co-opts a spatially organized mental representation, as adults exploit a spatially oriented horizontal continuum to represent not only information learnt in a conventional fixed order, like numbers (e.g., Dehaene et al., 1993) or letters of the alphabet (e.g., Gevers, Reynvoet, & Fias, 2003), but also non-ordered newly-learnt information, such as lists of unrelated words (e.g., Previtali, de Hevia, & Girelli, 2010). This evidence has been recently extended to preverbal infants, who, at 7 months, can extract and learn rule-like patterns (i.e., ABB or ABA) specified by items' order in spatio-temporal visual sequences presented along a left-to-right orientation, but not along a right-to-left orientation (Bulf, de Hevia, Gariboldi, & Macchi Cassia, 2017). This finding extends earlier demonstrations that 7-month-olds can extract and learn a numerical ordinal (increasing vs. decreasing) rule when sequences of numerical displays are presented from left to right, but not when presented from right to left (de Hevia, Girelli, Addabbo, & Macchi Cassia, 2014), and 8-month-olds relate an increase in number to an increase in spatial extent (de Hevia & Spelke, 2010). Together, these findings show that space is involved in order processing from the earliest stages of development, when infants lack symbolic knowledge and formal education, and that, at least from the age of 7 months, infants are prone to represent ordered information along a left-to-right spatial continuum.

In light of this evidence, in the present study we exploited the OM effect to investigate the mapping of order into space in infants younger than 7 months - i.e., 4-month-olds -, when exposure to culturally-shaped routines is even more limited. We chose to test infants at this particular age because recent research has shown that 4-month-olds are able to extract ordinal information from both numerical and size-based sequences, at least when confronted with increasing order. After habituation to increasing sequences composed of a single shape varying in size by a 1:2 ratio, 4-month-old infants looked longer to a newly-sized sequence of a reversed ordinal direction (Macchi Cassia, Picozzi, Girelli, & de Hevia, 2012). More recently, these findings were extended to numerical sequences of large numerosities that increased/decreased following a 1:3 ratio: Again, infants habituated to increasing numerical sequences looked longer to the reverse order at test (de Hevia et al., 2017).

Because at 4 months infants are able to perform ordering operations on both numerical and continuous magnitudes, by testing for the presence of the OM effect for number and/or size we were able to explore whether the mapping of ordinal information into directional space constitutes an early predisposition that applies to both discrete and continuous magnitudes, or whether it emerges first for number and is later extended to size.

Building on previous research (Macchi Cassia et al. 2012; de Hevia et al., 2017), we tested infants' proneness to show an OM effect by using the ratios that allowed successful ordinal discrimination at 4 months: a 1:2 ratio for size sequences and a 1:3 ratio for numerical sequences.

Experiment 1

In Experiment 1 4-month-old infants were habituated with a series of increasing or decreasing size-based sequences and were then tested with new sequences in which the same ordinal direction was composed of larger and smaller sizes. If infants show an OM effect while ordering size, as they do at 12 months (Macchi Cassia et al., 2016), they should look longer at test to the series that violate the momentum created during habituation: Infants habituated to a series of increasing size should look longer to a series containing smaller sizes at test, and those habituated to a series of decreasing size should look longer to a series containing larger sizes at test.

Methods

Methods were modelled after Macchi Cassia et al. (2016). Specifically, we used the same Stimuli and Procedure as in that earlier study, and accordingly repeat the relevant textual descriptions to describe methods as appropriate.

Participants

Participants were 40 4-month-old infants (22 females, mean age = 4 months 21 days, range = 4 months 3 days to 5 months 0 days) assigned randomly and in equal number ($N = 20$) either to the increasing or the decreasing order condition. Data from an additional 19 infants were discarded due to fussiness resulting in failure to complete all testing trials ($n = 10$), looking time in at least one test trial shorter than 1.5 s ($n = 7$), technical error ($n = 1$), or parental interference ($n = 1$). 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 squares 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 set (see Figure 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).

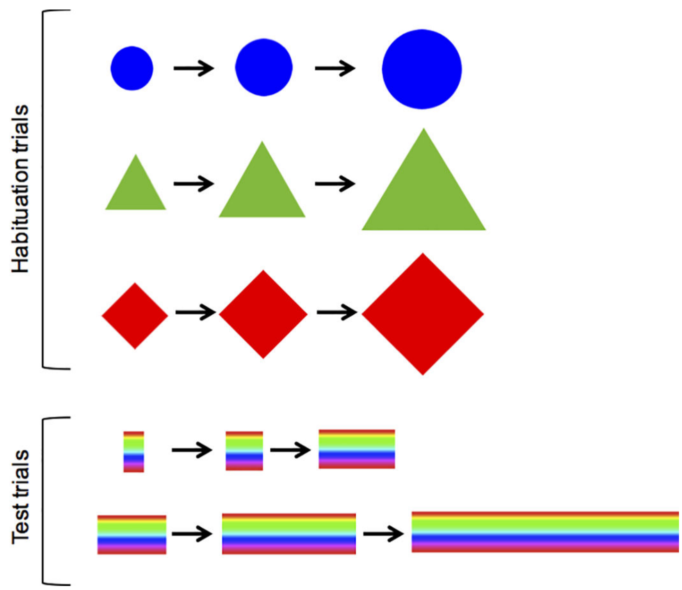

Figure 1. The five sets of colored shapes as they were presented to infants in the increasing order condition of Experiment 1. Arrows represent passage of time; objects were presented serially, centered on the screen. Blue circles, green triangles, and red diamonds were presented in a fixed order during habituation, and the smaller and larger sets of rainbow-colored bars were presented, respectively, during the against-OM and the with-OM test trials, with presentation order counterbalanced across participants. For infants in the decreasing order condition the same habituation shapes were presented in reversed order (from the larger to the smaller), starting from the red diamonds and proceeding to the green triangles and the blue circles, and the smaller and larger sets of bars were presented, respectively, during the with-OM and the against-OM test trials.

Design

Infants were habituated to increasing or decreasing sequences of blue circles, red squares, and green triangles, and were then tested with increasing or decreasing sequences containing newly-sized bars (see Figure 1). Half of the infants were randomly assigned to the increasing habituation condition (N = 20). 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 increasing condition (i.e., 9-18-36, 11-22-44, 13-26-52 cm^2), from the largest to the smallest shape for the decreasing 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 and 21-42-84 cm^2), with the order of presentation counterbalanced across participants. For infants in the increasing habituation condition the with-momentum test sequence comprised bars measuring 21, 42, 84 cm^2, and the against-momentum test sequence comprised bars measuring 5.5, 11, 22 cm^2; the opposite was true for infants in the decreasing 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 X 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 to 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 = .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 and Discussion

All statistics are two-tailed. The average number of trials received during habituation did not differ for infants tested in the the increasing and decreasing order conditions (M = 7.45, SEM = 0.43 vs. M = 8.7, SEM = 0.62), $t(38) = 1.67$, p = .1). However, infants in the decreasing order condition needed more time overall to habituate than infants in the increasing condition (M = 70.83 s, SEM = 10.39 vs. M = 44.28 s, SEM = 6.97, $t(38) = 2.12$, p = .04), suggesting that information processing for the abstraction and representation of increasing order is less effortful than for decreasing order. A similar variation in habituation looking times did not emerge when considering only the first three and the last three habituation trials. A two-way analysis of variance (ANOVA) on mean habituation looking times with order condition (increasing vs. decreasing) 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 = 10.82 s, SEM = 1.2) to the last three habituation trials (M = 4.75 s, SEM = 0.5), $F(1,38) = 35.18$, MSe = 736.72, $p < .001$, $\eta_p^2 = .48$, in the absence of a main effect or interaction involving the factor order condition (ps > .26) (see Figure 2).

PsychOpen publishing psychology

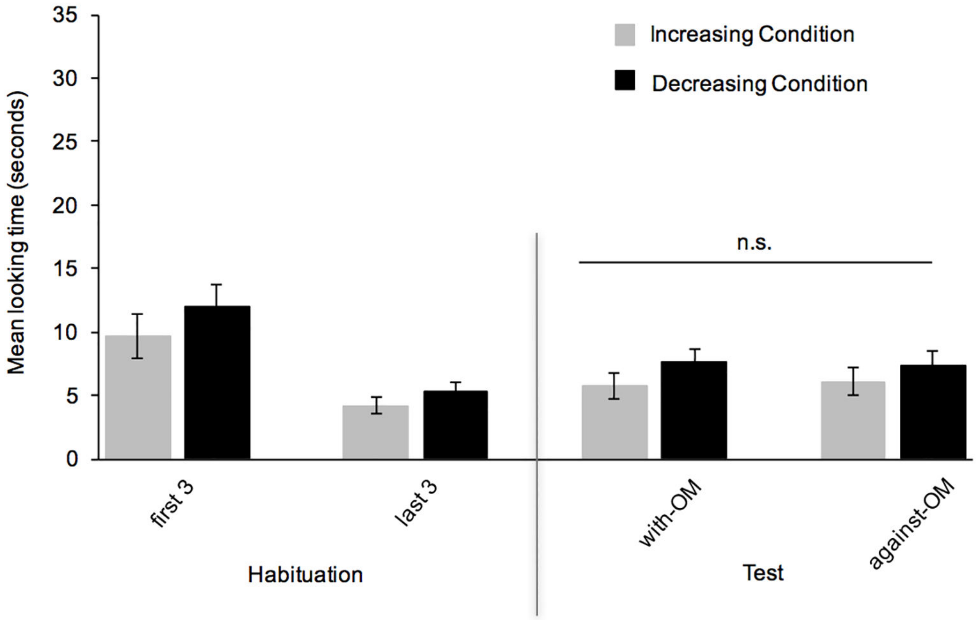

Figure 2. Overall mean total looking time (±SEM) to the first three and last three habituation trials, and to the with-OM and against-OM test trials displayed by infants in the increasing and decreasing order conditions in Experiment 1. Infants failed to show discrimination between the with-OM sequence and the against-OM sequence.

To determine whether during test trials 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 the two test trials were entered into a three-way ANOVA with order condition (increasing vs. decreasing) and test order (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 no significant main effects or interactions (all Fs < 1.65, ps > .2), indicating that looking times to the against-OM test trial did not differ from those to the with-OM trial for infants in either the increasing (M = 5.74 s, SEM = 0.9 vs. M = 6.1 s, SEM = 0.93) or the decreasing (M = 7.7 s, SEM = 1.04 vs. M = 7.4 s, SEM = 1.14) order conditions (see Figure 2). Finally, binomial tests confirmed the absence of an OM effect in this experiment, revealing that 22 out of 40 infants looked longer to the against-OM test trial compared to the with-OM one (22 vs. 18, p = .6; two-tailed), with a similar number of infants showing the pattern in the increasing and decreasing conditions (9 vs. 13, *n.s.*).

Overall, results show that infants did not manifest a differential looking behavior toward test sequences whose elements' size violated the momentum effect, relative to those whose elements' size followed the momentum. This pattern suggests that, unlike older, 12-month-old, infants (Macchi Cassia et al., 2016), 4-month-olds did not experience a momentum effect while ordering size. This may indicate that ordering operations do not elicit OM effects early in development (i.e., by 4 months of age); another possibility is that OM effects are absent in earlier stages of development for the dimension of size, but might be present for the dimension of number. This possibility builds on previous demonstration that the link between magnitude and space, as evident in spatial attentional tasks, is specific to number at 8 months and does not extend to the dimension of size (Bulf et al., 2016).

Experiment 2

In Experiment 2, a new group of 4-month-old infants was habituated to a series of either increasing or decreasing numerical sequences and then tested with new sequences in which the same ordinal direction was composed of larger or smaller numerosities. If infants experience an OM effect while ordering number, then they should look longer at the test series that violate the momentum created during habituation: Those habituated to increasing number should look longer to smaller test numerosities, and those habituated to decreasing number should look longer to larger test numerosities. Numerical sequences included numerosities that varied by a 1:3 ratio, as infants at this age succeed in numerical ordinal tasks when provided with this ratio (de Hevia et al., 2017).

Methods

The methods were the same as in Experiment 1, except as follows.

Participants

The final sample included 40 4-month-olds (20 females, mean age = 4 months 17 days, range = 3 months 28 days to 5 months 4 days) assigned randomly and in equal number (N = 20) either to the increasing or the decreasing order condition. Data from an additional 19 infants were discarded due to fussiness resulting in failure to complete all testing trials (n = 6), looking time in at least one test trial shorter than 1.5 s (n = 12), or technical error (n = 1). Parents gave their written informed consent before testing began.

Stimuli

The five stimulus sets used in the current experiment were created after de Hevia et al. (2017), in which 4-month-olds showed successful discrimination of numerical order. They were generated using E-Prime 1.0 software, and consisted of five sequences of three numerical arrays each containing colored rectangular-shaped items enclosed in a white area, randomly arranged, with the item's shorter side aligned with the horizontal plane. Three different exemplars were generated for each stimulus set that differed in item configuration. Three of the five sets were used for the habituation phase, and two for the test phase. The habituation sets were composed of 8-24-72, 9-27-81, and 10-30-60 blue (rgb: 0, 0, 255) items, and the two test sets were composed of 5-15-45 and 16-48-144 purple (rgb: 201, 28, 195) items. The shape of the white envelope area enclosing the items varied across the habituation sets and was the same within each set, although its size was positively correlated with numerosity (i.e., smaller numbers were enclosed in smaller-sized envelope areas and larger numbers in larger-sized areas) (see Figure 3). Therefore, density was constant across numerosities in each given habituation set, while envelope area and cumulative surface area were positively correlated with number. In fact, item size was constant at 0.18 cm^2, and density was 0.06 elements per cm^2 for all numerosities. Inversely, in the test sets, both the shape (i.e., hexagon) and the size of the envelope area were constant across numerosities so that density covaried with number, and non-numerical continuous variables were controlled both within and between sets by keeping cumulative surface area constant. In fact, item size was inversely correlated to number: The size of each single item in the smaller, medium and larger numerosity displays was, respectively, 0.45 cm^2, 0.15 cm^2 and 0.05 cm^2 in the 16-48-144 test set, and 1.44 cm^2, 0.48 cm^2 and 0.16 cm^2 in the 5-15-45 test set, and cumulative surface area was constant at about 7 cm^2. Overall, non-numerical variables that varied during habituation were held constant during test, and vice-versa.

PsychOpen
publishing psychology

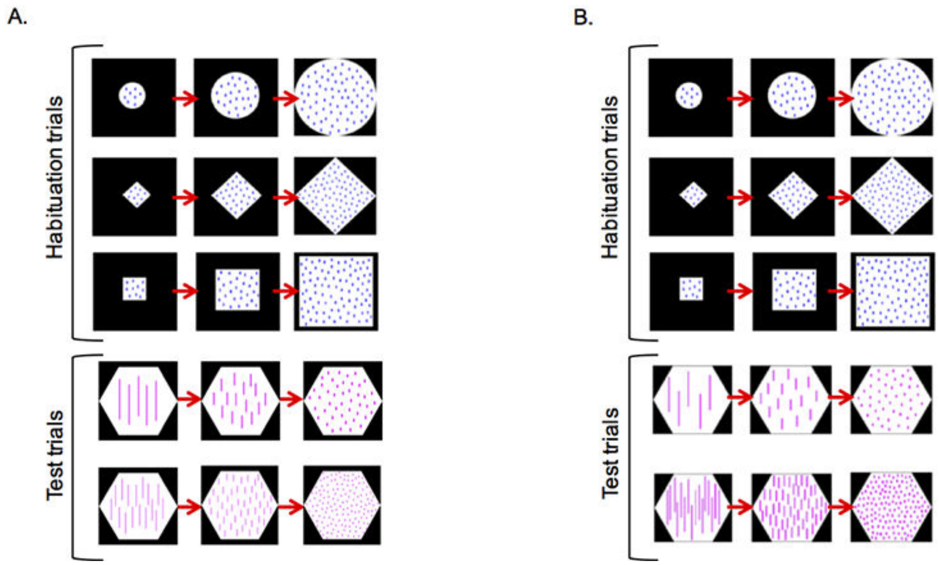

Figure 3. A) The five sets of numerical displays as they were presented to infants in the increasing order condition of Experiment 2. Arrows represent passage of time; objects were presented serially, centered on the screen. The numerical sequences 8-24-72, 9-27-81 and 10-30-90 were presented in a fixed order during habituation, and the numerical sequences 5-15-45 and 16-48-144 were presented, respectively, during the against-OM and the with-OM test trials, with presentation order counterbalanced across participants. For infants in the decreasing order condition, the same habituation displays were presented in reversed order (from the larger to the smaller), starting from the 90-30-10 sequence and proceeding to the 81-27-9 and the 72-24-8 sequence, while the 45-15-5 and the 144-48-16 sequences were presented, respectively, during the with-OM and the against-OM test trials. B) The five sets of numerical displays as they were presented to infants in the increasing order condition of Experiment 3. Habituation sets were identical to those used in Experiment 2, whereas the two test sets included the same number of items as in Experiment 2 (5-15-45 and 16-48-144) but differed for cumulative surface area (8 cm^2 and 26 cm^2, respectively).

Results and Discussion

All statistics are two-tailed. The average number of trials received during habituation did not differ for infants in the increasing and decreasing order conditions (M = 7.4 s, SEM = 0.48 vs. M = 7.8 s, SEM = 0.5), $t(38) = 0.5$, $p = .62$). Similarly, infants needed an equivalent amount of time to habituate to the increasing and decreasing sequences (M = 100.44 s, SEM = 10.91 vs. M = 96.69 s, SEM = 15.48, $t(38) = 0.19$, $p = .84$). The two-way ANOVA on mean habituation looking times with order condition (increasing vs. decreasing) 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 = 19.22 s, SEM = 2.2) to the last three habituation trials (M = 7.2 s, SEM = 1.1), $F(1,38) = 31.76$, $MSe = 2888.15$, $p < .001$, $\eta_p^2 = .46$, with no main effect or interaction involving the factor order condition (ps > .25) (see Figure 4).

To determine whether infants' looking times during test trials differed for the numerical sequence that violated the momentum effect and for the sequence that followed momentum, mean looking times to the two test trials were entered into a three-way ANOVA with order condition (increasing vs. decreasing) and test order (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 no significant main effects or interactions (all Fs < 2.7, ps > .11), indicating that neither infants tested with increasing order nor those in the decreasing order condition looked longer to the against-OM than to the with-OM test trial (increasing condition: M = 7.1 s, SEM = 1.2 vs. M = 6.3

s, *SEM* = 0.85; decreasing condition: *M* = 6.8 s, *SEM* = 1.6 vs. *M* = 4.9 s, *SEM* = 0.6) (see Figure 4). Binomial tests confirmed that only 15 out of 40 infants looked longer to the against-OM test trial compared to the with-OM one (15 vs. 25, *p* = .8, two-tailed), with a similar number of infants showing the pattern in the increasing and decreasing order condition (8 vs. 7, *n.s.*).

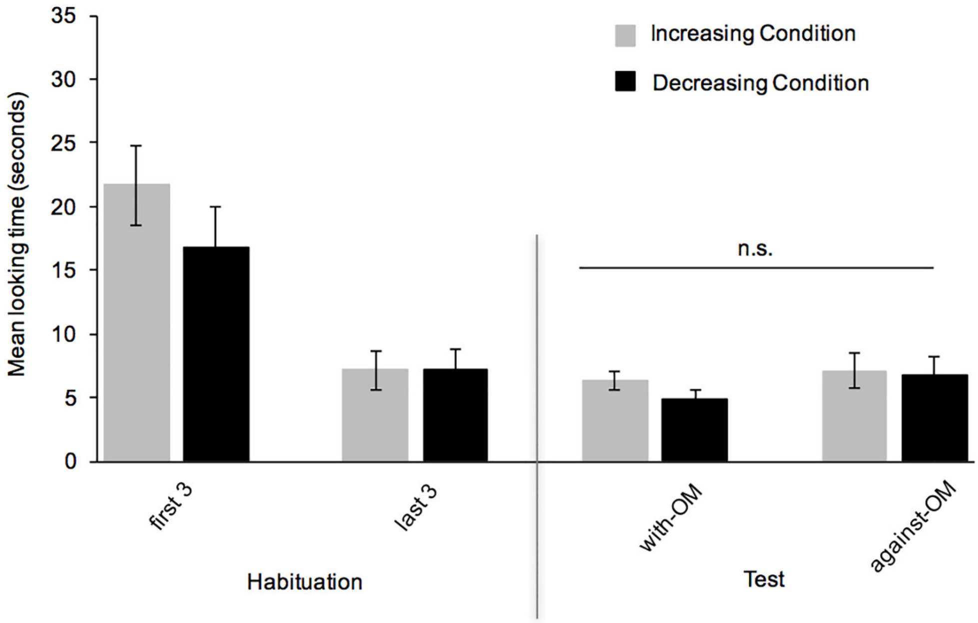

Figure 4. Overall mean total looking time (±SEM) to the first three and last three habituation trials, and to the with-OM and against-OM test trials displayed by infants in the increasing and decreasing order conditions of Experiment 2. Infants failed to show discrimination between the with-OM sequence and the against-OM sequence.

Results show that infants fail to exhibit an OM effect while ordering numerical sequences, as indexed by their comparable looking times at both ordered test sequences, the one violating the OM and the one following the OM generated during habituation. When considered together with the results of Experiment 1, this finding suggests that at 4 months of age ordering of both discrete and continuous quantities do not engender momentum-like effects. When the two test sequences differed only by numerical information, as non-numerical variables were strictly controlled, no OM effect was observed.

Research on infant numerical cognition has consistently shown that providing infants with multiple cues boosts their sensitivity to numerical differences (Jordan, Suanda, & Brannon, 2008) as well as their ability to extract ordinal numerical relations (Suanda, Tompson, & Brannon, 2008). Therefore, in Experiment 3 we tested a new group of 4-month-old infants using a new set of test stimuli, in which the magnitude difference between the with -OM and the against-OM sequences was provided not only by number, but also by cumulative surface area, as the two cues covaried one with the other between the sequences (the habituation stimuli for Experiment 3 remained identical to those in Experiment 2). In so doing, we increased the saliency of the magnitude variation that might allow infants to differentiate the two test trials, and therefore reveal the momentum generated during habituation.

PsychOpen
publishing psychology

Experiment 3

In Experiment 3, a new group of 4-month-old infants was habituated with a series of either increasing or decreasing numerical sequences and then tested with new sequences in which the same ordinal direction was composed of larger and smaller numerosities. During test, however, they received multiple cues to magnitude differences between test trials, as not only number differed across trials, but also cumulative surface area. Unlike in Experiment 2, this dimension covaried with number across the with-OM and the against-OM test sequences. Again, if infants experience an OM effect while ordering number, then they should look longer at the test series that violate the momentum created during habituation: Those habituated to increasing number should look longer to smaller numerosities, and those habituated to decreasing number should look longer to larger numerosities. In Experiment 3, as in Experiment 2, numerical sequences included numerosities that varied by a 1:3 ratio.

Methods

The methods were the same as in Experiment 2 except as follows.

Participants

The final sample included 40 4-month-olds (16 females, mean age = 4 months 21 days, range = 4 months 7 days to 5 months) assigned randomly and in equal number (N = 20) to the two order conditions. Data from an additional 9 infants were discarded due to fussiness resulting in failure to complete all testing trials (n = 1), looking time in at least one test trial shorter than 1.5 s (n = 6), technical error (n = 1), or parental interference (n = 1). Parents gave their written informed consent before testing began.

Stimuli

The habituation sets were identical to Experiment 2. However, the test sets differed from Experiment 2, as the cumulative surface area was held constant at 8 cm^2 in one set and 26 cm^2 in the other set, so that the two sets differed not only in number but also in cumulative surface area (see Figure 3). The items' size was constant across the two sets for the two smallest numerosities (1.62 cm^2 for the numerosities 5 and 16), the two medium numerosities (0.54 cm^2 for the numerosities 15 and 48) and the two large numerosities (0.18 cm^2 for the numerosities 45 and 144).

Results and Discussion

All statistics are two-tailed. Infants in both the increasing and decreasing order conditions required almost the same number of trials (M = 7.2 s, SEM = 0.40 vs. M = 7.4 s, SEM = 0.46), $t(38) = 0.33$, $p = .74$), and needed an equivalent amount of time to habituate (M = 100.79 s, SEM = 8.27 vs. M = 123.44 s, SEM = 17.09, $t(38) = 1.19$, $p = .24$). The two-way ANOVA on mean habituation looking times with order condition (increasing vs. decreasing) 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 = 24.67 s, SEM = 2.9) to the last three habituation trials (M = 7.5 s, SEM = 0.6), $F(1,38) = 39.78$, $MSe = 5916.46$, $p < .001$, $\eta_p^2 = .51$, with no main effect or interaction involving the factor order condition (ps > .44) (see Figure 5).

A three-way ANOVA was performed on mean looking times during test trials to determine whether infants' performance at test revealed the presence of an OM effect. The ANOVA included the between-participants factors order condition (increasing vs. decreasing) and test order (with-OM first vs. against-OM first), and the within-subjects factor test trial type (with-OM vs. against-OM). Results revealed a significant main effect of order condition, $F(1, 36) = 7.87$, $MSe = 309.29$, $p = .008$, $\eta_p^2 = .18$, as overall looking times in test trials were longer for infants tested in the decreasing condition (decreasing: $M = 10.34$ s, $SEM = 1.19$ vs. increasing: $M = 6.41$ s, $SEM = .76$). More crucially, there was also a main effect of test trial type, $F(1, 36) = 11.218$, $MSe = 320.96$, $p = .002$, $\eta_p^2 = .24$, as infants looked significantly longer to the against-OM than to the with-OM test trial ($M = 10.4$ s, $SEM = 1.2$ vs. $M = 6.4$ s, $SEM = 0.74$). The Order condition x Test trial type interaction was nonsignificant ($F < .11$, $p > .70$), indicating that the pattern of increased looking towards the against-OM trial was not modulated by the direction of the ordinal relations infants had been tested with (see Figure 5). The other main effects and interactions were also non-significant (all Fs < .21, ps > .16).

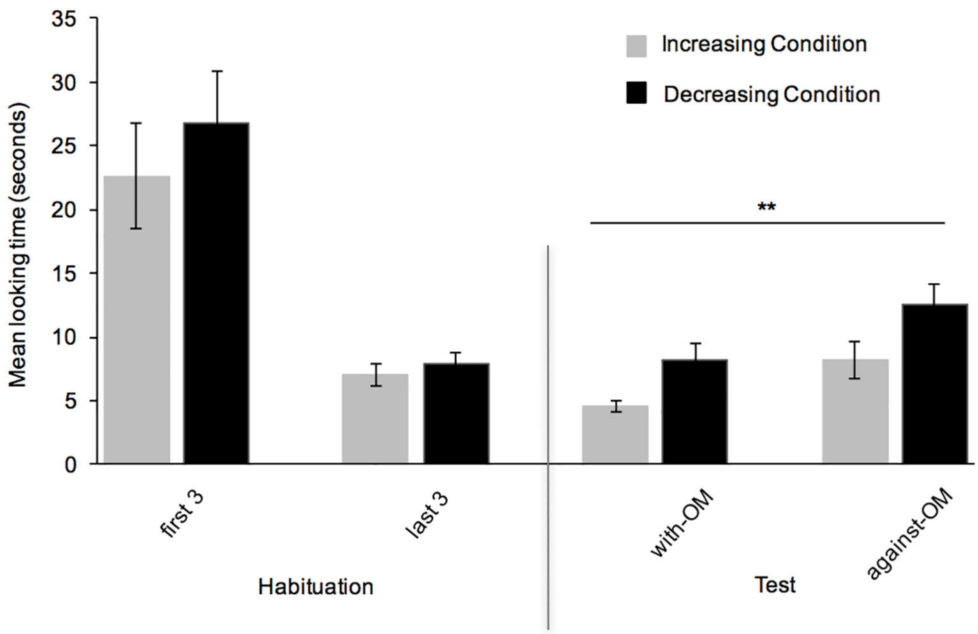

Figure 5. Overall mean total looking time (±SEM) to the first three and last three habituation trials, and to the with-OM and against-OM test trials displayed by infants in the increasing and decreasing order conditions of Experiment 3. Infants showed overall longer looking times to the against-OM sequence than to the with-OM sequence.

**$p = 0.002$.

Paired-sample t tests confirmed that looking times were significantly longer to the against-OM than to the with-OM test trial both for infants tested with increasing order ($M = 8.22$, $SEM = 1.5$ vs. $M = 4.6$, $SEM = 0.44$), $t(19) = 2.37$, $p =.028$, and for those tested with decreasing order ($M = 12.54$, $SEM = 1.7$ vs. $M = 8.14$, $SEM = 1.32$), $t(19) = 2.39$, $p = .027$ (see Figure 5). Binomial tests confirmed that 27 out of 40 infants looked longer to the against-OM test trial compared to the with-OM one (27 vs. 13, $p = .04$), with a similar number of infants showing the pattern in the increasing and decreasing habituation conditions (15 vs. 12, *n.s.*).

Overall, results indicate that, unlike in Experiment 2, infants in the current experiment manifested a differential looking behavior at test toward the ordered numerical sequence that violated the OM relative to the one that followed the OM, by showing a significantly higher looking time at the against-OM sequence, which we suggest was violating the numerical magnitude expectations formed during habituation. These findings reveal that 4-month-old infants do experience momentum-like effects while ordering magnitudes, but - unlike 12-month-olds - they only experience an OM effect when cumulative surface area and number co-occur as cues to magnitude during the test phase. Nevertheless, a four-way ANOVA with experiment (Exp. 3 vs. Exp. 2) as an additional between-participants factor failed to confirm a significant difference between the current experiment and Experiment 2, with a significant main effect of test trial type, $F(1,72) = 12.43$, $MSe = 288.45$, $p = .001$, $\eta_p^2 = .15$, but an Experiment x Momentum interaction, $F(1,72) = 3.01$, $MSe = 69.76$, $p = .087$, $\eta_p^2 = .04$, which failed to reach significance. In contrast, the same ANOVA comparing Experiment 3 vs. Experiment 1 provided evidence for a reliable differential pattern of results, with a main effect of test trial type, $F(1,72) = 8.45$, $MSe = 159.44$, $p = .005$, $\eta_p^2 = .11$, as well as a significant Experiment x Momentum interaction, $F(1,72) = 8.56$, $MSe = 161.52$, $p = .005$, $\eta_p^2 = .11$. Similar results were obtained when the factors order condition and test order were omitted from the ANOVAs (Experiment x Momentum: Exp. 3 vs Exp. 2, $p = .085$; Exp. 3 vs Exp. 1, $p = .004$).

General Discussion

This study investigated whether OM effects recently described for ordinal operations in size-based sequences by 12-month-old infants (Macchi Cassia et al., 2016) are present in 4-month-old infants, who are already able to represent ordinal information for the dimensions of size (Macchi Cassia et al., 2012) and number (de Hevia et al., 2017). In particular, we aimed to test whether at this younger age ordering size engenders momentum-like effects similar to those described in older infants for nonsymbolic arithmetic (McCrink & Wynn, 2009) and size ordering (Macchi Cassia et al., 2016), or whether at this stage these effects are specific to numerical transformations.

To this aim, in three experiments we tested 4-month-old infants in an ordinal task in which they had to extract and represent increasing and decreasing order within size-based sequences (Experiment 1) and numerical sequences (Experiment 2 and 3), and then respond to sequences that exhibited greater or lesser sizes or numerosities. The presence of OM was inferred from infants' longer looking times to sequences that violated the momentum generated during habituation relative to sequences that followed the momentum.

Infants' performance during test trials suggests that momentum effects were absent during ordinal tasks when single magnitude cues were available to discriminate between with-OM and against-OM test sequences (Experiments 1 and 2), but apparent when redundant magnitude cues were available (Experiment 3). In fact, infants failed to show an increased looking behavior when presented with the against-OM single-shape sequence after having been habituated to either increasing or decreasing single-shape sequences (Experiment 1). Similarly, infants did not show increased attention towards the against-OM test sequence after habituation to either increasing or decreasing sequences in which number covariated with envelope and cumulative area, when the test trials differed only by pure numerical information (Experiment 2). It was only when test trials differed in both number and cumulative area (Experiment 3), and therefore when redundant magnitude cues were available, that increased looking time was observed for the against-OM sequence, suggesting that infants' OM expectations were generated during habituation and later violated during the observation of the against-OM sequence.

Indeed, the habitation phases were identical in both Experiments 2 and 3, as infants in both studies were presented with the same exact habituation stimulus sets in which number covaried with envelope and cumulative area. Despite that, the momentum created during habituation was only expressed when infants received converging evidence on magnitude differences between the test sequences from multiple cues, suggesting that the covariation of cumulative area, envelope area, *and* number during ordering operations is critical in triggering an OM effect in 4-month-old infants. Nevertheless, it is also worth noting that, although the two conditions tested in Experiments 2 and 3 yielded different results in terms of post-habituation preference (i.e., nonsignificant preference in Experiment 2 vs. significant preference in Experiment 3), the comparison between infants' performance in the two conditions only showed a trend towards significance (p = .087), suggesting the presence of a quantitative and not qualitative difference in OM between the purely numerical and the multiple cues conditions. In contrast, infants' performance differed significantly (p = .005) between Experiment 3 and Experiment 1, indicating a qualitative difference in the OM generated during ordering operations computed over physical size and those computed over multiple quantitative dimensions.

A related phenomenon within the ordering literature has been observed previously, with infants younger than 11 months of age being able to extract numerical order only if additional cues such as spatial extent (Suanda et al., 2008) or items' shape (Picozzi et al., 2010) are present in the sequences. Why, then, would infants perform differently when given multiple overlapping cues to an ordering principle, compared to a single cue? According to the intersensory redundancy hypothesis (Bahrick & Lickliter, 2000), infants' attentional selectivity is guided by stimuli that share overlapping information in multiple sensory domains. For example, when two films are superimposed on each other (a keyboard being played, and slinky expanding) and a soundtrack to only one provided (e.g. the sound of keys being struck), infants preferentially process the sound-specified film (Bahrick, Walker, & Neisser, 1981). Our findings bring this principle to bear on two variables *within* the same modality (sight), and as such it could be considered a within-modality version of this principle - a kind of intra-variable redundancy -, in which all quantity variables (area, perimeter, convex hull, and numerical magnitude) being in congruency emphasize to the infant the overarching ascending or descending ordinal rule.

A notable finding to emerge from this study is that variations along the dimension of physical size by itself do not appear to engender momentum effects at 4 months of age. In fact, when size was the only available information that monotonically changed within ordered sequences for both the habituation and test phases, infants did not show any evidence of momentum (Experiment 1). However, note that changes in numerosities in Experiments 2 and 3 were indeed accompanied by corresponding changes in size of their enclosing area during habituation (smaller numerosities were embedded in smaller envelope areas, and larger numerosities in larger envelope areas), in addition to changes in overall surface area. Therefore, it is possible that, in these experiments, envelope area acted as an additional non-numerical cue that helped create OM during habituation, by enhancing perceived magnitude differences within the sequences. Performance during test trials could not be based on this dimension, as envelope area was constant across the with-OM and the against-OM test sequences. However, it is possible that the redundant ordering cues for numerosity (changing number), surface area (changing cumulative area) and size (changing envelope) in the habituation phase of both Experiments 2 and 3 were necessary to engender an OM effect (i.e., "anticipate larger/smaller"), and the corresponding expectations transfer only to stimuli whose magnitude is signaled by confounded cumulative surface area and numerical cues. Therefore, although linear changes in physical size by itself did not engender momentum effects at 4 months of age, the combination of different magnitude cues allowed the formation of OM expectations during habituation (i.e., number + cumulative surface area + size of envelope area), and triggered infants' response to the violation of OM expectations during test (i.e., number + cumulative surface area).

Previous demonstrations of momentum effects during non-symbolic arithmetic in infancy have been interpreted as suggestive of attentional shifts along the internal oriented representational space for number (McCrink et al., 2007; McCrink & Wynn, 2009). Along these lines, the present results might be accounted for as infants mapping number onto a spatial representation already at 4 months. At this age, the mapping might be absent for the dimension of size, and require the use of multiple magnitude cues, as the OM effect did not emerge when infants ordered size-based sequences during habituation and only size was available as a cue to discriminate between the with-OM and the against-OM sequences at test (Experiment 1). These results align somewhat with earlier demonstrations of a number-space mapping using a different paradigm, where shifts of visuo-spatial attention towards peripheral regions of space were related to number, but not to size, such that smaller numbers (but not smaller sizes) elicited faster orientations toward the left side, and larger numbers (but not larger sizes) toward the right (Bulf et al., 2016). In the current study, the distinction between number-driven shifts of attention and size-driven shifts of attention is not as stark, suggesting that OM is a more complex phenomenon that blends multiple representations of magnitude early in infancy.

Finally, there are two aspects of infants' performance in the current study that merit further elaboration. First, in Experiment 1, where infants were required to order size, infant-controlled procedure resulted in different amounts of time required by infants to reach the habituation criterion depending on the order condition. In fact, infants exposed to the decreasing order needed significantly more time than infants exposed to the increasing order. Similarly, in Experiment 3, where infants were required to order arrays of discrete elements varying on numerical and non-numerical dimensions, overall looking times in test trials were longer for infants presented with decreasing order than for those presented with increasing order. Finally, visual inspection of Figure 5 reveals that, for infants in the increasing condition, but not for those in the decreasing condition, the decrement in looking time occurring during habituation extended well into test for the with-OM trial, which can be assimilated to the hypothetical next trial of habituation if an OM effect has arised. Crucially, these order effects did not interact with infants' longer looking behavior towards the against-OM test trial, which was present for infants in both order conditions. Nevertheless, together these findings suggest that a stronger representation was built by infants while viewing increasing order relative to decreasing order during habituation, and that additional cognitive resources were devoted to the representation of decreasing ordinal relations, compared to increasing, for both numerical and size-based sequences. This pattern resonates with earlier reports of an asymmetry in ordinal sensitivity for infants of the same age as in the current study, by which ordering increasing magnitudes enjoys an advantage over ordering decreasing magnitudes, and this processing/representational constraint applies to ordering operations of both the dimensions of size (Macchi Cassia et al., 2012) and number (de Hevia et al., 2017).

A second aspect of the current results that deserves consideration is that the strength of the OM effect generated during the ordering operation was comparable for both the increasing and decreasing orders, and that OM was present when infants were habituated to arrays of discrete elements but not to single shapes varying in size. This pattern of results, together with the previously reported asymmetry in infants' ordinal abilities for both size (Macchi Cassia et al., 2012) and number (de Hevia et al., 2017), indicate that ordering operations and momentum effects exhibit different behavioral signatures, and therefore they might not tap on the same cognitive mechanisms. If one assumes that the OM phenomenon signals the overshoot of the attentional shift along a spatial numerical representation during ordinal operations, then it might be concluded that at 4 months of age a spatially oriented framework is invoked during ordinal operations, but is dependent on multiple cues to magnitude being represented when infants must shift their attention. Later in development, at 12 months of age, infants do show OM effects when representing a single dimension (i.e., size; Macchi Cassia et al., 2016). Future studies are needed to establish a more precise developmental pattern of the emergence of the OM effect for numerical and non-numerical quantities, so as to shed further light on the nature of infants' magnitude representations.

Funding

The authors have no funding to report.

Competing Interests

The authors have declared that no competing interests exist.

Acknowledgments

The authors are indebted to parents and infants who donated their time to participate in the study. The authors also thank Carlo Toneatto for invaluable contribution in programming the experiment, Valeria Gariboldi and Gaia Ambrosoni for their help in testing infants. VMC was supported by a grant from the University of Milano-Bicocca (Fondo di Ateneo-Quota Competitiva 2015). KMC was supported by award R15 HD077518-01A1 from the National Institute of Child Health and Human Development. MDdH was supported by a grant from the Agence Nationale de la Recherche Scientifique, France (ANR-15-CE28-0003-01 NUMSPA), and by a Research Grant from the Fondation Fyssen, France.

References

Bahrick, L. E., & Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy. *Developmental Psychology, 36*, 190-201. doi:10.1037/0012-1649.36.2.190

Bahrick, L. E., Walker, A. S., & Neisser, U. (1981). Selective looking by infants. *Cognitive Psychology, 13*, 377-390. doi:10.1016/0010-0285(81)90014-1

Berch, D. B., Foley, E. J., Hill, R. J., & Ryan, P. M. (1999). Extracting parity and magnitude from Arabic numerals: Developmental changes in number processing and mental representation. *Journal of Experimental Child Psychology, 74*, 286-308. doi:10.1006/jecp.1999.2518

Brannon, E. M. (2002). The development of ordinal numerical knowledge in infancy. *Cognition, 83*, 223-240. doi:10.1016/S0010-0277(02)00005-7

Bulf, H., de Hevia, M. D., Gariboldi, V., & Macchi Cassia, V. (2017). Infants learn better from left to right: A directional bias in infants' sequence learning. *Scientific Reports,* Article 2437. doi:10.1038/s41598-017-02466-w

Bulf, H., de Hevia, M. D., & Macchi Cassia, V. (2016). Small on the left, large on the right: Numbers orient visual attention onto space in preverbal infants. *Developmental Science, 19*, 394-401. doi:10.1111/desc.12315

Coubart, A., Streri, A., de Hevia, M. D., & Izard, V. (2015). Crossmodal discrimination of 2 vs. 4 objects across touch and vision in 5-month-old infants. *PLOS ONE, 10*, Article e0120868. doi:10.1371/journal.pone.0120868

PsychOpen publishing psychology

Dehaene, S. (1997). *The number sense.* New York, NY, USA: Oxford University Press.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122*, 371-396. doi:10.1037/0096-3445.122.3.371

de Hevia, M. D., Addabbo, M., Nava, E., Croci, E., Girelli, L., & Macchi Cassia, V. (2017). Orders are not all the same: Infants' detection of increasing number comes first. *Cognition, 158*, 177-188. doi:10.1016/j.cognition.2016.10.022

de Hevia, M. D., Girelli, L., Addabbo, M., & Macchi Cassia, V. (2014). Human infants' preference for left-to-right oriented increasing numerical sequences. *PLOS ONE, 9*, Article e96412. doi:10.1371/journal.pone.0096412

de Hevia, M. D., & Spelke, E. S. (2010). Number-space mapping in human infants. *Psychological Science, 21*, 653-660. doi:10.1177/0956797610366091

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences, 8*, 307-314. doi:10.1016/j.tics.2004.05.002

Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10*, 126-132. doi:10.1037/0278-7393.10.1.126

Gallistel, C. R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition, 44*, 43-74. doi:10.1016/0010-0277(92)90050-R

Gevers, W., Reynvoet, B., & Fias, W. (2003). The mental representation of ordinal sequences is spatially organized. *Cognition, 87*, B87-B95. doi:10.1016/S0010-0277(02)00234-2

Göbel, S. M., Shaki, S., & Fischer, M. H. (2011). The cultural number line: A review of cultural and linguistic influences on the development of number processing. *Journal of Cross-Cultural Psychology, 42*, 543-565. doi:10.1177/0022022111406251

Hubbard, T. L. (2014). Forms of momentum across space: Representational, operational, and attentional. *Psychonomic Bulletin & Review, 21*, 1371-1403. doi:10.3758/s13423-014-0624-3

Izard, V., Sann, C., Spelke, E. S., & Streri, A. (2009). Newborn infants perceive abstract numbers. *Proceedings of the National Academy of Sciences of the United States of America, 106*, 10382-10385. doi:10.1073/pnas.0812142106

Jordan, K. E., & Brannon, E. M. (2006). The multisensory representation of number in infancy. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 3486-3489. doi:10.1073/pnas.0508107103

Jordan, K. E., Suanda, S. H., & Brannon, E. M. (2008). Intersensory redundancy accelerates preverbal numerical competence. *Cognition, 108*, 210-221. doi:10.1016/j.cognition.2007.12.001

Knops, A., Viarouge, A., & Dehaene, S. (2009). Dynamic representations underlying symbolic and nonsymbolic calculation: Evidence from the operational momentum effect. *Attention, Perception & Psychophysics, 71*, 803-821. doi:10.3758/APP.71.4.803

Lourenco, S. F., & Longo, M. R. (2010). General magnitude representation in human infants. *Psychological Science, 21*, 873-881. doi:10.1177/0956797610370158

Macchi Cassia, V., McCrink, K., de Hevia, M. D., Gariboldi, V., & Bulf, H. (2016). Operational momentum and size ordering in preverbal infants. *Psychological Research, 80*, 360-367. doi:10.1007/s00426-016-0750-9

Macchi Cassia, V., Picozzi, M., Girelli, L., & de Hevia, M. D. (2012). Increasing magnitude counts more: Asymmetrical processing of ordinality in 4-month-old infants. *Cognition, 124*, 183-193. doi:10.1016/j.cognition.2012.05.004

McCrink, K., Dehaene, S., & Dehaene-Lambertz, G. (2007). Moving along the number line: Operational momentum in nonsymbolic arithmetic. *Perception & Psychophysics, 69*, 1324-1333. doi:10.3758/BF03192949

McCrink, K., & Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychological Science, 15*, 776-781. doi:10.1111/j.0956-7976.2004.00755.x

McCrink, K., & Wynn, K. (2009). Operational momentum in large-number addition and subtraction by 9-month-olds. *Journal of Experimental Child Psychology, 103*, 400-408. doi:10.1016/j.jecp.2009.01.013

Picozzi, M., de Hevia, M. D., Girelli, L., & Macchi Cassia, V. (2010). Seven-month-olds detect ordinal numerical relationships within temporal sequences. *Journal of Experimental Child Psychology, 107*, 359-367. doi:10.1016/j.jecp.2010.05.005

Previtali, P., de Hevia, M. D., & Girelli, L. (2010). Placing order in space: The SNARC effect in serial learning. *Experimental Brain Research, 201*, 599-605. doi:10.1007/s00221-009-2063-3

Suanda, S. H., Tompson, W., & Brannon, E. M. (2008). Changes in the ability to detect ordinal numerical relationships between 9 and 11 months of age. *Infancy, 13*, 308-337. doi:10.1080/15250000802188800

Turati, C., Gava, L., Valenza, E., & Ghirardi, V. (2013). Number versus extent in newborns' spontaneous preference for collections of dots. *Cognitive Development, 28*, 10-20. doi:10.1016/j.cogdev.2012.06.002

PsychOpen is a publishing service by Leibniz Institute
for Psychology Information (ZPID), Trier, Germany.
www.zpid.de/en

PsychOpen
publishing psychology