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Infants' detection of increasing numerical order comes before detection of decreasing number

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ABSTRACT

Ordinality is a fundamental aspect of numerical cognition. However, preverbal infants' ability to represent numerical order is poorly understood. In the present study we extended the evidence provided by Macchi Cassia, Picozzi, Girelli, and de Hevia (2012), showing that 4-month-old infants detect ordinal relationships within size-based sequences, to numerical sequences. In three experiments, we showed that at 4 months of age infants fail to represent increasing and decreasing numerical order when numerosities differ by a 1:2 ratio (Experiment 1), but they succeed when numerosities differ by a 1:3 ratio (Experiments 2 and 3). Critically, infants showed the same behavioral signature (i.e., asymmetry) described by Macchi Cassia et al. for discrimination of ordinal changes in area: they succeed at detecting increasing but not decreasing order (Experiments 2 and 3). These results support the idea of a common (or at least parallel) development of ordinal representation for the two quantitative dimensions of size and number. Moreover, the finding that the asymmetry signature, previously reported for size-based sequences, extends to numerosity, points to the existence of a common constraint in ordinal magnitude processing in the first months of life. The present findings are discussed in the context of possible evolutionary and developmental sources of the ordinal asymmetry, as well as their implication for other related cognitive abilities.

1. Introduction

The ability to represent and discriminate quantities is foundational to human reasoning, and is considered one of the core knowledge systems upon which humans build new concepts and abilities (Carey, 2009; Gallistel & Gelman, 2000; Spelke, 2011). Human and non-human animals use this ability in everyday activities, from detecting the greatest patch of food in the wild to solving more or less sophisticated math problems. During the last few decades, cognitive science has provided strong evidence in support to the view that numerical estimation and reasoning may rest on a core cognitive system (Dehaene, 1997; Feigenson, 2007), which is evolutionary ancient (Vallortigara, Regolin, Chiandetti, & Rugani, 2010), functional at birth (Coubart, Izard, Spelke, Marie, & Streri, 2014; de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Izard, Sann, Spelke, & Streri, 2009), and universal across different cultures (Dehaene, Izard, Spelke, & Pica, 2008). In humans, formal mathematics is thought to build on this so-called 'number sense', the faculty that allows us to perceive the cardinality of sets intuitively (Burr & Ross, 2008; Butterworth, 1999; Dehaene, 1997).

Increased interest in the processing of ordinality, as a numerical aspect distinct from cardinality, has emerged very recently in the study of human adult numerical cognition (Delazer & Butterworth, 1997). In particular, some neuroimaging and neuropsychological studies with adults suggest that processing of ordinal and cardinal information dissociate at both the behavioral and biological levels (Rubinsten, Sury, Lavro, & Berger, 2013; Turconi, Jemel, Rossion, & Seron, 2004; Turconi & Seron, 2002). It has been recently proposed the existence of a core system for representing ordinal information, which would allow us to automatically analyze any perceptual input based on the ordinal information it conveys (Rubinsten et al., 2013).

Evidence for ordinality as a foundation of numeracy comes from studies where ordinality comprehension is critical for arithmetic

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performance in both adults (Lyons & Beilock, 2011) and school-aged children (Lyons, Price, Vaessen, Blomert, & Ansari, 2014). In a large cross-sectional study with children in Grades 1–6, Lyons et al. (2014) showed that the understanding of ordinality is a unique predictor for children's math abilities, and that by Grade 6 it is the most significant basic numerical predictor. Yet, most of these studies investigated order processing of symbolic numbers, and, critically, it has been recently claimed that ordinal processing may substantially differ between symbolic and non-symbolic numbers. In particular, based on both behavioral and neural data, Lyons and Beilock (2013) proposed that symbolic number ordering relies largely on associations between elements, mostly established and consolidated through counting routines, rather than on the magnitude of the elements themselves. On the contrary, ordinality in non-symbolic numbers would mainly emerge from iterative cardinality judgments (i.e., comparing each pair of numerosities in succession), as magnitude is intuitively and readily available to non-symbolic numbers. Accordingly, Lyons and Beilock (2013) showed that non-symbolic ordinal and cardinal processing, together with cardinal, but not ordinal, processing of symbolic number, elicited overlapping responses in a canonical number processing area of the brain (i.e., right IPSa; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999), signalling access to quantitative information.

Therefore, although this is still a topic for further investigation, we could expect ordinal processing of non-symbolic numbers to be even more strictly linked to numeracy than symbolic ordinal processing. Along these lines, evidence for altered ordinal estimation of non-symbolic numerosities has been reported in adults with developmental dyscalculia (DD), suggesting that a deficit in non-symbolic order processing might be characteristic of DD (Rubinsten & Sury, 2011). The hypothesis that (non-symbolic) ordinal knowledge may critically contribute to the early acquisition of numerical skills and, later on, to mathematical learning, calls for a full understanding of its origins and development. To this aim, the goal of the current study was to explore the presence of numerical ordinal knowledge in preverbal infants.

Non-verbal numerical cognition is thought to be achieved through two different cognitive mechanisms (Feigenson, Carey, & Hauser, 2002; Hyde, 2011). On the one hand, the analog number system, or ANS (Dehaene, 1997; Halberda, Mazzocco, & Feigenson, 2008), is thought to represent and operate in an approximate way over (perhaps any) large numerosity (generally $\geqslant 4$). Imprecision is a key feature of the ANS and it is responsible for the ratio-dependent performance observed across the lifespan (Halberda et al., 2008): in preverbal infants, the ratio needed to discriminate two numerosities decreases with age, from a 1:3 ratio at birth (Izard et al., 2009), to a 1:2 ratio from 4-to-6 months of life (Libertus & Brannon, 2010; Xu & Spelke, 2000), and a 2:3 ratio by 9 months (Lipton & Spelke, 2003). On the other hand, the object-file system is thought to be responsible for processing small numerosities ($\leqslant 3$), being able to individuate and keep track of each individual object in a precise way. In the current study, we will focus on computations over the numerical outputs of the ANS, as we will investigate 4-month-old infants' capacity to represent the relationship between three numerical sets each formed by at least 4 objects and differing one from the other according to a 1:2 (Experiment 1) or a 1:3 (Experiments 2 and 3) ratio.

Besides the ability to represent and discriminate quantities, preverbal humans and non-human animals have been shown to operate over representations of both small and large numerosities, for instance by adding (Livingstone et al., 2014; McCrink & Wynn, 2004) or subtracting them (Brannon, Wusthoff, Gallistel, & Gibbon, 2001; McCrink & Wynn, 2004). A crucial computation on numerical representation is ordering; however, preverbal infants' understanding of ordinality has received very little attention compared to numerical discrimination and comparison. This is partially due to the assumption that understanding the ordinal relation between numerical sets is a later achievement with respect to the ability to compare and discriminate numerosities. Developmental researchers have indeed proposed that the ability to recognize ordinal relations, in which more than two numerosities are involved, is particularly difficult, and that this capacity appears to emerge in the preschool years (Mix, Huttenlocher, & Levine, 2002). Nonetheless, numerical ordering abilities are available in monkeys (Brannon & Terrace, 1998, 2000; Judge, Evans, & Vyas, 2005), and even in animal species phylogenetically distant from humans and other primates, such as rats (Suzuki & Kobayashi, 2000), bees (Dacke & Srinivasan, 2008), fish (Petrazzini, Lucon-Xiccato, Agrillo, & Bisazza, 2015), and few-day-old chicks (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010; Rugani, Regolin, & Vallortigara, 2007). This suggests that the ability to compute ordinal information is a basic skill that might have been selected because it can enhance survival in several ecological contexts (Vallortigara et al., 2010). Along these lines, there is evidence that human infants possess a rudimentary ordinal ability, as they are able to detect statistically defined temporal patterns in simple sequences of visual shapes (Kirkham, Slemmer, & Johnson, 2002), starting from birth (Bulf, Johnson, & Valenza, 2011). However, to date, little is known about the full-fledged understanding of ordinality in humans during the first months of life.

There is evidence that by the end of the first year infants succeed at discriminating the ordinal relations (increasing vs. decreasing) characterizing sets formed by non-symbolic numerosities (Brannon, 2002; de Hevia & Spelke, 2010; de Hevia, Girelli, Addabbo, & Macchi Cassia, 2014; Picozzi, de Hevia, Girelli, & Macchi Cassia, 2010; Suanda, Tompson, & Brannon, 2008). After being habituated to increasing or decreasing sequences of large numerosities, 7-month-old infants generalize habituation at test to new numerical displays arranged in the familiar order while dishabituate to the same displays arranged in a novel order, even when non-numerical continuous variables are controlled for (de Hevia, Girelli, et al., 2014; Picozzi et al., 2010). Moreover, 8-month-old infants habituated to a five-set numerical sequence that increases (4–8–16–32–64) or decreases (64–32–16–8–4) in numerosity look significantly longer at test displays that show five-item line-length sequences following the opposite ordinal direction, showing that infants at this age are able to abstract the ordinal information from one dimension (i.e., non-symbolic number) and apply it to a different one (i.e., surface area) (de Hevia & Spelke, 2010). Finally, when spatial information is introduced in the numerical ordinal task 7-month-old infants show a preference for increasing, left-to-right oriented, numerical sequences and fail to discriminate order information when numerical sets appear along a right-to-left orientation (de Hevia, Girelli, et al., 2014).

Still, the view that cardinal understanding precedes ordinal understanding finds some support in available studies with infants in the first year of life. While the ability to discriminate numerosities has been reported to be functional from birth (Izard et al., 2009), the ability to make ordinal judgments on numerical stimuli has not been reported in infants younger than 7 months (de Hevia, Girelli, et al., 2014; Picozzi et al., 2010). Brannon and colleagues (Brannon, 2002; Suanda et al., 2008) have suggested that the ability to represent ordinal relations emerges first for continuous quantities, specifically size, and later extends to numerical quantities. Accordingly, the authors showed that, although at 9 months infants are able to discriminate the ordinal direction of size-based sequences, as well as sequences containing multiple quantitative dimensions including size (i.e., number, element size and overall area), it is not before the age of 11 months that they can discriminate ordinal relations within numerical sequences when continuous dimensions are controlled for. Although the age at which infants are able to discriminate ordinal relationships in numerical and size-based sequences has now been anticipated to, respectively, 7 (Picozzi et al., 2010) and 4 months (Macchi Cassia, Picozzi, Girelli, & de Hevia, 2012), no studies have so far explored the ability to process numerical order before the age of 7 months.

Numerical order is a way to arrange a sequence of numerosities, and this can be either increasing or decreasing. To investigate whether ordinal discrimination for numerosities is available before 7 months of age, in the present study we tested 4-month-old infants' ability to discriminate inversion in the direction (increasing vs. decreasing) of numerical ordinal relations. Following earlier investigations on infants' numerical ordering abilities (Brannon, 2002; Brannon, Cantlon, & Terrace, 2006; Brannon & Terrace, 1998, 2000; Cooper, 1984; de Hevia & Spelke, 2010; de Hevia, Girelli, et al., 2014; Picozzi et al., 2010; Suanda et al., 2008), in the current study numerical order is operationalized as the relation characterizing the progressions (either incrementing or decrementing) between at least three non-symbolic numerosities: the direction of change (increasing vs. decreasing) must be repeated at least twice and be the same for the numerosities within a given set (e.g., 6–12–24 or 24–12–6). In this way, order processing implies iterative 'greater than' and 'less than' comparisons between constituent pairs of numbers in a given sequence. This computation contrasts with the one taking place in numerical discrimination and comparison, as infants can succeed in these tasks by simply perceiving the numerical dissimilarity between two sets of objects (e.g., $6 \neq 12$) without computing the 'greater than' or 'less than' relationship between them.

Since earlier studies have shown that infants' appreciation of ordinal information is partially disrupted when small and large numerosities are intermixed within numerical sets (Brannon, 2002; Cooper, 1984; Suanda et al., 2008), possibly due to incompatibility between the outputs of the object-file and approximate number systems, in the current study we presented infants exclusively with numerical sets each composed of at least four items. Our method was modeled after Picozzi et al. (2010), who added to their numerical sequences featural information (i.e. color and shape of the numerical displays) as well as redundant cues to ordinality within and across sequences (de Hevia, Girelli, et al., 2014; Picozzi et al., 2010). In the present study featural information was made available to infants as additional cues to ordinality both within (i.e., items' shape) and between (i.e., background shape) the numerical sequences, with the aim of favouring infants' abstraction and learning of the ordinal rule. Specifically, the items' shape covaried with number to emphasize the distinctiveness of each constituent display within the sequences, and the background shape of the displays varied between the sequences to favor clustering of the sequences. As for the redundant cues to ordinality, numerical displays were presented in such a way that the same order (increase or decrease) was present both within and between each numerical sequence, as in previous studies (de Hevia, Girelli, et al., 2014; Picozzi et al., 2010): for instance, in the increasing habituation condition, not only numerosities increased within each given sequence, but also consecutive numerical sequences were presented in a fixed increasing order (e.g., first trial: 6, 12, 24; second trial: 9, 18, 36; third trial: 12, 24, 48).

If, under these facilitating testing conditions, 4-month-old infants are able to discriminate numerical order, the finding would add to earlier demonstration of 4-month-olds' discrimination of order in size-based sequences (Macchi Cassia et al., 2012), thus supporting the view of a common, or at least parallel, development of the ability to discriminate ordinal information for the two quantitative dimensions of size and number. Moreover, we tested 4-month-old infants because at this age infants' discrimination of size order yields a reliable asymmetry, whereby a successful discrimination of increasing order is accompanied by a failure to discriminate decreasing order (even when decreasing order is contrasted with a random order, Macchi Cassia et al., 2012). Thus, in the present study the presence of asymmetry in ordinal processing for numerical sequences would support the idea that the encoding of ordinality for both quantitative dimensions, number and size, share a common processing signature. The hypothesis that the asymmetry signature might be present also for numerical ordinal discrimination is highly plausible in light of the interpretation of this phenomenon provided by Macchi Cassia et al. (2012): the asymmetry might constitute a developmental precursor of the 'addition advantage', which refers to the better performance and earlier acquisition of addition relative to subtraction arithmetic operations in older children (Baroody, 1984; Campbell & Xue, 2001; Carpenter & Moser, 1984). This advantage has been described for both symbolic and non-symbolic arithmetics (Barth, Beckmann, & Spelke, 2008; Shinskey, Chan, Coleman, Moxom, & Yamamoto, 2009). Given that the addition advantage refers to computations over discrete numerosities, we hypothesized that if infants in our study succeed in extracting the ordinal information, then we might observe the asymmetry (i.e., success with increasing but failure with decreasing sequences) in their performance.

In each experiment of the current study, 4-month-old infants were habituated to either increasing or decreasing numerical sequences and were then presented with pairs of test trials alternating both numerical orders. Non-numerical quantitative cues such as element size, cumulative area, contour length, and density were controlled during the habituation or the test phase so that they could not be used as a consistent cue to ordinal discrimination.

2. Experiment 1 (1:2 ratio)

In Experiment 1 infants were habituated to either increasing or decreasing numerical sequences, and were tested with new sequences displaying both the familiar and the novel orders in alternation. The ratio difference between numerical displays contained in the increasing and decreasing sequences was 1:2.

2.1. Methods

2.1.1. Participants

Twenty-four healthy, full term 4-month-old infants (mean age = 4 months, 16 days; range = 4 months, 0 days – 4 months, 29 days; 11 female) took part in the experiment. Eight additional infants were excluded from the final sample because they failed to complete testing due to fussiness or lack of interest (n = 4; equally distributed across habituation conditions), looking times in at least one test trial more than 3 standard deviations (SD) from the overall group mean (n = 3) or because they did not reach the habituation criterion (n = 1). Infants were recruited via a database of parents who had agreed to participate in the study. Parents gave their informed written consent before testing.

2.1.2. Stimuli

Stimuli were sequences of three numerical displays each containing different rectangular-shaped items with the shorter side aligned with the horizontal plane (Fig. 1). Items were arranged randomly on a white area that appeared on a black background. Stimuli were generated using E-Prime 1.0 software. Three sets of stimuli were used for the habituation phase and one for the test phase. The first set of stimuli of the habituation phase was composed of 6, 12, 24 blue (rgb: 0, 0, 255) items contained in a rhombus-shaped area; the second one was composed of 9, 18, 36 blue items contained in a circle-shaped area, and the third one of 12, 24, 48 blue items in a square-shaped area. The set of stimuli

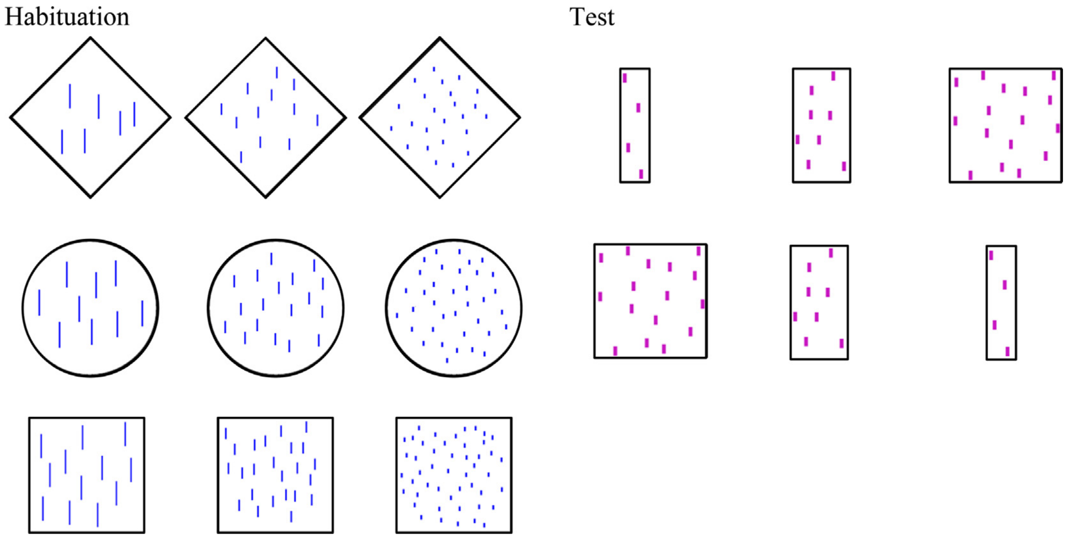

Fig. 1. Examples of the stimuli presented in Experiment 1, including the three stimuli set used in habituation (left) and the stimuli used in test (right). In habituation, numerical displays within a given numerical sequence had the same background shape (rhomboid, circular, squared). Numerical displays differed by a 1:2 ratio.

presented in the test phase was composed of 4, 8, 16 purple (rgb: 201, 28, 195) items contained in a rectangular-shaped area. Thus, the number of items contained in each sequence differed (either by increasing or decreasing) by a 1:2 ratio. Three different exemplars of each stimulus set were generated by varying item spatial configuration.

Non-numerical continuous variables were controlled by keeping cumulative surface area and contour length constant within each habituation set. Therefore, item size and length were inversely correlated to number. For each set, the heights of the single items in the smaller, medium and larger numerosity display were, respectively, 3.5, 1.7, and 0.7 cm, with the width constant at ≈0.2 cm. The area of each display was held constant at approximately 256 cm^2 within the first set and 260 cm^2 within the second and the third sets, so that number covaried with density. Inversely, for test displays the cumulative surface area and contour length were positively correlated with number. Item size was kept constant (0.5 cm × 1.3 cm) while the display size varied across numbers, so that density was held constant at 0.06 elements per cm^2. In this way, the continuous, non-numerical variables that varied during habituation were held constant during test, and vice versa.

2.1.3. Design and procedure

During the habituation phase, half of the infants viewed increasing sequences and the other half viewed decreasing sequences. Infants were randomly assigned to each habituation condition. The three different numerical sequences were cycled until the infant reached the habituation criterion and were presented in a fixed order: from the smallest to the largest numerical display for the increasing condition (i.e., 6–12–24; 9–18–36; 12–24–48), and from the largest to the smallest for the decreasing condition (i.e., 48–24–12; 36–18–9; 24–12–6). In this way, the numerical magnitudes increased or decreased within, as well as between, each habituation sequence, so as to provide redundant cues to ordinality. Following habituation, all infants viewed six test trials with new numerical values alternating increasing and decreasing sequences. Test order was counterbalanced across participants.

Infants sat in an infant seat at approximately 60 cm from the stimulus presentation monitor (24″ screen size, 1920 × 1200 pixel resolution). A video camera positioned just above the monitor recorded the infants' face and sent visual input to another computer monitor, thus allowing the online coding of infants' looking times through an E-Prime program by an experimenter who was blind to the experimental condition. The infants' face was also recorded via a Mini-Dv digital recorder, so that a second observer could code offline gaze direction for half of the infants in the sample to establish inter-observer reliability. Intercoder agreement between the two observers who coded the data live or from digital recording, as computed on total fixation times on each of the six test trials, was very robust (r = 0.98, Pearson correlation; 0.99 Intra-Class Correlation coefficient).

Each trial began as soon as the infant looked in the direction of a cartoon-animated image associated to a varying sound displayed in the center of the screen. Every trial consisted in a repeating cycle (6500 ms in total) composed of a gray screen (500 ms) followed by the three numerical displays, consecutively presented on a black background (each numerical display appeared every 2 s and was composed of 250 ms blank + 1750 ms numerical array; Fig. 2). Each trial continued until the infant looked for a minimum of 500 ms and ended when the infant looked away continuously for 2 s or looked for a maximum of 120 s. The three habituation sequences were presented in a fixed order until the infant viewed 14 trials or met the habituation criterion (a 50% decline in looking time on three consecutive trials, relative to the looking time on the first three trials that summed to at least 12 s). Following habituation, infants viewed six test trials in which a novel sequence (increasing for infants habituated to decreasing sequences, and vice versa) was presented alternated to a familiar one, with half of the infants seeing the novel test sequence first.

2.2. Results and discussion

An ANOVA with habituation condition (increasing vs. decreasing) as between-subjects factor, and habituation trials (first three vs. last three) as within-subjects factor revealed a significant effect of habituation trials, $F(1,22) = 42.69$, $p < 0.001$, due to average looking time on the first three habituation trials ($M = 18.3$ s) being significantly longer than average looking time on the last three trials ($M = 6.6$ s). There was no main effect or interaction involving habituation condition (both Fs < 1, n.s.). No differences in overall looking time or number of trials to habituate were found across the two habituation conditions: For the increasing sequences infants required an average of 100.5 s and 6.9 trials to habituate,

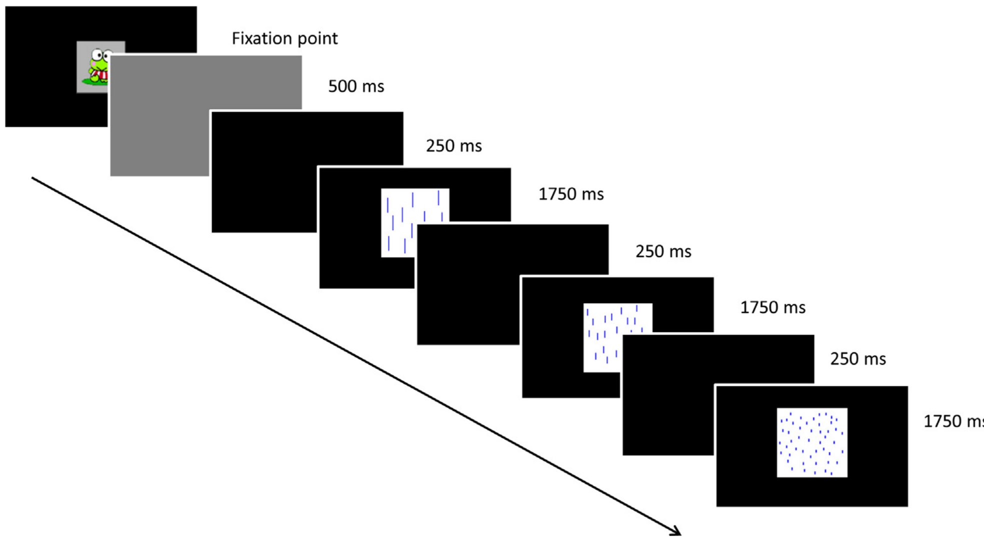

Fig. 2. Description of the procedure of stimuli presentation.

for the decreasing sequences infants required 87.7 s and 7.4 trials (unpaired t-tests, both *t*s < 1, n.s., two-tailed).

To assess whether infants were able to discriminate the familiar from the novel order at test, an ANOVA with habituation condition (increasing vs. decreasing) and first test trial (familiar vs. novel) as between-subjects factors, and trial pair (first vs. second vs. third) and test trial type (familiar vs. novel ordinal direction) as within-subjects factors was performed on total looking times during test trials. There were no significant main effects or interactions (all *F*s < 1.42, all *p*s > 0.24), except for a significant Test trial type x First test trial interaction, $F(1,20) = 7.35$, $p = 0.013$, $\eta_p^2 = 0.27$. Although, overall, infants' looking times were virtually identical for the novel ($M = 9.1$ s, $SD = 3.3$) and familiar orders ($M = 9.2$ s, $SD = 4.3$) in test trials, $F(1,20) < 1$, $p = 0.83$ (see Table 1), LSD post hoc comparisons revealed that differences in looking times for familiar and novel test trials were marginally significant only for infants who received the novel test trial first, with longer looking to novel ($M = 10.8$ s, $SD = 4.3$) than to familiar ($M = 8.7$ s, $SD = 2.7$; $p = 0.051$) trials (Fig. 3).

The failure to discriminate numerical order at test was confirmed by separate paired t-tests (two-tailed) for each habituation condition: in the increasing habituation condition infants' looking times to the decreasing (novel) order at test ($M = 8.6$ s, $SD = 4.5$) were identical to their looking times to the increasing (familiar) order ($M = 8.4$ s, $SD = 3.1$; $t < 1$, $p = 0.86$); in the decreasing habituation condition, looking times to the increasing (novel) order ($M = 9.9$ s, $SD = 4.1$) were also identical to the looking times to the decreasing (familiar) order ($M = 9.8$ s, $SD = 3.3$; $t < 1$, $p = 0.94$). Only 5 out of 12 infants in both the increasing (sign test: $z = 0.29$, $p = 0.77$; Wilcoxon signed-rank test: $z = 0.47$, $p = 0.64$), and the decreasing habituation conditions (sign test: $z = 0.29$, $p = 0.77$; Wilcoxon signed-rank test: $z = 0.08$, $p = 0.94$) showed a novelty preference at test.

In Experiment 1, where changes in numerosity followed a 1:2 ratio, infants did not show a reliable ability to discriminate numerical ordinal directions, and no asymmetry was found either, as infants failed in both the increasing and decreasing habituation conditions. However, it is possible that such failure depended on infants' poor discrimination of numerical information and not to their inability to detect and represent numerical order per se. Since acuity for number discrimination increases with age, from a required 1:3 ratio at birth (Izard et al., 2009) to a 1:2 ratio at 6 months of age (Xu & Spelke, 2000), it might be possible that 4-month-old infants needed a larger ratio to encode numerical order and show successful discrimination of order inversion at test. Therefore, a new group of infants was tested in Experiment 2, in which the ratio difference between the numerical displays was increased to 1:3.

Table 1
Looking times (in seconds) during Novel and Familiar test trials (3 pairs) for infants habituated to increasing or decreasing numerical sequencing, separately for each Experiment. Note that in Experiment 1 the ratio was 1:2, while in Experiments 2 and 3 the ratio was 1:3.

Experiment		Habituation type		Test pairs					
				Pair 1		Pair 2		Pair 3	
				Familiar	Novel	Familiar	Novel	Familiar	Novel
1	Ratio 1:2	Increasing	Mean	8.68	8.20	8.69	9.18	7.77	8.53
			SEM	1.65	1.58	1.72	2.79	1.39	1.56
		Decreasing	Mean	10.08	11.62	11.08	10.30	8.22	7.66
			SEM	1.48	2.07	2.92	2.35	1.62	1.51
2	Ratio 1:3	Increasing	Mean	9.39	12.52	5.58	10.07	6.64	8.66
			SEM	1.69	2.39	1.44	3.20	0.89	1.48
		Decreasing	Mean	17.28	16.43	7.00	9.01	7.32	6.36
			SEM	3.45	3.12	1.37	2.88	2.98	0.66
3	Ratio 1:3	Increasing	Mean	5.84	10.28	3.79	4.66	4.71	6.27
			SEM	1.23	2.40	0.59	0.90	0.72	1.01
		Decreasing	Mean	6.13	8.91	3.78	4.99	6.70	4.08
			SEM	0.96	1.84	0.62	0.93	1.56	1.07

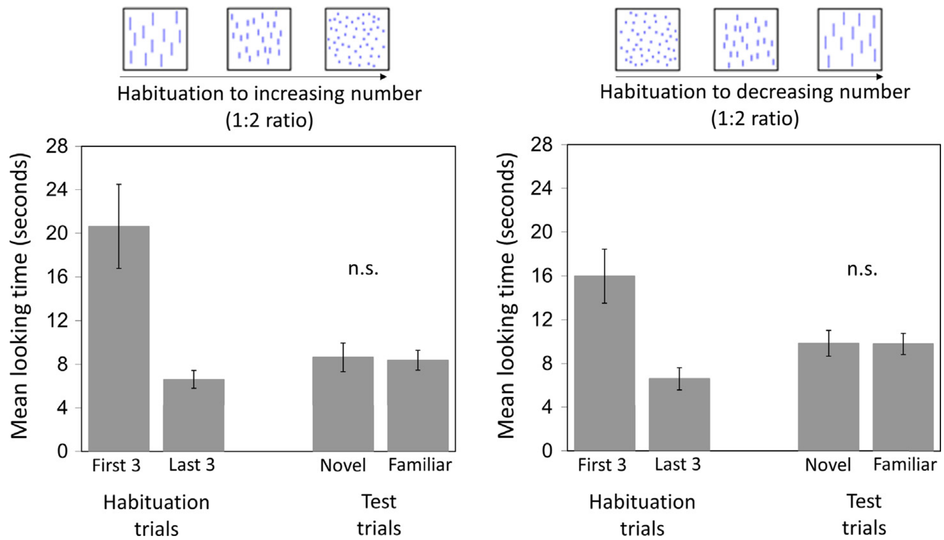

Fig. 3. Mean total looking time (±SE) in Experiment 1 to the first three and last three habituation trials and to familiar and novel test trials for infants in the increasing (left) and decreasing (right) habituation conditions. Numerical displays differed by a 1:2 ratio.

3. Experiment 2 (1:3 ratio)

In Experiment 2, infants were habituated to either increasing or decreasing numerical sequences, and were tested with new sequences displaying both the familiar and the novel orders in alternation. The ratio difference between numerical displays contained in the increasing and decreasing sequences was 1:3.

3.1. Methods

Apparatus, design and procedure were the same as in Experiment 1, with the exception that the numerical values in each sequence differed from one another by a 1:3 ratio.

3.1.1. Participants

Twenty-four healthy, full term 4-month-old infants (M age = 4 - months, 19 days; range = 4 months, 4 days – 4 months, 30 days; 14 female) took part to this experiment. Twelve additional infants were excluded from the final sample because they failed to complete testing due to fussiness or lack of interest (n = 11; 5 in the increasing and 6 in the decreasing habituation condition), or looking times in at least one test trial more than 3 SD from the overall group mean (n = 1).

3.1.2. Stimuli

The first set of habituation stimuli was composed of 4, 12, 36 items, the second of 6, 18, 54 items, and the third one of 8, 24, 72 items. The set of stimuli presented in the test phase was composed of 5, 15, 45 items. Thus, the number of items contained in each sequence increased or decreased by a 1:3 ratio (Fig. 4).

As in Experiment 1, non-numerical continuous variables were controlled by keeping cumulative surface area and contour length constant within each habituation set. The heights of the single items in the smaller, medium and larger numerosity display were, respectively, 8.3, 2.6, and 0.7 cm in the first two sets, and 7.0, 2.2, and 0.6 cm in the third set, with the width constant at ≈0.2 cm. For all sets the area of each habituation display was held constant at approximately 261 cm^2, so that number covaried with density. For test sets, cumulative surface area and contour length were positively correlated with number. Item size was kept constant (0.3 cm × 0.7 cm) while the display size varied across numbers, so that density was held constant at 0.17 elements per cm^2. This way, the continuous, non-numerical variables that varied during habituation were held constant during test, and vice versa.

3.1.3. Design and procedure

Intercoder agreement between the two observers who coded the data live or from digital recording, as computed on total fixation times on each of the six test trials, was very robust (r = 0.99, Pearson correlation; 0.99 Intra-Class Correlation coefficient).

3.2. Results and discussion

An ANOVA with habituation condition (increasing vs. decreasing) as the between-subjects factor, and habituation trials (first three vs. last three) as the within-subjects factor revealed a significant effect of habituation trials, $F(1,22) = 173.75$, $p < 0.001$, due to average looking time on the first three habituation trials ($M = 14.6$ s) being significantly longer than average looking time on the last three habituation trials ($M = 5.3$ s). Neither the effect of habituation condition $F(1,22) = 2.42$, $p = 0.13$, nor the interaction involving this factor, $F < 1$, n.s., were significant. No differences in overall looking time and number of trials to habituate were found across the two habituation conditions: For the increasing numerical sequences, infants required an average of 56.7 s and 6.3 trials to habituate; for the decreasing numerical sequences, infants required 72.9 s and 6.3 trials (unpaired t-tests, both *ts* < 1.6, n.s., two-tailed).

To assess discrimination of numerical order at test, an ANOVA with habituation condition (increasing vs. decreasing) and first test trial (familiar vs. novel) as between-subjects factors, and trial pair (first vs. second vs. third) and test trial type (familiar vs. novel ordinal direction) as within-subjects factors was performed on total looking times during test trials. There was a significant main effect of trial pair, $F(2,40) = 12.1$, $p < 0.001$, due to a decrease in overall looking times across the three pairs of test trials (first pair, $M = 13.9$ s, $SD = 8.8$; second pair, $M = 7.9$ s, $SD = 6.7$; third pair, $M = 7.2$ s, $SD = 4.3$). Critically, there was also a main effect of test trial type, $F(1,20) = 6.2$, $p = 0.02$, $\eta_p^2 = 0.24$, which was qualified by a significant Test trial type x Habituation condition interaction, $F(1,20) = 5.7$, $p = 0.02$, $\eta_p^2 = 0.22$. Infants looked overall longer to the novel ($M = 10.5$ s, $SD = 5.9$) than to the familiar ($M = 8.9$ s, $SD = 5.4$) order across the three test trial pairs, but this was true only for infants habituated to the increasing order (familiar order,

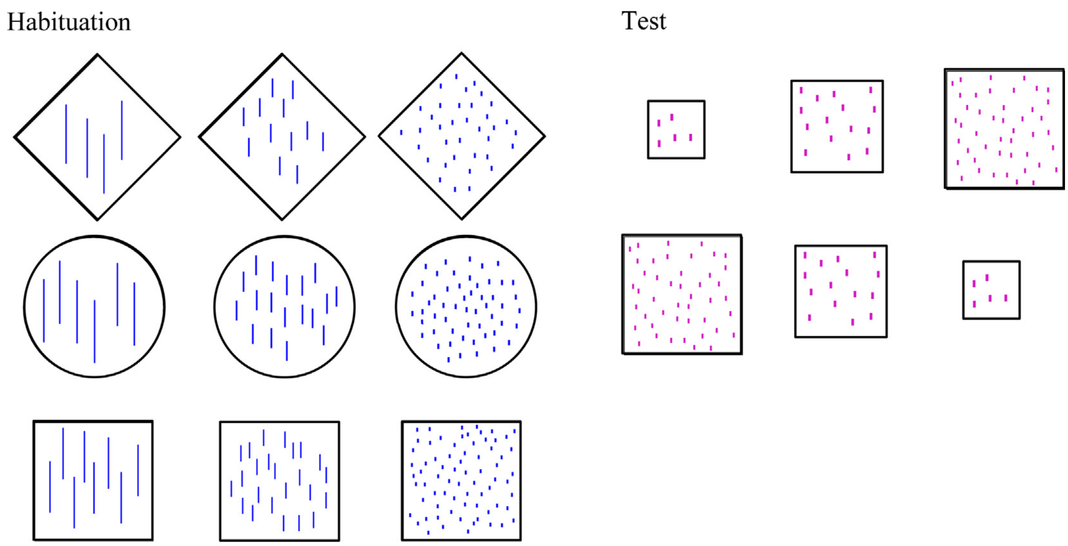

Fig. 4. Examples of the stimuli presented in Experiment 2, including the three stimuli set used in habituation (left) and the stimuli used in test (right). In habituation, numerical displays within a given numerical sequence had the same background shape (rhomboid, circular, squared). Numerical displays differed by a 1:3 ratio.

M = 7.2 s, *SD* = 3.2 vs. novel order, *M* = 10.4 s, *SD* = 5.4; *p* = 0.002, LSD post hoc tests), not for those habituated to the decreasing order (familiar order, *M* = 10.5 s, *SD* = 6.7 vs. novel order, *M* = 10.6 s, *SD* = 6.5; *p* = 0.9) (see Table 1). No other effects or interactions were significant, all *ps* > 0.06 (Fig. 5).

The presence of the asymmetry was confirmed by a series of paired t-tests (two-tailed) within each habituation condition: again, infants habituated to the increasing order looked significantly longer at the decreasing (novel) order (*M* = 10.4 s, *SD* = 5.4) than to the increasing (familiar) order at test (*M* = 7.2 s, *SD* = 3.2; *t* = 3.53, *p* = 0.004); in contrast, infants habituated to the decreasing order looked equally long to the increasing (novel) order (*M* = 10.6 s, *SD* = 6.5) and to the decreasing (familiar) order (*M* = 10.5 s, *SD* = 6.7; t < 1, *p* = 0.94). This novelty preference in the increasing habituation condition was shown by 11 of the 12 infants (sign test: *z* = 2.6, *p* = 0.009; Wilcoxon signed-rank test: *z* = 2.9, *p* = 0.002), while it was shown only by 7 of the 12 infants in the decreasing habituation condition (sign test: *z* = 0.29, *p* = 0.77; Wilcoxon signed-rank test: *z* = 0.39, *p* = 0.69).

Results of Experiment 2 show that at 4 months of age infants reliably discriminate numerical order provided that the numerical displays differ by a 1:3 ratio, and the sequence is organized in an increasing order. When considered together with an earlier demonstration that 4-month-old infants can order surface area in size-based sequences (Macchi Cassia et al., 2012), these findings support the idea of a common, or at least parallel, development of the ability to extract ordinality from both discrete and continuous quantity dimensions. Moreover, the finding that the asymmetry signature previously found for the dimension of size, with successful discrimination of increasing order but failure with decreasing order (Macchi Cassia et al., 2012), is also present for the dimension of number, shows that a common processing constraint characterizes ordinal representation for both number and size.

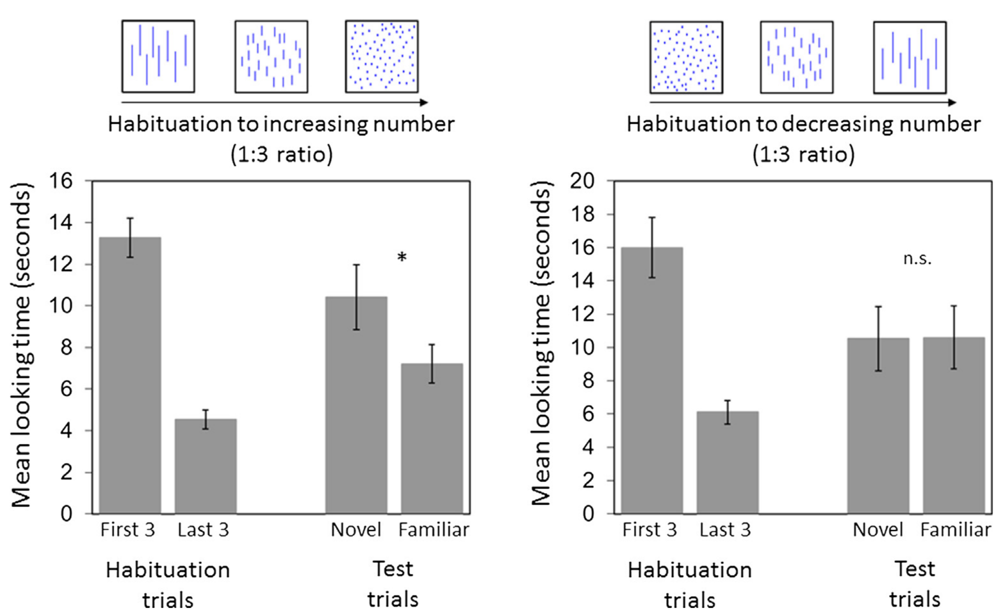

Fig. 5. Mean total looking time (±SE) in Experiment 2 to the first three and last three habituation trials and to familiar and novel test trials for infants in the increasing (left) and decreasing (right) habituation conditions. Numerical displays differed by a 1:3 ratio.

In order to strengthen our claims, we conducted Experiment 3 so as to replicate the presence of the asymmetry in numerical order discrimination at 4 months of age. We employed the same 1:3 ratio as in Experiment 2, but the numerosities considered changed slightly: the ratio of the numerical variations across habituation trials was raised to 1:2, and the numerosities used in the test trials were larger than in Experiment 2.

4. Experiment 3 (1:3 ratio; replica with different numerosities)

Experiment 3 was conducted to replicate the findings of Experiment 2. We used the same ratio as in Experiment 2 for within-trials variations (i.e., 1:3), but the chosen numerosities partially differed from Experiment 2: we employed a new set of numerical items in the habituation phase, as well as a new set of numerical items in the test phase.

4.1. Methods

Apparatus, design, procedure, and ratio were the same as in Experiment 2, with the exception that one set of habituation and test stimuli were composed of different items.

4.1.1. Participants

Twenty-four healthy, full term 4-month-old infants (M age = 4 - months, 14 days; range = 3 months, 29 days – 5 months, 9 days; 14 female) took part in this experiment. Three additional infants were excluded from the final sample because of being uncooperative.

4.1.2. Stimuli

The first set of habituation stimuli was composed of 4, 12, 36 items, the second of 8, 24, 72 items, and the third one of 16, 48, 144 items. The set of stimuli presented in the test phase was composed of 9, 27, 81 items (Fig. 6). Thus, the number of items contained in each sequence increased or decreased by a 1:3 ratio as in Experiment 2. As in Experiments 1 and 2, non-numerical continuous variables were controlled by keeping cumulative surface area and contour length constant within each habituation set. The heights of the single items in the smaller numerosity display were 8.3, 2.6, and 0.7 cm; in the medium numerosity display 7.0, 2.2, and 0.6 cm; in the larger numerosity display 8, 2.5, 0.5 cm. The width was kept constant at ≈0.2 cm in all displays, and the area of each habituation display was held constant at approximately 261 cm^2, so that number covaried with density. For test sets, cumulative surface area and contour length were positively correlated with number. Item size was kept constant (0.2 cm × 0.5 cm) while the display size varied across numbers, so that density was held constant at 0.17 elements per cm^2. This way, the continuous, non-numerical variables that varied during habituation were held constant during test, and vice versa.

4.1.3. Design and procedure

Intercoder agreement between the two observers who coded the data live or from digital recording, as computed on total fixation times on each of the six test trials, was very robust (r = 0.99, Pearson correlation; 0.99 Intra-Class Correlation coefficient).

4.2. Results and discussion

An ANOVA with habituation condition (increasing vs. decreasing) as between-subjects factor, and habituation trials (first three vs. last three) as within-subjects factor revealed a significant effect of habituation trials, $F(1,22) = 20.598$, $p < 0.001$, due to average looking time on the first three habituation trials ($M = 11.1$ s) being significantly longer than average looking time on the last three habituation trials ($M = 4.2$ s). Neither the effect of habituation condition, nor the interaction involving this factor, were significant, both $Fs < 0.1$, n.s. No differences in overall looking time and number of trials to habituate were found across the two habituation conditions: For the increasing numerical sequences, infants required an average of 57.7 s and 9.3 trials to habituate; for the decreasing numerical sequences, infants required 60.1 s and 7.5 trials (unpaired t-tests, both $ts < 1.5$, n.s., two-tailed).

To assess discrimination of numerical order at test, an ANOVA with habituation condition (increasing vs. decreasing) and first test trial (familiar vs. novel) as between-subjects factors, and trial pair (first vs. second vs. third) and test trial type (familiar vs. novel ordinal direction,) as within-subjects factors, was performed on total looking times during test trials. There was a significant main effect of trial pair, $F(2,40) = 6.03$, $p = 0.005$, $\eta p^2 = 0.23$, due to the higher looking times in the first pair of test trials (first pair, $M = 7.8$ s, $SD = 5.2$; second pair, $M = 4.3$ s, $SD = 2.5$; third pair, $M = 5.4$ s, $SD = 3.6$). Critically, there was a main effect of test trial type, $F(1,20) = 10.77$, $p = 0.004$, $\eta p^2 = 0.25$, which was qualified by a significant Test trial type x Habituation condition interaction, F

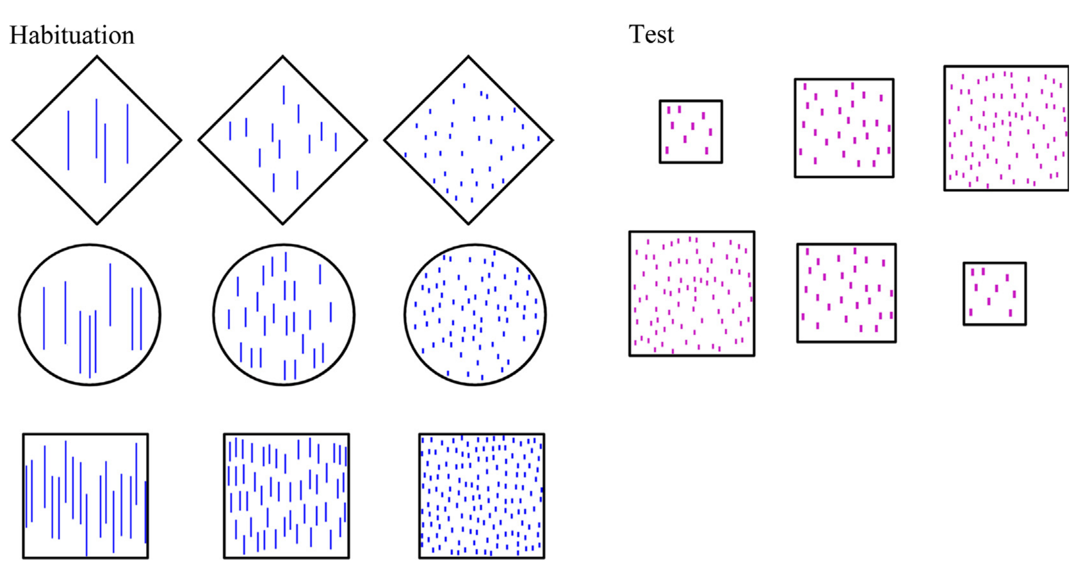

Fig. 6. Examples of the stimuli presented in Experiment 3, including the three stimuli set used in habituation (left) and the stimuli used in test (right). In habituation, numerical displays within a given numerical sequence had the same background shape (rhomboid, circular, squared). Numerical displays differed by a 1:3 ratio.

(1,20) = 4.76, $p = 0.041$, $\eta p^2 = 0.19$. Infants looked significantly longer to the novel ($M = 6.5$ s, $SD = 3.4$) than to the familiar ($M = 5.1$ s, $SD = 2.4$) order at test, but this was true for infants habituated to the increasing order only (familiar order, $M = 4.8$ s, $SD = 2.6$ vs. novel order, $M = 7.1$ s, $SD = 4.2$; $p < 0.001$, LSD post hoc tests). Those habituated to decreasing order looked equally long to both orderings at test (familiar order, $M = 5.5$ s, $SD = 2.3$ vs. novel order, $M = 6$ s, $SD = 2.5$; $p = 0.45$) (Fig. 7). The interaction between Test trial type × Trial pair was also significant, $F(2,40) = 4.7$, $p = 0.015$, as the difference between looking times towards familiar and novel ordering at test, overall for both habituation conditions considered together, was significant only for the first pair of test trials (familiar, $M = 6.0$ s, $SD = 3.9$ vs. novel, $M = 9.6$ s, $SD = 7.6$, $p < 0.001$ LSD post hoc tests) but not for the second (familiar, $M = 3.8$ s, $SD = 2.1$ vs. novel, $M = 4.8$ s, $SD = 3.3$, $p = 0.3$) or the third pair (familiar, $M = 5.7$ s, $SD = 4.4$ vs. novel, $M = 5.2$ s, $SD = 3.8$, $p = 0.6$) (see Table 1). No other effects or interactions were significant, all $ps > 0.2$.

The presence of the asymmetry in infants' discrimination performance at test was confirmed by a series of paired t-tests (two-tailed) within each habituation condition: infants habituated to the increasing order looked significantly longer to the decreasing (novel) order ($M = 7.1$ s, $SD = 4.2$ s) than to the increasing (familiar) order ($M = 4.8$ s, $SD = 2.6$; $t = 3.19$, $p = 0.009$), while infants habituated to the decreasing order looked equally long to the increasing (novel) order ($M = 6$ s, $SD = 2.5$) and to the decreasing (familiar) order ($M = 5.5$ s, $SD = 2.3$; $t < 1.5$, $p = 0.23$). The novelty preference in the increasing habituation condition was shown by 10 of the 12 infants (sign test: $z = 2$, $p = 0.04$; Wilcoxon signed-rank test: $z = 2.4$, $p = 0.01$), while it was shown only by 7 of the 12 infants in the decreasing habituation condition (sign test: $z = 0.29$, $p = 0.77$; Wilcoxon signed-rank test: $z = 0.47$, $p = 0.64$).

Results of Experiment 3 closely replicate those found in Experiment 2 when using slightly different numerosities, and provide further evidence that at 4 months of age infants reliably discriminate numerical order when the difference between numerosities follows a 1:3 ratio, and, most critically, when the sequence is organized in an increasing order. Together with Experiment 2, these findings support the idea of an early asymmetry in the understanding of numerical order, with successful discrimination of increasing order and a failure to discriminate decreasing order.

5. General discussion

This study investigated the ability to represent and discriminate increasing versus decreasing numerical sequences in early infancy. The results show that, at least from 4 months of age, infants can discriminate numerical order, provided that numerical differences are large enough (i.e., a 1:3 ratio in the present study) and, most important, that changes in numerosity follow an increasing order. This pattern of results is not related to differences in the amount of information available during the habituation phase, as infants received a comparable number of trials and looked for equal amounts of time before being presented with the testing phase. Although one might argue that, in order for infants in the increasing habituation condition to successfully discriminate between the familiar and novel sequences at test successful abstraction of decreasing order must occur, we think this is not the case. Infants might discriminate increasing from decreasing order at test without truly representing the ordinal information conveyed by the decreasing test sequence. The decreasing sequence might be in fact simply represented as a collection of different numerical sets, with no encoding of the directionality of the change. Indeed, in the case of size ordering, it has been shown that 4-month-olds fail to discriminate a sequence in which the size of an object consistently decreases from a sequence where the same size values follow no consistent directional change (Macchi Cassia et al., 2012). While the magnitude differences between the numerical displays in the decreasing condition of the current study were probably successfully processed, the ordinal information contained in the progressive changes was not encoded.

The ratio-dependent performance across experiments (1:2 in Experiment 1 vs. 1:3 in Experiments 2 and 3) reinforces the view that discrimination involved in this task was supported by the ANS, whose main processing signature is that discrimination follows Weber's law (Dehaene et al., 1999). Indeed, although 4-month-old infants in this study needed a 1:3 ratio (i.e., the same ratio required by newborns) to discriminate increasing numerical sequences, results do not imply that infants at this age need the same numerical difference as newborns in order to successfully discriminate two numerical quantities. Although no study has tested for this possibility, it is plausible that acuity for numerical discrimination significantly increases during the first four months

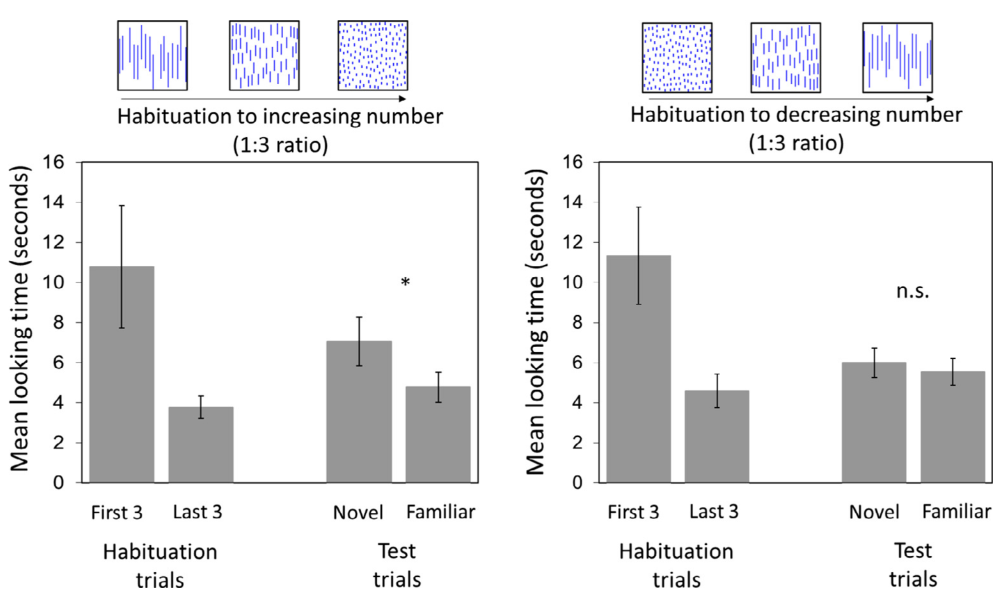

Fig. 7. Mean total looking time (±SE) in Experiment 3 to the first three and last three habituation trials and to familiar and novel test trials for infants in the increasing (left) and decreasing (right) habituation conditions. Numerical displays differed by a 1:3 ratio.

of life from a 1:3 ratio (e.g., 4 vs. 12) to a ratio slightly larger than 1:2, as for instance 1:2.5 (e.g., 4 vs. 10). Available studies show that 6-month-old infants succeed at discriminating 1:2 ratio numerical differences (Xu & Spelke, 2000); that is, we cannot exclude that 4-month-olds could successfully discriminate numerosities differing by the same ratio under specific conditions, such as an exposure time to the numerical displays longer than the one used in the present study (i.e., 1750 ms). In fact, it has been shown that 4- to 5-month-old infants can discriminate two numerosities differing by a 1:2 ratio provided that numerical displays are presented for 2 s, but not when the displays are presented for a shorter time (i.e., 1 s or 1.5 s; Wood & Spelke, 2005).

Of note, in previous studies on size-based ordinal discrimination with 4-month-old infants, a 1:2 ratio difference was enough for obtaining successful discrimination under the same testing conditions (i.e., stimulus duration) used in the present study (Macchi Cassia et al., 2012). Therefore, current results suggest that acuity in magnitude discrimination is lower for number than size at 4 months of age. Indeed, although infant research has advocated for similar ratio signatures during the first year of life for number and size (Brannon, Lutz, & Cordes, 2006; Feigenson, 2007), it is possible that subtle differences in processing these two quantitative dimensions remained undetected in previous studies. This is plausible in light of recent demonstration that the developmental trajectory of the acuity of 3- to 6-year-old children's representations of number and size differs in important respects, such that size representations have higher acuity than number representations and improvements in acuity occur more quickly for size than number (Odic, Libertus, Feigenson, & Halberda, 2013). On the basis of the present and previous findings, it could be claimed that infants compute ordinal operations by manipulating differentially developed representations of quantity (for number and size separately) while both sharing common ordinal signatures.

With regard to infants' sensitivity to discrete and continuous dimensions, one could claim that infants' performance in the current study was not based on them attending solely to the dimension of number, but also to other continuous dimensions. Indeed, it might be possible that during habituation infants were attending to changes in density across the displays (as habituation displays differed in density as well as in number), and were then mapping the directionality of those changes to physical size during test (as test displays differed in the size of the enveloping area as well as in number). However, we favor the interpretation of infants' performance in terms of numerical processing. In fact, infants' studies have shown that, when number is pitted against continuous variables, such as cumulative surface area, infants spontaneously attend to numerical information (Brannon, Abbott, & Lutz, 2004; Cordes & Brannon, 2009). Moreover, when infants are presented with sets of discrete items, as in the present study, they not only favor number over elements' size, contour length, and/or cumulative surface area in their response, but also show greater sensitivity to changes across the former dimension than across the latter ones (Cordes & Brannon, 2011; Libertus, Starr, & Brannon, 2014). In light of this evidence, we view the interpretation of infants' performance in the current study as based on their processing of numerical changes, which remains available between both the habituation and the test phases, as the most parsimonious.

Irrespective of whether infants attended solely to number or also to other continuous dimensions, the present study provides new evidence on the developmental origins of the ability to represent ordinal information in human infants. By employing non-symbolic numerical displays, our findings indicate that discrimination of ordinal numerical sequences is present at 4 months of age, as it does for the dimension of size. This supports the view of a common (or at least parallel) development of the ordinal ability for these two dimensions of magnitude (number and size). Future studies investigating this ability in human newborns could determine whether there is an initial advantage for discriminating order in any of these dimensions at birth. In any event, the present study adds to previous evidence suggesting that at 4 months, the earliest age at which this ability has been tested, infants display the ordinal ability for both number and size dimensions. The view of a common development of the ordinal ability is in line with evidence showing that the intraparietal sulcus (IPS) is involved in the processing of both numerical order and size-based ordinal sequences in children (Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009), and that the internal structure of children's conception of different ordered sequences (numbers, letters, months) is the same, such that an initial logarithmic mapping shifts gradually towards a linear one across numerical and non-numerical sequences (Berteletti, Lucangeli, & Zorzi, 2012).

This study shows, most crucially, that sensitivity to ordinal relations in non-symbolic numbers at 4 months of age is characterized by the signature of asymmetry, that is, the advantage for processing increasing over decreasing magnitudes. Since this asymmetry has been previously reported in size discrimination, this result supports the view of a common processing signature of ordinal discrimination for size and number at this age. The asymmetry in infants' sensitivity to non-symbolic ordinal information has been also reported in non-human animals; studies with monkeys report an advantage for increasing over decreasing order, such that monkeys are able to generalize to new numbers a previously learned increasing order, but they fail this generalization for decreasing order (Brannon & Terrace, 2000). Of note, the advantage for increasing over decreasing order is not apparent by the time human infants are aged 7–9 months, neither for the dimensions of number (de Hevia & Spelke, 2010; Picozzi et al., 2010), nor for size (de Hevia & Spelke, 2010; Srinivasan & Carey, 2010). It is still plausible, however, that the asymmetry signature might be at the roots of related cognitive operations mediated by the ANS, operations that carry in their performance pattern the computational attributes of this system.

In fact, as previous reports of an asymmetry in ordering size by 4-month-olds have suggested (Macchi Cassia et al., 2012), this phenomenon might be a developmental precursor of the easiness of addition relative to subtraction, as reflected in arithmetical performance from childhood to adulthood (Barth et al., 2008; Campbell & Xue, 2001). With large non-symbolic sets, adults and young children are more accurate with addition than with subtraction problems (Barth et al., 2006; Kamii, Lewis, & Kirkland, 2001). The 'addition advantage' in symbolic arithmetic has been explained by the fact that more time is allowed in formal education to addition problems, as addition and subtraction are taught hierarchically. Addition is indeed considered the foundation for subtraction, and the processing of counting-down for subtraction is commonly more time-consuming that the processing of counting-up for addition (Baroody, 1984; Canobi, 2005; Carpenter & Moser, 1984; Fuson, 1984). Other researchers have interpreted this phenomenon as due to differences in the variance associated to the numerical representations, and not necessarily to an intrinsic difficulty in subtraction compared to addition: for a given quantity (e.g., 5), the representation is fuzzier when it is the result of a subtraction relative to an addition, as variance associated to each operand is added up (e.g., 10–5 vs. 3 + 2) (Barth et al., 2006).

We believe that both factors, i.e., variability in counting and fuzziness, might account for this phenomenon only partially, as other early cognitive constraints that precede counting skills and formal education might underlie this phenomenon. On the one hand, young children's performance in arithmetical operations (addition and subtraction) with large non-symbolic numbers seems to be independent from counting abilities, and heavily relies on the ANS (Shinskey et al., 2009; Slaughter, Kamppi, & Paynter, 2006). On the other hand, when the variance of the numerical sets is controlled for, performing addition seems to be as easy as performing a simple comparison, but performance in subtraction is still worse than in a simple comparison (Gilmore & Spelke, 2008). In fact, the variance associated to the different numerical displays in the present study is exactly the same for both orderings, as both increasing and decreasing orders contain the same numerosities, the only difference being the direction of numerical change. The fact that representing the decrease in numerical magnitude is harder that the reverse in the first months of life might be at the origins of the addition advantage, or it might share with it common psychological roots. Since the asymmetry signature might constitute a processing constraint of the ANS characterizing the ordering of numerical representations, this signature might permeate cognitive tasks that rely on such system.

There is indeed evidence that the specific order in which quantities are processed strongly impacts adults' performance in comparison tasks. In particular, adults exhibit the so-called 'ascending order advantage', which reflects higher performance in comparing two quantities when the smaller is temporally followed by the larger one (increasing order), relative to when the smaller is temporally preceded by the larger one (decreasing order) (Müller & Schwarz, 2008). This effect has been shown for numerical quantities (Müller & Schwarz, 2008), physical size (Ben-Meir, Ganor-Stern, & Tzelgov, 2013), and even fractions (Ganor-Stern, 2015). Although initially thought to reflect established counting habits that create forward associations between consecutive numbers (Müller & Schwarz, 2008), evidence showing that it extends to physical size and fractions undermines this interpretation. A more ecological view known as 'Embodied Arithmetic' has proposed that the increasing order advantage might emerge from extensive experience with natural objects that grow in size across time, such that associations of the type 'early in time-small size' and 'later in time-larger size' are created (Lakoff & Núñez, 2000). Nonetheless, our study provides evidence that the advantage for increasing order for numerical sequences is present at an age when infants have had a relatively limited exposure to the growing dynamics of natural objects. It is therefore plausible that this phenomenon might find its roots in our evolutionary history.

In fact, from an evolutionary perspective, the advantage for increasing vs. decreasing order might have been selected because it is relevant for survival. The ability to successfully detect and keep track of increasing number and/or increasing size might be critical in ecological contexts: a progressively approaching object and/or an increasing number of predators is more harmful than the progressive decreasing in their number/size. However, this idea should be put to test. Another possibility is related to the ability that humans and non-human animals possess from very early in life to perceive impending collision and react defensively to a stimulus that is approaching but not to one that withdraws from viewer's location (Ball & Tronick, 1971; Schiff, Caviness, & Gibson, 1962). Human infants from the first weeks of life react defensively to a 'looming' (expanding) stimulus by blinking and withdrawing their heads, as this type of display optically signals approach, but they do not react with avoidance to a 'zooming' (contracting) stimulus as it signals a receding object (Ball & Tronick, 1971; Náñez, 1988). Moreover, looming stimuli enhance infants' detection and reaction towards increasing stimuli (Walker-Andrews & Lennon, 1985), and continue to exert similar effects into adulthood (Cléry, Guipponi, Odouard, Wardak, & Ben Hamed, 2015). We propose that, as a result of the alerting effect associated to perceptual looming, infants might develop a processing advantage for the ordinal information embedded in looming stimuli (which entail increasing order), whereas this enhancement might not emerge for the information of ordinality associated to zooming stimuli (which entail decreasing order). This would explain why, even in the absence of objective looming stimuli (as they are absent in this and in an earlier study by Macchi Cassia et al. (2012)), processing of increasing magnitude is enhanced and/or privileged in 4-month-old infants. Therefore, we suggest that the looming/zooming phenomena might be at the roots of the asymmetry signature in ordinal processing (i.e., advantage for increasing relative to decreasing), both for ordinality in size (even when the looming/zooming effects are controlled for), as found in Macchi Cassia et al. (2012) study, and for ordinality in number, as found in the present study.

In order to fully understand both the origins and the developmental course of ordinal understanding, future research will have to establish whether all continuous dimensions (e.g., time, luminance or loudness), which by their nature are intrinsically ordered, show the same asymmetry signature described in infants and adults for physical size (Ben-Meir et al., 2013; Macchi Cassia et al., 2012) and number (Müller & Schwarz, 2008; current study). While it is possible that all magnitude dimensions share this signature from the earliest stages of development, it is also possible that the advantage for increasing order is a unique property of a specific dimension, like number and/or size, and generalizes to other similarly structured magnitude dimensions during development. However, this generalization is likely to take place after the first year of life. In fact, although ordinal information can be generalized from sets of numerosities to sets of line lengths at 8 months (de Hevia & Spelke, 2010), infants at this same age fail to generalize order from numerical sequences to sequences that contain changes in luminance intensity (de Hevia & Spelke, 2013), or from changes in size to changes in loudness (Srinivasan & Carey, 2010), suggesting that the dimensions of number, luminance, size and loudness do not all share an abstract sense of ordinality early in development.

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