**UNIVERSITÀ DEGLI STUDI di MILANO-BICOCCA**

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# ORDINAL KNOWLEDGE AND SPATIAL CODING OF CONTINUOUS AND DISCRETE QUANTITIES IN INFANCY

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# INTRODUCTION

An important issue in human cognition concerns the origins and nature of the capacity to represent number. Number represents a particularly interesting arena for the nature-nurture debate, because on the one hand, number is an abstract concept that is taught to children starting in the pre-school years and continuing through further education, but, on the other hand, even nonhuman animals show an impressive understanding of quantity, especially with respect to food caches and predators.

Over the past two decades, many studies have explored the extent of infants' numerical knowledge and have sought to determine the earliest ages at which infants can demonstrate some understanding of number in order to answer the question about what do very young infants know about number and clarify the origins of adults' numerical knowledge.

A great deal of research has focused on infants' comprehension of the cardinal properties of number, that is the ability to extract and represent numerical magnitudes, and to appreciate the numerical equivalence of sets whose members can be placed into one-to-one correspondence. Another essential component of the concept of number is ordinality, which refers to the inherent "greater than" or "less than" relationships between numbers. Until recently, the development of this aspect of human numerical cognition in infancy had received little attention.

Specifically, only three studies have directly investigated ordinal numerical knowledge in preverbal infants, providing mixed results on the age of its first appearance, and thus dating the onset of this ability around 9 months of age for non-numerical magnitudes (Brannon, 2002) and around 11 months of age for numerical visual arrays (Brannon, 2002; Suanda, Tompson, & Brannon, 2008).

Nevertheless, recent findings have demonstrated that by 2 months of age infants are able to detect defined temporal patterns in simple visual sequences composed of different stimuli (Kirkham, Slemmer, & Johnson, 2002) and that between 4 and 8 months infants became capable of learning serially organized visual item sequences (Lewkowicz, 2004). The ability to detect the ordinal information embedded in a series of sequentially presented numerical displays implies the ability to associate numerical and temporal information. The aim of the current series of studies was to investigate whether the ability to appreciate ordinal relationships between numerical magnitudes is present in preverbal infants at an earlier age than previously reported (Brannon, 2002; Suanda et al., 2008).

The current investigation thus includes a series of 6 experiments conducted with infants of 4 and 7 months of age. Using an infant-controlled habituation paradigm, as in the studies by Brannon (2002) and Suanda et al. (2008), we tested 4-month-olds with ascending and descending visual sequences of non-numerical magnitudes (continuous quantities), in order to verify if the ability to extract ordinal relationships is already in place at this age (Exp. 1). Results surprisingly showed that only infants habituated to ascending sequences successfully detected the reversal in the ordinal direction. Infants habituated to descending ordered sequences, instead, did not discriminate between familiar and novel order sequences, suggesting that it is more difficult to abstract and represent the ordinal rule in the context of descending sequences as compared to the ascending sequences. Thus, in Exp. 2 we tested a second group of 4-month-olds for their ability to discriminate between descending and non-ordered sequences, in order to clarify whether infants are at least able to discriminate between an ordered descending sequence and a non–ordered, random sequence in test trials. Results interestingly showed that 4-month-olds did not discriminate between the familiar and novel test trials, suggesting that, at this age, infants cannot appreciate the difference between a descending sequence and a non-ordered sequence. Together with the results from Exp. 1, these findings demonstrate that by the age of 4 months infants are able to grasp ordinal information, however they successfully discriminate the reversal in the direction of the ordinal relationships embedded in test sequences only if they were previously exposed to ascending sequences. However, the evidence provided from Exp. 1 and 2 do not allow us to definitively conclude that infants at this age are really able to grasp ordinal information embedded in ascending sequences without excluding the hypothesis that successful discrimination obtained in Exp. 1 was driven by the detection of qualitative perceptual changes between the ascending and descending sequences. This hypothesis was tested in Exp. 3 by investigating whether 4-month-olds are able to represent the ordinal relations between continuous magnitudes that are controlled for any zooming/looming perceptual effects. Results demonstrated that infants did show a novelty preference only when the reversal in the ordinal direction is presented in the first test trial. We interpreted the lack of an overall novelty preference in the current experiment as resulting from the low saliency of the stimuli used, which did not carry enough salient information to keep the babies engaged in the task.

In Exp. 4 we investigated whether the ability to appreciate ordinal relationships between numerical magnitudes is present at an earlier age than previously reported (Brannon, 2002; Suanda et al., 2008), when multiple sources of information (i.e. color and shape) and redundant cues to ordinality are provided throughout the task. The results demonstrate that, under these conditions, 7-month-old infants can represent numerical ordinal relations and detect reversals in ordinal direction. Given this pattern of results, in Exp. 5 we investigated the role of spatial information and tested 7 month-olds also for the presence of a basic mapping of space to number, within the same stimuli and procedure used in Exp.4. We tested the possibility that an oriented spatial-numerical link could be found in infants as young as 7 months, verifying whether the direction of the spatial information provided throughout the task, that was congruent with the direction of the mental number line, will influence the encoding of numerical information within ordinal sequences. Results showed that 7-month-olds are able to link oriented spatial codes to representations of numerical magnitude. Moreover, because infants in both habituation conditions looked longer during test to ascending sequences, that are series with the smallest number on the left and the largest on the right, in Exp. 6 we investigated whether infants' performance was effectively a manifestation of a spontaneous preference for ordinal relationships that are presented according to the direction of the mental number line. Thus, in Exp. 6 infants were presented with ascending and descending numerical sequences, from left-to-right, with previous habituation to a left-to-right sequence in which ordinal relationships were eliminated by equating the numerical values. Results did not revealed any difference in the looking time spent on the two ordinal sequences in test, suggesting that 7-month-old infants did not show a spontaneous preference for ascending sequences that are displayed following the direction of the mental number line, in accordance with small-left and large-right. We concluded that the mapping of number to space found in Exp.

5 could occur at a representational level, for that ordinal information provided through the habituation phase was indeed essential. Therefore the results from Exp.6 put in prospective the importance of the ordinal cues provided during habituation in Exp. 5, through which infants have the chance to form a representation of the two order during habituation phase. However, further investigation is needed to answer the question about whether infants spontaneously prefer ordinal relationships that are presented according to the direction of the mental number line.

Overall, the present study provided evidence for the debate about functional affordances of infants' numerical representation, demonstrating that, under certain conditions, the ability to detect and grasp ordinal information embedded in non-numerical and numerical sequences of visual stimuli could be present early in infancy, at respectively 4 months and 7 months of age. Importantly, this study provided also evidence that account for the existence of a basic mapping of number to space the presence, showing that 7-month-old infants are able to link oriented spatial codes to representations of numerical magnitude.

# CHAPTER 1: THE ORGANIZATION OF NUMERICAL KNOWLEDGE IN INFANCY

## *1.1 The "number sense"*

A number of investigators have proposed that human adults' number representations and mathematical thinking depend, at least in part, on a sense of approximate numerical magnitudes, or so-called "number sense" (Dehaene, 1997; Gallistel & Gelman, 1992). This elementary knowledge of numerical quantities and their relations is particularly important for number comparison, and is considered the precursor to the uniquely human ability to develop symbols and formal arithmetic rules through which exact numerical values can be represented (Dehaene, Dehaene-Lambertz, & Cohen, 1998).

A handful of studies have demonstrated that even non-human animals possess a "number sense" that accounts for nonverbal representation of numerical magnitudes. A wealth of research by behavioral ecologists and comparative psychologists provided evidence for capacities to represent numerosity in animals such as birds, rodents, and primates (Dehaene, 1997; Gallistel, 1990). Abilities to discriminate between sets of different numbers of items, and to base that discrimination on number, rather than on other perceptual variables, have been found in numerous experiments (Church & Meck, 1984; Pepperberg, 1987; Thomas & Chase, 1980).

Research over the past several decades has led some investigators to conclude that an ability to discriminate sets on the basis of their number is also present in preverbal human infants. Using the behavioral paradigm of visual habituation-recovery of looking time, both newborns and preverbal infants have been shown to discriminate sets of visual objects (Antell & Keating, 1983; Starkey & Cooper, 1980), as well as tones or words that differed in the number of syllables (Bijeljac-Babic, 1991), on the unique basis of their numerosity (e.g. Xu & Spelke, 2000).

Such animal and infant data, taken together, suggest that the sensitivity to the numerical aspect of the world does not depend on an acquired ability to manipulate symbols, but is based on a non-verbal amodal representation of numerosity. Moreover, all these findings had lead to the hypothesis that an elementary number system is present very early in life in both humans and animals, and constitutes the start-up tool for the development of symbolic numerical thinking (Dehaene, 1997). According to Dehaene's view, the "number sense" can be considered as part of our biological heritage, in that, as in the case of other evolutionary relevant environmental categories, such as faces (Kanwisher, 2000) or linguistic sounds (Naatanen et al., 1997), specialized regions of the brain have emerged through phylogeny for the representation and manipulation of numbers (Spelke & Dehaene, 1999).

Nevertheless, to demonstrate that human abilities for arithmetic have a biological basis, it is not sufficient to demonstrate that animals and preverbal infants possess rudimentary number processing abilities, but it is necessary to show that there are profound homologies between human and animal abilities and between adult and infant abilities that suggest a phylogenetic continuity. Two striking shared characteristics of number processing in humans and animals have been identified: the distance effect and the size effect.

### *1.2 The distance effect and the size effect*

The distance effect is a systematic, monotonous decrease in numerosity discrimination performance as the numerical distance between the numbers decreases.

The size effect indicates that for equal numerical distance, performance also decreases with increasing number size. Both effects indicate that the discrimination of numerosity, like that of many other physical parameters, obeys Fechner-Weber's Law, according to which the discriminability of two quantities is a function of their ratio(Gallistel & Gelman, 1992; Wynn, 1998).

Distance and size effects have been reported in various animal species whenever the animal must identify the larger of two numerical quantities or tell whether two numerical quantities are the same or not (review in Gallistel & Gelman, 1992). It should be noted that animals are not limited to processing small numbers only. Pigeons, for instance, can reliably discriminate 45 pecks from 50 (Rilling & McDiarmid, 1965). The number size effect merely indicates that, as the numbers get larger, a greater numerical distance between them is necessary to achieve the same discrimination level.

Number size and distance effects in human infants have not been directly tested and systematically investigated like in adults or animals, nevertheless in the last 30 years a handful of studies provided evidence suggesting the presence of both effects. It has been demonstrated that 6-month-old infants successfully discriminate between visual arrays of 8 vs. 16 visual objects (Xu & Spelke, 2000), and of 16 vs. 32 dots (Xu, Spelke, & Goddard, 2005), but they failed when displays contained 12 vs. 8 dots (Xu & Spelke, 2000). Moreover, successful discrimination of numerical arrays containing 8 vs. 12 dots has been though demonstrated in older infants, at 10 months of age (Xu & Arriaga, 2007). However, 10-month-olds failed to discriminate between visual arrays in which numerical distance was shorter 8 vs. 10 (Xu & Arriaga, 2007). All these findings can account for the presence of an analogous of the adult's distance effect. It is important to note that in these studies all the potentially confounding variables were controlled, so that displays differed only in numerosity and discrimination could not be based on the detection of perceptual variables such as the amount of contour, average brightness, element density, or display size.

An analogous of the size effect has been first demonstrated in 5-6-month-old infants, who were shown to successfully discriminate 2 versus 3 dots, but not 3 versus 4 (Starkey & Cooper, 1980). More recently, the demonstration that 6 month-old infants can discriminate 8 from 16 (distance 8) (Xu & Spelke, 2000), but not 16 from 24 (Xu et al., 2005), provided further evidence for the presence of a size effect in infancy.

The distance and size effects seem to indicate that animals and infants possess a fuzzy representation of numbers, in which imprecision grows proportionally to the number being represented. As a consequence, only very small numbers (up to about 3) generate exact representations, whereas representations of larger numerical quantities are increasingly imprecise. Superficially, this analogical mode of representation may seem to differ radically from the kind of representation that human adults use in arithmetic, because animals and preverbal infants are severely limited to elementary, approximate, and non-symbolic calculations, while adults can make symbolic calculations with arbitrary accuracy. However, distance and size effects have been extensively found also in adults, not only when representing the numerosity of object sets (Buckley & Gillman, 1974a; van Oeffelen, 1982), but even when processing Arabic digits or number words (Buckley & Gillman, 1974b; Dehaene, 1996; Dehaene, Dupoux, & Mehler, 1990; Moyer & Landauer, 1967). For instance, when comparing Arabic digits, adults are faster and more accurate at deciding that 8 is larger than 4 than that 8 is larger than 7, even after intensive training. The distance effect is found even with two-digit numerals (Dehaene et al., 1990). The number size effect relates to "subitizing", our ability to rapidly name the numerosity of a set of simultaneously presented objects when it is below 3 or 4, but not beyond (Dehaene & Cohen, 1994; Mandler & Shebo, 1982).

According to Dehaene (2001), the fact that also adults behavior obeys distance and size effects suggests two conclusions:

1) the adult human brain contains an analogical representation of numerical quantity very similar to the one observed in animals and young infants, organized by numerical proximity and with increasing fuzziness for larger and larger numbers.
2) when presented with number words and Arabic numerals, the human brain converts these numbers internally from their symbolic format to the analogical quantity representation. This internal access to quantity seems to be a compulsory step in number processing, because a distance effect is found even when subjects merely have to say whether two digits are same or different (Dehaene & Akhavein, 1995), or in priming experiments in which the mere presentation of a digit or a numeral facilitates the subsequent processing of a numerically close target number (Brysbaert, 1995; Dehaene et al., 1998;

Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; den Heyer & Briand, 1986; Koechlin, Naccache, Block, & Dehaene, 1999).

### *1.3 From the 'Triple Code Model' to the 'Core Systems of Number'*

In his "Triple Code Model", Dehaene (1992) assumes the existence of three different codes in which numbers can be mentally represented: a *visual code*, where numbers are encoded as strings of Arabic numerals; a *verbal code*, where numbers are encoded as syntactically organized sequences of words; and *an analogical-quantity code*, where numbers "... are represented as inherently variable distributions of activation over an oriented analogical number line" (Dehaene, 1992).

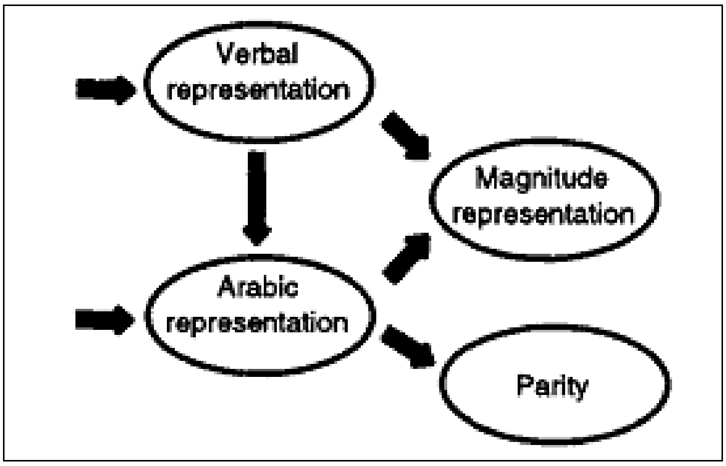



**Figure 1.1** Schematic representation of the "Triple Code Model" by Dehaene

Dehaene proposed that those three types of numerical representations coexist, directly and bidirectionally interconnected to each others. In particular the *analog code*, conceived as an inner line oriented from left to right (i.e. "mental number line") representing the numerosities from small to large, can be conceived as the semantic representation of magnitude because it contains the semantic information of a number. At this level, the numerical representation is non-verbal, and only approximate, consisting of variable distributions of activation along the spatial "mental number line" (Dehaene, Sergent, & Changeux, 2003).

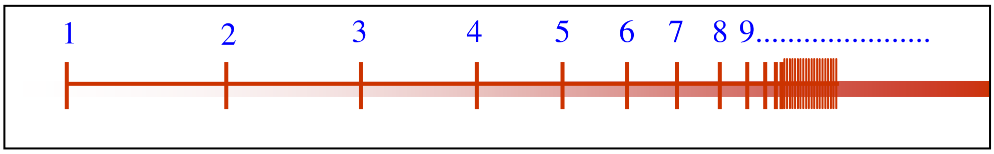



**Figure 1.2** Schematic representation of the "Mental Number Line"

As discussed in the previous paragraph, the evidence on infants' numerical abilities suggests the existence of an approximate magnitude-estimation system, in which numbers are represented inexactly because of inherent error in the enumeration process. More precisely, the number of items in a set is represented as a single magnitude proportional to number, therefore the number of individuals is represented by a magnitude that is a linear function of the cardinal value of the set. The magnitude exhibits a scalar variability, and thus quantity discrimination is subject to Weber's law. Adult humans, irrespective of formal education, are relatively proficient and can discriminate two magnitudes that differ by a factor of roughly 1.15 (Pica, Lemer, Izard, & Dehaene, 2004). Six-month-old infants, in contrast, have much noisier systems and successfully discriminate magnitudes only when they differ by at least a factor of 2.0 (Lipton & Spelke, 2003). The finding that numerical discrimination in infants relies on proportionate, rather than absolute, differences between values is a signature of an analog magnitude-representation system.

However, it has been suggested (Simon, 1997; Uller, Carey, Huntley-Fenner, & Klatt, 1999) that infants' numerical competence is a result not of a numerical representation system, but rather of an automatic system for tracking and reasoning about individual objects in the world, via "object files" or other object-tracking mechanisms (e.g. Kahneman, Treisman, & Gibbs, 1992; Scholl & Leslie, 1999; Trick & Pylyshyn, 1994). In this account, each individual object in an array is represented by a distinct symbol, a "file". Numerical equivalence/difference between two sets is established by a one-to-one correspondence between the files (Simon, 1997; Uller et al., 1999). By this theory, infants' longer looking times to incorrect outcomes in addition and subtraction paradigms are due to a mismatch between the object-files stored in memory and the objects present visually; no one-to-one correspondence is possible. Unlike the magnitude-representation system, whose job is to represent numerosity, object-files are largely used to track objects' locations and paths of movement.

In the attempt to conciliate these two opposite accounts of the format of infants' numerical representation, Feigenson and collaborators (Feigenson, Dehaene, & Spelke, 2004) have proposed that two distinct core systems of numerical representations are present in human infants, as well as in human adults and other animal species. These two systems are automatically deployed, are tuned only to specific types of information, and continue to function throughout the lifespan.

One system, the "Core System 1" serves to represent approximate numerical magnitudes independently of non-numerical quantities, while the other system, "Core System 2", serves to represent numerically distinct individuals of various types, and allows multiple computations over these representations.

### *1.3.1 Core System 1 in infants: approximate representations of numerical magnitude*

One of the first studies showing discrimination of large numbers is that by Xu and Spelke (2000). In this study infants were habituated to visual arrays containing 8 or 16 dots and then were tested with new, alternating dot arrays of the two numerosities.

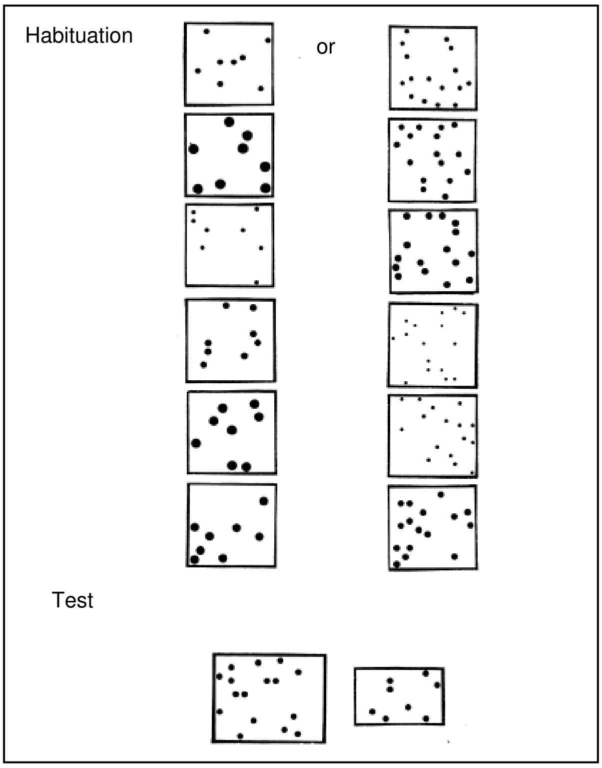



**Figure 1.3** Examples of the stimuli used in the study by Xu & Spelke (2000)

In order to demonstrate that numerosity was the crucial parameter that drove infants' behaviour, all other potentially confounding variables in the stimulus design were controlled. More specifically, stimuli were accurately controlled for the continuous variables of total array size, total filled surface area, element size, and element density in by equating the first two variables in the habituation displays and the last two variables in the test displays, thus the continuous variables that varied across habituation were equated across the test displays and vice versa. Results showed that infants looked longer at the novel numerosity than at the familiar numerosity, provided evidence that the ratio difference between two numerosities was sufficiently large. The authors conclude that true representations of number, rather than representations of continuous quantities or capacity-limited mechanisms of object-based infants' responses attention, underlie infants’ responses.

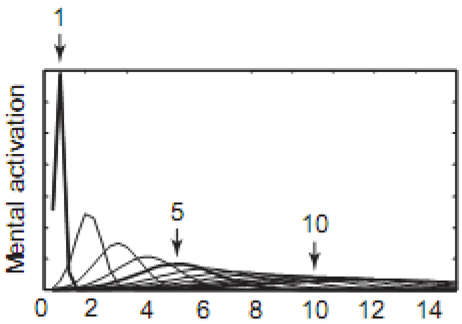
In subsequent experiments, with the same procedure and applying the same controls to the stimuli, same age infants were found to discriminate visual arrays of 32 versus 16 dots, but not 12 versus 8 dots or 24 versus 16 dots (Xu et al., 2005). Successful discrimination of numerical arrays containing 8 vs. 12 dots has been demonstrated in older infants, at 10 months of age (Xu & Arriaga, 2007), and even at 9 months of age, when the task was to discriminate between auditory sequences of sounds and not visual displays (Lipton & Spelke, 2003).

All these findings provide evidence that infants are able to discriminate large numerosities but that their large-number discrimination is imprecise, that discriminability depends on the ratio of the two set sizes, and that the precision of numerical discrimination increases over the infancy period.

The existence of a ratio limit on numerical discrimination suggests that the variability in infants’ number representations is proportional to numerical magnitude (Weber’s Law), as it is for adults and for other animals (Gallistel, 1990).

The available evidence suggest that in tasks involving large numbers of elements, with total surface area, contour length, display size, item size and item density are all neutralized, infants compute discrete number. Furthermore, large number arrays appear spontaneously to trigger numerical representations only, because infants have difficulty extracting information about the continuous properties of large number arrays when number is controlled for (Brannon, Abbott, & Lutz, 2004).

In conclusion, the Core system 1 yields a noisy representation of approximate number that captures the inter-relations between different numerosities, and is robust across variations in continuous properties. This system shows a signature ratio limit that is probably explained by logarithmic compression of its underlying representation of numerical magnitude.



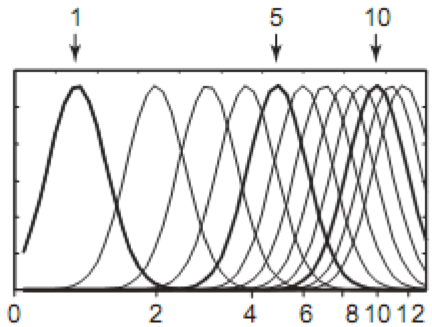




**Figure 1.4** Two models of the mental number line (Core system 1), a linear model (on the left) and a logarithmic model (on the right), depicting mental activation as a numerosity

### *1.3.2 Core system 2 in infants: precise representations of distinct individuals*

Over the past 20 years, simple habituation experiments have provided ample evidence that infants and newborns are sensitive to numerical distinctions among sets of one, two, and three elements (e.g. dots: Antell & Keating, 1983, Starkey & Cooper, 1980, familiar objects: Strauss & Curtis, 1981, continuously moving figures: van Loosbroek & Smitsman, 1990).

However, more recent research has challenged this claim. In the earlier studies, infants were habituated to dot arrays or slides of household objects that contained a common number of elements (e.g. 2 or 3) and then shown new stimuli that contained the same number and a new number of elements (e.g. 2 and 3).

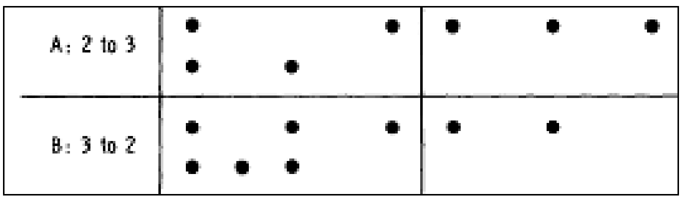



**Figure 1.5** Examples of stimuli used in the study by Antell & Keating (1983)

Infants looked preferentially at the novel numerosity, suggesting that they could discriminate the two numerosities. Continuous variables such as area, contour length and density, however, were not carefully controlled and tended to co-vary with number. This made it impossible to determine exactly which quantity infants used as the basis for their discriminations.

In a widely cited and influential study, Clearfield & Mix (1999) found that infants preferentially attended to continuous variables over number. In this study, 6–8-

month-old infants were habituated to arrays of 2 (or 3) squares that had an unvarying total contour length. The infants were then tested with arrays that had the same number of squares but were novel in total contour length, and with arrays that were novel in number but had the same total contour length as the habituation displays. Infants looked longer at the arrays that contained the novel contour length/familiar number compared with the last three habituation trials, but did not dishabituate.

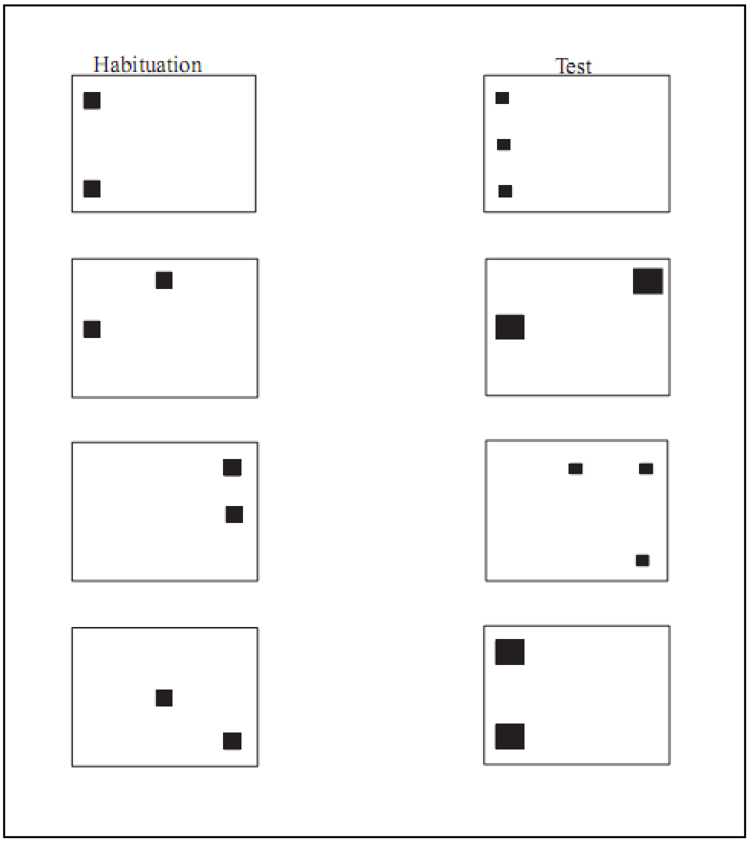



**Figure 1.6** Examples of the stimuli used in the study by Clearfield & Mix (1999)

Nevertheless, the results of a more recent study (Cordes & Brannon, 2009) that tried to replicate Clearfield & Mix's showed that infants detected a change in continuous extent when number remained unchanged from that of habituation;

however, infants also detected a change in number and showed no preference for one change or the other.

Overall, the available evidence so far suggests that the system for representing small numbers of distinct individuals yields a consistent signature across abstract representations. Just as with object arrays, infants precisely represent the individuals in visual-event and auditory sequences (e.g. puppet jumps and sounds Brannon, Lutz, & Cordes, 2006) but they fail to represent arrays greater than 3, fail to represent number when continuous variables are controlled (Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002), and often respond instead to summary representations of amount of motion, amount of sound, or amount of surface area. For example, given a choice between two quantities of food, infants opt to maximize the total quantity of food rather than the number of pieces of food (Feigenson, Carey, & Hauser, 2002). However, the system for representing numerically distinct individuals also supports discrete numerical computations. Infants search for hidden objects based on the number of objects hidden, not on the total amount of continuous 'object-stuff' hidden (Feigenson & Carey, 2003). And in a habituation task with strict controls for continuous variables, infants respond to discrete number if the array contains objects with highly dissimilar features (Feigenson, 2005).

In summary, infants' processing of large versus small numbers exhibits two dissociations. First, large approximate number discrimination varies relative to the ratio between numerosities, whereas small-number discrimination varies relative to the absolute number of individuals, with a set-size limit of about 3. Second, large-number discrimination is robust over variations in continuous variables, whereas small-number discrimination is often affected by such continuous properties.

According to Feigenson et al. (2004), these dissociations suggest that large and small numerosities are the province of different systems with different functions. Large arrays primarily activate a system for representing sets and comparing their approximate cardinal values. Small arrays primarily activate a system for representing and tracking numerically distinct individuals, which allows for computations of either their continuous quantitative properties or of the number of individuals in the array.

## *1.4 ATOM: A Theory Of Magnitude*

The mental representations of time, space, size, number and other magnitudes are largely studied within separate literatures, but the neuropsychological evidence from patients strongly suggested some commonality in the locus of lesions causing deficits in these domains. Walsh (2003) proposed in a theory of magnitude (ATOM) that commonalities between time, space, number, size, speed and other magnitudes were to be found in the parietal cortex because of the need to learn about the environment through motor interactions and therefore to encode these variables for action.

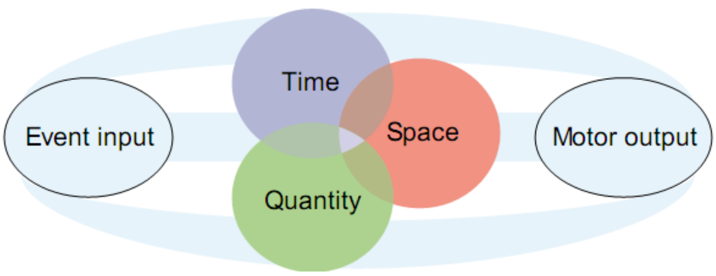



**Figure 1.7** Schematic representation of the commonalities between time, space and quantity, according to Walsh (2003)

Based on some TMS studies, behavioural data and reinterpretations of imaging and single-unit studies, he suggested that different magnitudes originated from a single developmental algorithm for more than–less than distinctions of any kind of stuff in the external world. The development of magnitude processing have been thought to proceed by interactions with the environment and is therefore closely linked with motor reaching, grasping and manipulating of objects. It was further suggested that the emergence of our ability to manipulate discrete quantities evolved from our abilities with continuous quantities.

In the infant's behavioral literature a pair of recent developmental studies seem to suggest that number representation converge with representations of space, defined as amount of area occupied by visual objects, and time. Six-month-old-infants successfully discriminate an auditory sequence of 8 tones from 16 (but not from 12) and a visual sequence of 4 puppet jumps from 8 (but not 6). This finding suggests that the ratio-dependence of numerical discrimination in infants generalizes across experimental paradigms and sensory modalities (Lipton & Spelke, 2003; Wood & Spelke, 2005).

Remarkably, recent studies have provided convergent evidence that 6-month-old-infants require at least a twofold change in the size (surface area) or duration (extension in time) of a single item or event, in order to notice a change. In the study by Brannon and colleagues (2006), 6-month-old infants were habituated to either a single small or a single large cartoon face, and then were tested with alternating trials of both a small and a large face. The two faces differed by a 1:4, 1:3, 1:2 or 2:3 ratio in total area. Results showed that infants discriminated all but the 2:3 change.

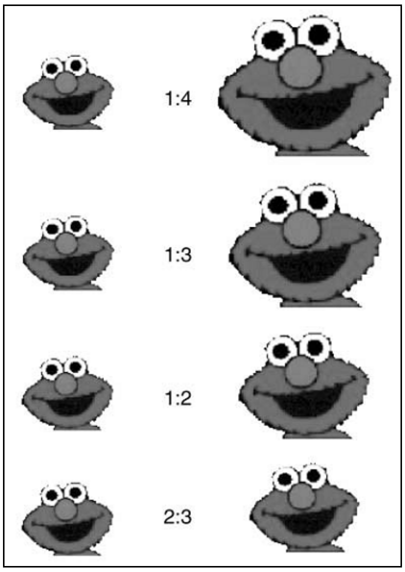



**Figure 1.8** Examples of the stimuli used by Brannon et al. (2006)

In another study, vanMarle and Wynn (2006) used a similar method to study infants' temporal discrimination. Six-month-olds were habituated to a puppet that emitted a tone of either 2 s or 4 s duration (looking time was recorded after the tone had stopped). When tested with alternating trials of both 2 s and 4 s, infants looked longer on trials with the novel duration. However, when the tones were changed to 3 s versus 4.5 s, infants showed no preference. The authors also showed that infants discriminated 0.5 s from 1 s, but not 0.67 s from 1 s. Crucially then, infants' threshold for duration discrimination remains constant over changes in scale and also matches the threshold for number discrimination.

The finding that six-month-old infants detect a 1:2 change but fail to detect a 2:3 change in number, area and duration is consistent with the view, proposed by Walsh (Walsh, 2003), that all three dimensions rely on a shared representational format. This conclusion finds further support from evidence showing the same improvement in numerical discrimination precision that takes place between 6 and 9 months (from 2-fold to 1.5-fold change discrimination in number: Lipton & Spelke, 2003; Wood & Spelke, 2005) has been observed for duration discrimination (from 2-fold to 1.5-fold change discrimination in stimulus duration: Brannon, Suanda, & Libertus, 2007).

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| | 1.5-Fold | 2-Fold | 3-Fold | 4-Fold |
|---|---|---|---|---|
| Time | X | √ | | |
| Large Number | X | √ | √ | |
| Area (1 item) | X | √ | √ | √ |
| Cumulative Area | | X | X | √ |

**Figure 1.9** Table summarizes the pattern of successes (√ ) and failures (X) obtained in quantity discrimination tasks with 6-month-old infants

All together these findings suggest that discrete and continuous quantities may be represented in the same analogical format and support the existence of a shared mechanism that account for number, area and temporal discrimination in infancy.

### *1.5 The mapping of number on space*

The deep connection between numbers and space has been recognised by mathematicians since ancient times. However, it is only recently that the cognitive mechanisms underlying this association have been systematically investigated, strengthening the hypothesis of a strict link between spatial cognition and number processing. The existence of a spatially organised numerical representation was formalised at the beginning of the 90's and since then has received increasing empirical evidence. This representation is conceptualised as a left-to-right oriented mental number line along which numbers would be represented as analogical portions of a continuum.

The association between space and numbers in adults has been extensively investigated in the last 20 years, nevertheless very little is known about the developmental origins of the capacity to relate these representations. A handful of studies have conceptualised the mapping of number to space in adults as an analogue continuum in which numerical magnitude is represented along an oriented axis (Dehaene, 1992; Restle, 1970) and takes the form of a “mental number line”. Number lines appear to be universal across humans, although there is cultural variability in their direction (oriented left-to-right in most western cultures: Dehaene, Bossini, & Giraux, 1993).

The most convincing evidence supporting the hypothesis of a spatially organised magnitude representation comes from a stimulus/response compatibility effect that emerges as a systematic association between number magnitude and lateralised response in number classification tasks (i.e., SNARC effect -Spatial Numerical Association of Response Codes: Dehaene et al., 1993). The SNARC effect consists in a temporal advantage for responding to small numbers with the left hand and large numbers with the right hand. This effect has been claimed to reflect a sort of congruency between the side of the response (left and right sides of the egocentric space) and relative position of a number on a hypothetical number line (left and right sides of the representational space).

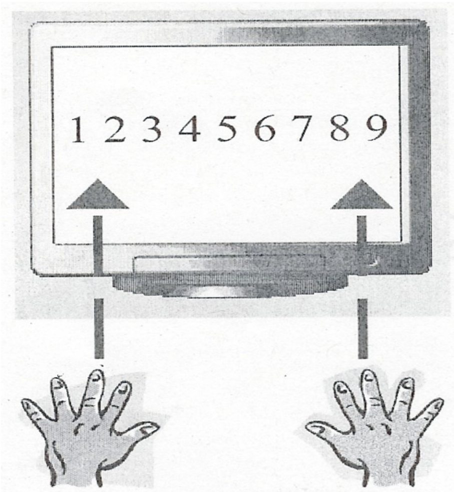


**Figure 1.10** Schematic representation of the association between number magnitude and lateralized response in number classification tasks.

Number lines are activated even when adults perform no relevant numerical task, enhancing their responses to numbers whose value accords with the spatial position of the response. For example there are evidence from neurological patients with left hemifield neglect that suggest the existence of a common signature bias both in bisecting a line and in bisecting a numerical interval, overestimating the midpoint number consistently with a rightward bias on a mental number line(Rossetti et al., 2004; Zorzi, Priftis, & Umilta, 2002). Nevertheless, it has been argued that the association between number and spatial laterality is specifically related to the ordinal meaning of numbers (Gevers, Reynvoet, & Fias, 2003, 2004), and is modulated by visual scanning habits related to reading (Dehaene et. al., 1993, Zebian, 2005, but see also Bachtold, Baumuller, & Brugger, 1998; Ito & Hatta, 2004; Shaki, Fischer, & Petrusic, 2009).

Further evidence for a number–space interaction comes from experiments using a particular version of line bisection task. In this task, subjects are presented with horizontal lines flanked by Arabic digits, and they are asked to indicate the subjective midpoint of each line. Although the flanking numbers are irrelevant to the task, adults show a spatial bias towards the larger number, irrespective of its lateral position. This phenomenon is thought to reflect a cognitive illusion of length brought about by numerical information: a relative expansion of the lateral extent ipsilateral to the larger number (de Hevia, Girelli, Bricolo, & Vallar, 2008; de Hevia, Girelli, & Vallar, 2006; Fischer, 2001). It suggests that representations of length and numerosity are mapped onto an integrated representation of magnitude (Moyer & Landauer, 1967).

Notwithstanding the available evidence, the ontogenesis of the association between numbers and space is still unclear, because this mapping could either be a cultural construction or a reflection of a more fundamental link between the domains of number and space. Some evidence suggests that number-space mappings develop through the acquisition of culture-specific skills and formal education: children show evidence of an oriented number line only some years after they begin schooling (Berch, Foley, Hill, & Ryan, 1999; van Galen & Reitsma, 2008), and the orientation of this representation is modulated by the orientation of the culture's writing system (Zebian, 2005). Nevertheless, humans may be predisposed to treat space and number as intrinsically related. Adults with little or no formal education map numbers onto space when asked to place quantities on a horizontal line, revealing their internal organization of magnitude (Dehaene, Izard, Spelke, & Pica, 2008). Recent research suggests also that the directional mapping of numbers onto space is not entirely triggered by reading performance, since preliterate children display an intuition for the left-to-right organization of numerical magnitude, which the authors identify as deriving from experience in counting (Opfer & Thompson, 2006). These findings suggest that aspects of the spatial representation of number are influenced by experience, culture or instruction, but they do not reveal whether humans have an unlearned, automatic, and non-directional mapping of number to space. Furthermore, the spatial/numerical mapping tested in the above experiments is directional: a mapping of larger numbers to the right or left side of space. A basic mapping of space to number may exist, but its direction may be fixed by experience.

This hypothesis has been the focus of a recent study which directly investigated the origin of the association between number and space by testing adults, young school children, and preschool children for number line representations in a manual bisection paradigm with both symbolic and non-symbolic numerical displays (de Hevia & Spelke, 2009).

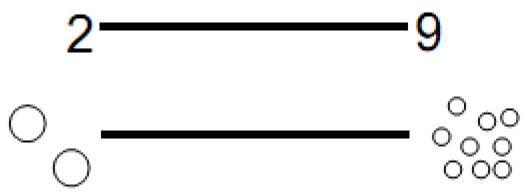


**Figure 1.11** Examples of stimuli used in the bisection tasks by de Hevia & Spelke (2009)

Results showed that non-symbolic numerical displays systematically distorted localization of the midpoint of a horizontal line at all three ages. More specifically, flanking numbers and collection of dots influences participants' perception of the midpoint of a line, inducing a bias towards the larger number or to the larger collection of dots. This phenomenon is thought to reflect a cognitive illusion of length brought about by numerical information: a relative expansion of the lateral extent ipsilateral to the larger number. Numerical and spatial representations therefore seem to be linked prior to the onset of formal instruction, in a manner that suggests a privileged relation between spatial and numerical cognition. More interestingly, the different manipulations of dot arrays yielded the same signature bias, suggesting a spontaneous and automatic mapping between number and space, providing thus evidence for the presence of a common system of magnitude devoted to the computation of these dimensions (Walsh, 2003). However is still unclear whether the connection between space and number may be independent of experience, because, as the authors suggest, the mapping may result from early, preschool experiences in which larger quantities of discrete elements tend to occupy larger spaces (Cooper, 1984). Only studies of infants could be able to elucidate the origins of quantitative intuitions and their interactions.

So far, only one study investigated the existence of a basic mapping of space to number in infants (de Hevia & Spelke, in press), providing evidence for an early developing predisposition to relate representations of numerical magnitudes and spatial length. In this study, 8-month-old infants were tested in a series of experiments aimed to investigate infants' ability to discriminate between ordered series of numerosities and to subsequently transfer the discrimination to ordered series of line lengths. In Experiment 1, infants were habituated to repeating sequences of arrays of visual elements that successively doubled or halved in number (from 4 to 64 or the reverse), while the non-numerical properties of item and array size were controlled. After habituation, infants were presented with sequences of horizontal lines that successively doubled or halved in length on alternating test trials. Results showed that infants looked longer at the test trials with the reversed ordering of lines (e.g., from increasing numbers of dots to decreasing line lengths), relative both to the test trials with the congruent ordering of lines, revealing the ability to generalize from an increasing (or decreasing) sequence of numbers to an increasing (or decreasing) sequence of line lengths.

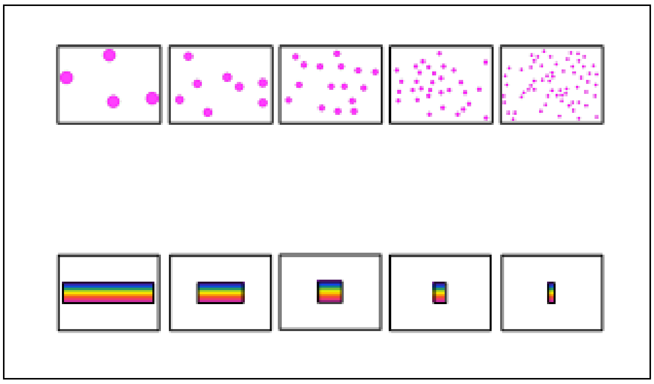

**Figure 1.12** Examples of stimuli used in Exp.1 by de Hevia & Spelke (in press)

In order to verify whether infants would be able to learn a specific, positive relationship between numbers and lengths and generalize the relationship to new numerical and spatial values, in Exp. 2 same age infants were tested with the same procedure, but viewed a series of displays of an array of dots above a horizontal line, in a quasi-random, unordered sequence. Across trials, the dots varied in number and the line varied in length, such that longer lines accompanied greater numbers of dots. Following familiarization, infants were shown two test trials presenting new numbers and line lengths, paired positively or inversely (shorter lines accompanying greater numbers of dots).

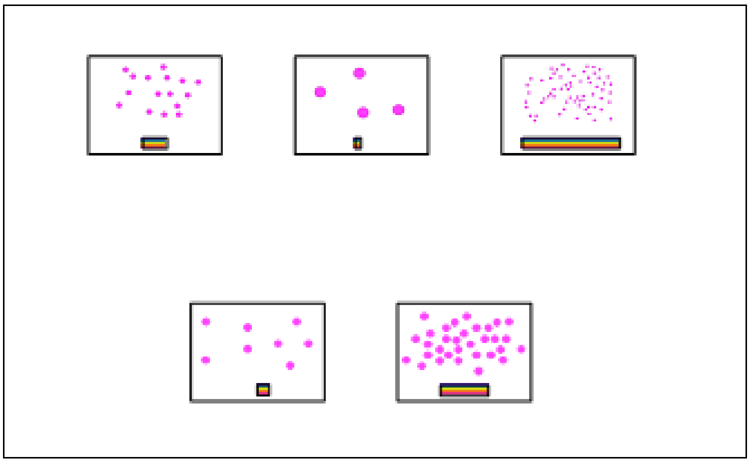

**Figure 1.13** Examples of stimuli used in Exp.2 by de Hevia & Spelke (in press)

Results demonstrated that infants learned the number/length relationship in the familiarization displays and were able to generalize this relationship to the new numbers and lengths in the test displays. Overall, these findings provide clear evidence for an early developing predisposition to relate representations of numerical magnitude and spatial length. Human infants form and use relationships between number and space prior to the acquisition of language and counting, and prior to encounters with visual symbols, rulers, or other measurement devices.

### *1.6 Ordinal knowledge in infancy*

Within the ATOM, an analog approximate representation of quantities applies to all magnitudes that can be described as "prothetic", meaning dimensions that can be experienced as "more than" or "less than": numerical quantity, space, time– one can speak of more/longer time, more objects and larger/smaller spaces etc.

Together with cardinality, in fact, another essential component of the concept of number is ordinality, which refers to the inherent "greater than" or "less than" relationships between numbers. Until recently, the development of this aspect of human numerical cognition in infancy had received very little attention. The finding that preschool children can appreciate the ordinal relationships between numerical magnitudes when other continuous extent cues are controlled (Cantlon, Fink, Safford, & Brannon, 2007; Huntley-Fenner & Cannon, 2000; but see Rousselle, Palmers, & Noel, 2004 for opposite findings) led researchers to the conclusion that mastering the symbolic, verbal counting system is not a necessary prerequisite for the understanding of ordinal relationships between numbers. At the same time, though, some authors have argued that the grasping of the cardinal principle precedes the emergence of ordinal knowledge in development. In particular, it is claimed that preverbal infants' initial ability to discriminate between numerosities does not include any understanding that the different numerosities are information about a single, quantitative dimension. Rather, such understanding emerges through infants' observation of numerical transformations (i.e. additions and subtractions) in their environment, and their noticing that these transformations result in a change from one numerosity to another (Cooper, 1984; Dehaene & Changeux, 1993; Strauss & Curtis, 1981). In fact, although infants have been shown to discriminate between numbers as early as 5-6 months (e.g., Wynn, Bloom, & Chiang, 2002; Xu & Spelke, 2000), and recently even at birth (Izard, Sann, Spelke, & Streri, 2009), available evidence suggest that is not before the age of 11 months that they manifest the ability to make ordinal numerical comparisons (Brannon, 2002; Suanda et al., 2008).

Specifically, only few studies have directly investigated ordinal numerical knowledge in preverbal infants, providing mixed results concerning the age of its first appearance. Cooper (1984) habituated 10- to 16-month-old infants to non-repeating pairs of successively presented numerical displays, by measuring looking time to the second display of each pair. The displays within each pair differed by a 1:2 ratio and maintained a constant ordinal relationship (i.e., ascending or descending), while the absolute numerical values varied between pairs (range 1-4). During test infants were presented with three possible pairs of numerical displays, in which the ordinal relationship was either the same as in habituation, was eliminated by equating the numerical values of the two displays, or was reversed. Fourteen- to 16-month-old infants dishabituated to both types of novel test pairs (reversal and elimination of ordinal relations), whereas 10- to 12- month-olds dishabituated only to the test pairs in which no ordinal information was present. These results were taken as evidence that infants younger than 14 months can differentiate equal and unequal numerical relations but are still not sensitive to ordinal relationships between numbers.

Infants' ability to discriminate reversals in ordinal directions of numerical relations was the focus of a more recent study by Brannon (2002). In this study Brannon investigated infants' ability to detect a reversal in the ordinal direction of sequences of numerical displays (Exp. 1 and 2) as well as sequences of displays that differed in the size of a single square (Exp. 3). In Experiment 1 and 2, 9- and 11-month-old infants were habituated to three-item sequences of numerical displays, whose values increased or decreased by a 1:2 ratio, presented in ascending or descending numerical order (e.g. 4-8-16 or 16-8-4). The sequences were dynamic in that they repeated continuously and the absolute numerical values were varied between trials (range 1-16), while surface area (Exp. 1) and element size, cumulative surface area and density were controlled (Exp. 2).

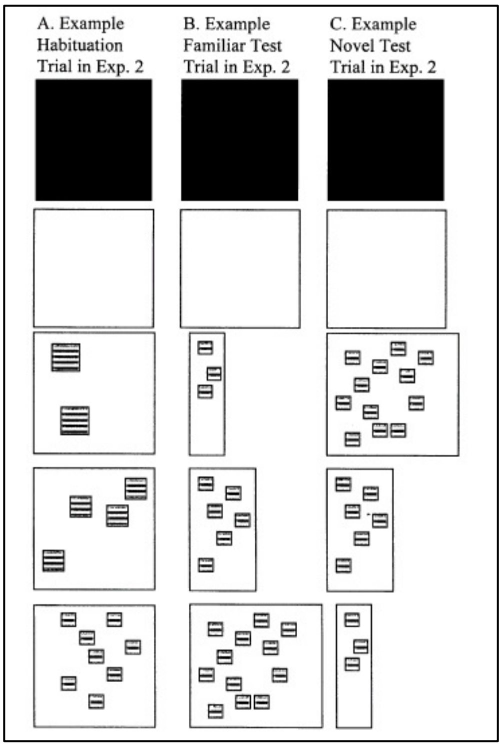


**Figure 1.14** Example of stimuli used in Exp. 2 by Brannon (2002)

Results from Experiment 1 and 2 showed that 11-month-old infants successfully discriminated the reversal in the ordinal direction, whereas 9-month-olds did not dishabituate when presented with the reversed ordinal sequence. However, Brannon argued that these results cannot answer whether the failure of 9-month-old infants is numerical in nature or depends on a more general cognitive ability such as the ability to contrast any two rapidly and successively presented visual displays and ran another experiment in order to test this alternative possibility. In Experiment 3, 9-month-olds were then tested in another version of the same task where displays differed in the size of a single square rather than in number (range 8-64 cm).

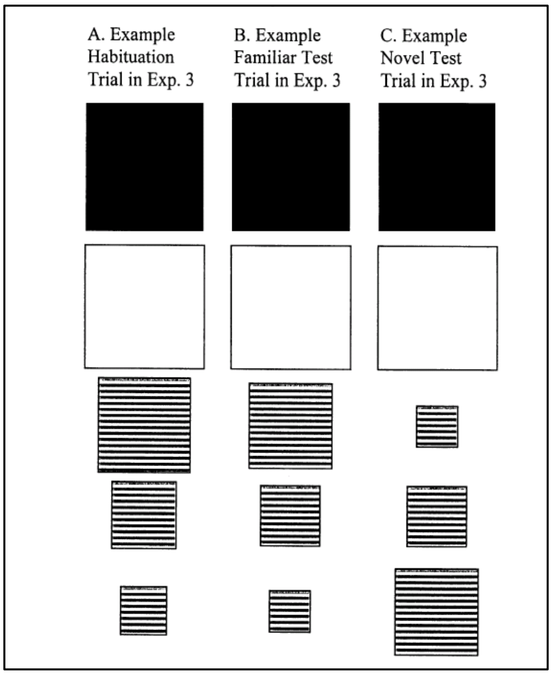


**Figure 1.15** Example of stimuli used in Exp. 3 by Brannon (2002)

Results showed that 9-month-olds successfully detected the reversal in ordinal direction, suggesting that at this age infants are able to represent the ordinal relations between continuous variables such as size but not the ordinal relations between numerosities.

In contrast with the data obtained by Cooper (1984), results obtained by Brannon (2002) seem to demonstrate that the ability to appreciate the “greater than” and “less than” relationships is already in place at the end of the first year of life. Brannon (2002) accounted for younger infants’ success in her task compared with Cooper’s study (1984) by speculating that at least three aspects of her procedure made ordinal numerical relationships more salient to the infants. First, Brannon presented infants with three-item sequences rather than two-item sequences. Second, the sequences were dynamic rather than static, in that each sequence repeated indefinitely until infants shifted their gaze away from the screen, and looking time was measured to the whole sequence rather than to single displays. Third, Brannon used three different sets of absolute values in habituation, rather than two. Together, these three features of the task may have helped infants to discern the ordinal direction embedded in the numerical sequences, thus facilitating successful discrimination of ordinal reversals.

Furthermore the pattern of finding obtained by Brannon (2002) seems to suggest that a capacity for non-numerical ordinal judgments may develop before a capacity for ordinal numerical judgments. This would be in accord with the hypothesis raised by Walsh’s theory of magnitude (2003) that the emergence of our ability to manipulate discrete quantities evolved from our abilities with continuous quantities.

Recently, Suanda and colleagues (Suanda et al., 2008) explored the nature of the changes that take place between 9 and 11 months in infants’ sensitivity to ordinal numerical relationships by testing same age infants and using the same stimuli and procedure originally used by Brannon (2002) in Experiment 1 and 2. Overall, the results confirmed the original Brannon’s (2002) observation of infants as young as 11 months being sensitive to the ordinal relationships between discrete numerical magnitudes when continuous extent cues are controlled (Exp. 1 and 2). Moreover, results extended Brannon’s (2002) findings by showing that 9-month-olds are equally unable to detect reversals in the ordinal direction of a number-based (Exp 1 and 3), size-based (Exp. 4a) or area-based sequence (Exp. 4b), when each of these cues is presented in isolation. The only condition under which 9-month-old infants were found to succeed at discriminating reversals in ordinal numerical sequences was when number, elements' size and cumulative surface area provided convergent, redundant cues to ordinality (Exp. 5).

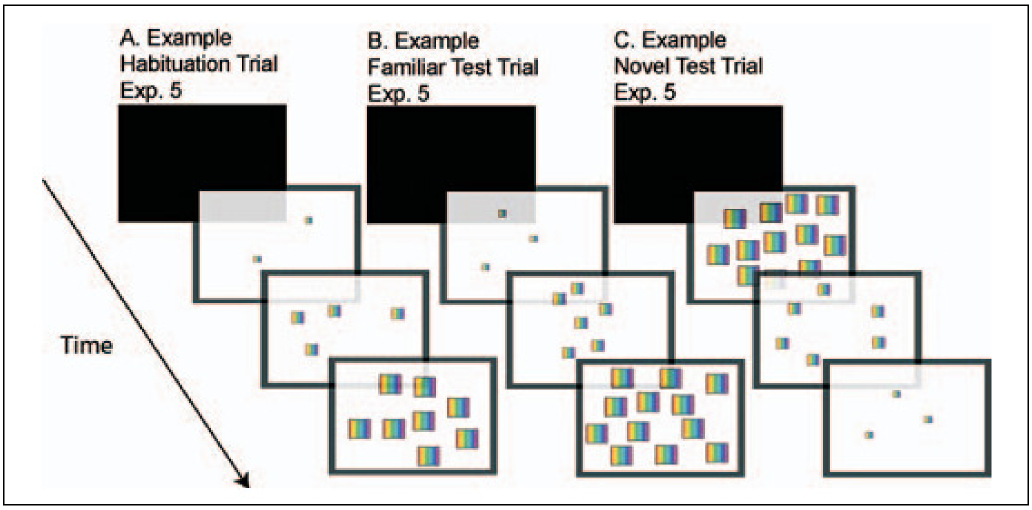


**Figure 1.16** Schematic representation of ordinal sequences used by Suanda et al. (2008), in Exp. 5

The authors therefore confirmed that it is from 11 months of age when infants can represent ordinal relations between purely numerical values: in order to appreciate ordinal quantitative relationships, younger infants require a confluence of numerical and non-numerical cues (Suanda et al., 2008).

In summary, evidence from the study of the development of ordinal numerical knowledge suggests that in infants younger than 11 months, the ability to discriminate ascending and descending sequences of numerical quantities is highly dependent on the amount of facilitating information that is available to the infant, such as multiple redundant cues to ordinality. Nevertheless, it seems still unclear if the ability to appreciate ordinal relationships between non-numerical quantities is achieved earlier than the ability to discriminate between numerical values.

## 1.7 *Open Questions Regarding the Development of Ordinal knowledge in infancy - Rationale for the current study*

Past and more recent research reviewed so far suggests that the ability to detect and represent "greater than" or "less than" relationships between numbers develops sometime between 9 and 11 months of age.

Nevertheless, it is important to note that the ability to detect the ordinal information embedded in a series of sequentially presented displays implies the ability to associate information of quantities (numerical or non-numerical) and temporal information, that is to link numerical magnitudes to the temporal information that defines the position of the displays within the sequence. Importantly, research on infants' temporal sequences learning indicates that the ability to detect statistically defined temporal patterns in simple visual sequences composed of static coloured shapes is available quite early in development, at around the age of 2 months, and it remains constant across development (Kirkham et al., 2002). In a recent study, Kirkham and colleagues (2002) familiarized 2-, 5-, and 8- month-old infants to a series of discrete visual stimuli whose ordering was defined solely by statistical regularities. After habituation, infants viewed the familiar pattern alternating with a novel sequence of identical stimulus components. Results showed that at all ages tested, infants exhibited a reliable preference for novel sequences whose ordering violated the transitional probability that defined grouping of the original stimuli.

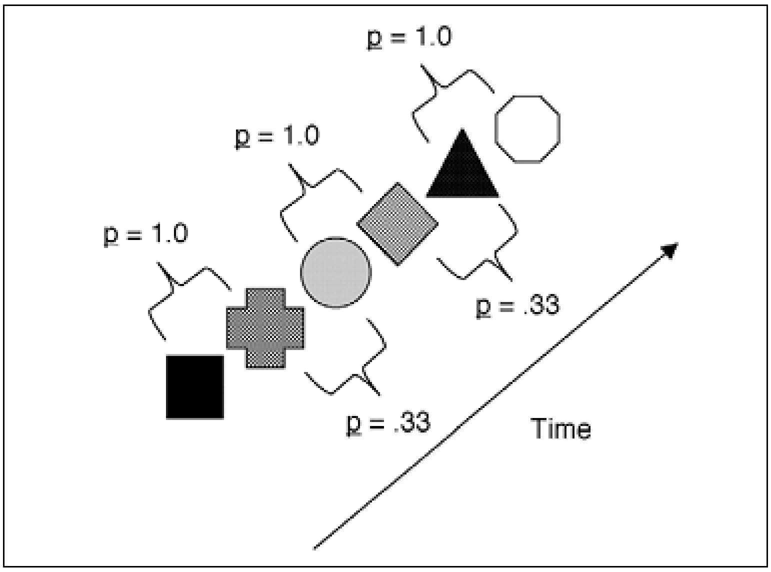


**Figure1.17** Schematic representation of the familiar stimulus sequence, showing the transitional probabilities defining pairs, in Kirkham et al (2002)

This pattern of results is consistent with the existence of a domain general statistical learning device that is available to even very young infants. The authors concluded that, given the youngest age tested in addition to the lack of observed development, it seems reasonable to posit an associative mechanism that is functional with the onset of visual experience and this statistical learning mechanism seems to be powerful enough to ascertain visual input structure after only a few minutes of exposure in a highly constrained, unnatural setting.

Another interesting evidence on infants' learning of serial order -serially organized visual item sequences- comes from a recent study by Lewkowicz (2004) in which 4- and 8-month-old infants were habituated to three sequentially moving objects and then tested on separate test trials for their ability to detect auditory, visual or auditory-visual changes in their ordering.

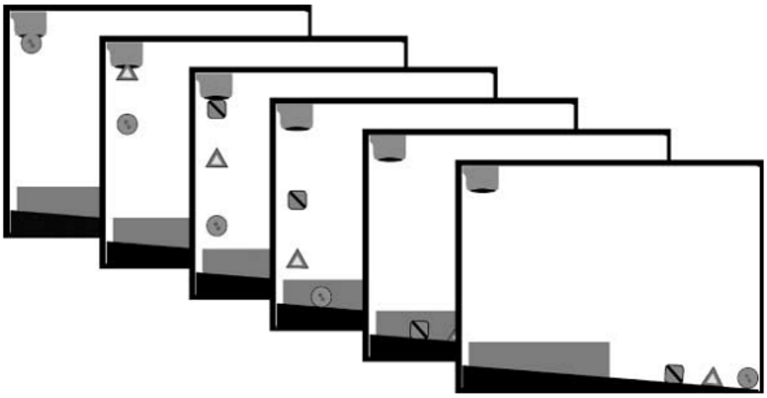

**Figure 1.18** The three visual objects and the schematic representation of their movement over time in Exp. 1 by Lewkowicz (2004)

Results showed that 4-month-olds did perceive the serial order feature of the event but only when it was multimodally specified, while 8-month-old infants perceived all three kinds of order changes regardless of whether the synchrony part of the event was visible or not. These findings demonstrate that perception of serial order of discrete stimuli emerges early in infancy and that its perception is initially facilitated by multimodal specification.

Given these evidence, the aim of the current study was to investigate whether the ability to appreciate ordinal relationships between numerical and non-numerical magnitudes is present in preverbal infants at an earlier age than previously reported (Brannon, 2002; Suanda et al., 2008).

The current investigation includes a series of experiments in which 4- and 7-month-old infants were tested in a visual habituation task for their ability to detect and abstract ordinal relationships among numerical or non-numerical magnitudes. More specifically, we tested 4-month-olds with visual sequential sequences of non-numerical magnitudes (continuous quantities), and 7 month-olds with visual sequential sequences of numerical magnitudes (discrete quantities), in order to verify whether the ability to extract the ordinal relationships is already in place at this ages and thus verify whether the ability to appreciate ordinal relationships between non-numerical quantities is achieved earlier than the ability to discriminate between numerical values, as Walsh (2003) hypothesized and Brannon (2002) suggested.

Based on previous research, we knew that a mechanism capable of detecting and learning simple temporal patterns is available early in development (Kirkham et al., 2002) and that infants around 4 months of age are already capable of detect and represent the serial order embedded in a visual sequence composed of single elements (Lewkowicz, 2004). Thus, we hypothesized that 4-month-olds would succeed in the discrimination of size-based squares presented in ascending and descending order, as in the task that Brannon (2002) proposed to older infants. The next chapter reports three experiments aimed at studying 4-month-olds' ability to grasp and represent the ordinal relationships embedded in sequences of size-based squares.

Moreover, based on available evidence on infants' learning of spatiotemporal sequences (Kirkham, Slemmer, Richardson, & Johnson, 2007) we knew that, at 8 months of age, integration of multiple sources of information plays an important role in supporting the extraction of structure from spatiotemporal sequences and in strengthening the representation of the sequence pattern. In the current study we adopted the logic of research on sequence learning and multiple cue integration to investigate whether, in absence of quantitative cues but in the presence of multiple visual features, infants would manifest the ability to detect ordinal numerical relationships within temporal sequences at an earlier age than what was previously found (Brannon, 2002; Suanda et al., 2008). In particular, we tested whether 7-month-old infants can extract the ascending or descending ordinal relationships among numerical displays when multiple visual features are available both within (shape) and between (colour) the ordinal sequences, and thus succeed in detecting a reversal in the sequences' ordinal direction even when quantitative cues are not available.

Finally, in light of recent evidence suggesting the existence of an early developing predisposition to relate representations of numerical magnitudes and spatial length in 8-month-old infants (de Hevia & Spelke, in press), we investigated the presence of a basic mapping of space to number in 7-month-old infants. More specifically, we tested infants' ability to detect an inversion in the direction of ordinal number-sequence sequences in which each element was dislocated in a different but contiguous spatial position from left to right along the horizontal plane.

# CHAPTER 2: THE DISCRIMINATION OF ORDINAL RELATIONSHIPS IN TEMPORAL SEQUENCES OF NON-NUMERICAL MAGNITUDES

This chapter presents 3 different experiments in which 4-month-old infants were tested using an infant-controlled habituation paradigm for their ability to discriminate inversions in the direction of ordinal sequences of non-numerical, continuous magnitudes. This ability has been previously reported in 9-month-old infants (Brannon, 2002; Suanda et al., 2008). The aim of our research project was to investigate whether the ability to appreciate ordinal relationships embedded in size-based sequences could be found in infants younger than 9 months.

The ability to detect an ordered sequence of continuous quantities refers to the capacity to detect the direction of change in the attended dimension, and therefore to discriminate between "greater than" and "less than" relations. This capacity, in turn, relies on the ability to associate magnitude and temporal information, that is to link magnitudes to the temporal information that defines the position of each magnitude display within the sequence. Available evidence suggests that these competencies are in fact part of the infants' information processing repertoire from the first months of life (Kirkham et al., 2002). Therefore, we reasoned that infants as young as 4 months would be able to use the temporal information provided through the sequential presentation of the stimuli and would be able to detect the statistically predictable pattern embedded in ordinal sequences during habituation, so that they could succeed in discrimination between familiar and novel order sequences presented during the test phase.

## 2.1 *Experiment 1: 4-month-olds' discrimination of ascending vs. descending ordinal relationships within size-based sequences*

The aim of the first experiment was to test whether at 4 months of age infants succeed at discriminating the inversion in the ordinal direction (ascending vs. descending) of sequences composed of a single element that varied in the size. As in Brannon (2002), infants were habituated to ascending or descending repeated dynamic sequences composed of three rainbow-colored squares of different size, and subsequently tested with a new set of squares presented in both the familiar and reversed ordinal direction. However, we departed from Brannon procedure by using only large magnitudes (range 6-48), by increasing the time of stimulus presentation to accommodate to the younger age of the participants tested (from 1000 ms to 1500 ms) and by introducing an inter-stimulus interval (ISI) between the presentation of the three squares composing each sequence. This last change was made in order to avoid that the sequential presentation of the squares might create the illusion of a single dynamic square that approached (zooming effect) or departed from (looming effect) the infant.

### 2.1.1 *Method*

***Participants***

Participants were 21 healthy, full term 4-month-old infants (*M* age = 4 months, 19 days; range = 4 months, 4 days – 4 months, 29 days). Twelve of the participants were female. Seven additional infants were tested but exclude from the final sample due to experimenter error (N=2) or failure in reach criteria established for data analyses (N=5). Data from additional 10 infants were discarded because of fussiness (N=8) or being not cooperative (N=2), resulting in failure to complete all the test trials. Infants were recruited via a written invitation, which was sent to parents based on birth records provided by the neighboring cities. The majority of participants were from Caucasian, middle class families. Parents gave their written informed consent before testing commenced.

***Stimuli***

Stimuli were single rainbow-colored squares that varied in size (range 6-48 cm²). They were presented on a white background in the center of the computer monitor. There were four sets of stimuli, three for the habituation phase and one for the test phase. The first habituation set contained squares that were 6, 12, 24 cm²; the second set contained squares of 9, 18, 36 cm² and the third habituation set contained squares of 12, 24, 48 cm². The test set contained three novel squares that were 8, 16, and 32 cm². Thus, the element size within each set differed by a 1:2 ratio (Xu & Spelke, 2000).

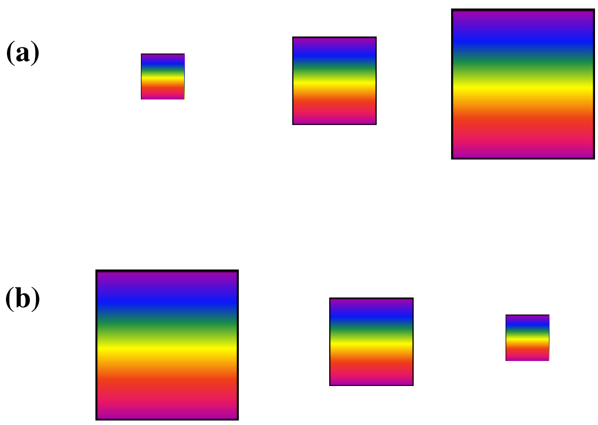


**Figure 2.1**
Example of stimuli used in Exp.1: (a) ascending sequence and (b) descending sequence.

### *Design*

Infants were habituated to ascending or descending sequences of three displays (e.g. 6-12-24 or 24-12-6) and then tested with both ascending and descending sequences containing novel element sizes. Half of the infants were randomly assigned to the ascending habituation condition.

Within each habituation condition, the three different stimulus sets were cycled in a fixed order until the infant met the habituation criterion: from the smallest to the largest display for the ascending condition (i.e., 6-12-24; 9-18-36; 12-24-48), and from largest to the smallest for the descending condition (i.e., 48-24-12; 36-18-9; 24-12-6). Following habituation, all infants were given six test trials alternating the ascending and descending sequences (i.e., 8-16-32; 32-16-8). Order of presentation was counterbalanced across participants. The use of a consistent fixed order of presentation of the habituation displays across trials for each of the two habituation conditions was intended to provide infants with additional redundant cues to ordinality between, as well as within, trials.

### *Apparatus*

Each infant was tested while sitting in an infant seat approximately 60 cm from the monitor where the stimuli were presented. A curtain separated the participant from the experimenter at all times. Parents were asked to remain on the experimenter's side of the curtain, so as to not distract the infant, but were free to go to the infant at any time should he or she show signs of distress. 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 TV monitor to allow the online coding of the infant's looking times by the experimenter, who was blind to the habituation condition to which the infant was assigned.

**Figure 2.2** The apparatus and the setting of the experiments

Looking behavior was recorded by holding a button down when the infant was looking at the computer monitor and letting it go when the infant looked away. The button input was fed into an E-Prime program, which automatically computed the parameters that determined the end of each trial, and when the habituation criterion was met. The live image of the infant's face was also recorded via a Mini-Dv digital recorder, and for half of the infants in each habituation condition data were subsequently coded offline.

***Procedure***

Before the start of each trial, one of twelve different cartoon animated images, accompanied with one of four different sounds, served as attention catcher . When the infant's eyes were directed toward the animated fixation point, the experimenter started the trial. Each trial consisted in a repeating cycle (5750 ms in total) beginning with a black screen (500 ms), followed by a white display (250 ms), and then by the three stimuli of the sequence, which appeared for 1500 ms each. A 250 ms Inter-Stimulus-Interval (ISI) followed the presentation of each stimulus display. 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 stimulus sets were presented in a fixed order and repeated until the infant either was given a maximum of 14 trials or met the habituation criterion, which was defined as a 50% decline in looking time on three consecutive trials, relative to the total looking time on the first three trials that summed to at least 12 s. Following habituation, infants were given 6 test trials, in which novel (ascending for infants habituated to descending sequences and viceversa) and familiar ordinal sequences appeared in alternation with half of the infants seeing the novel test sequence first.

***Data analyses***

In order to be included in the analyses infants has to provide a minimum looking time in each test trials of 1 sec. Inter-coder 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 six test trials was r = .85.

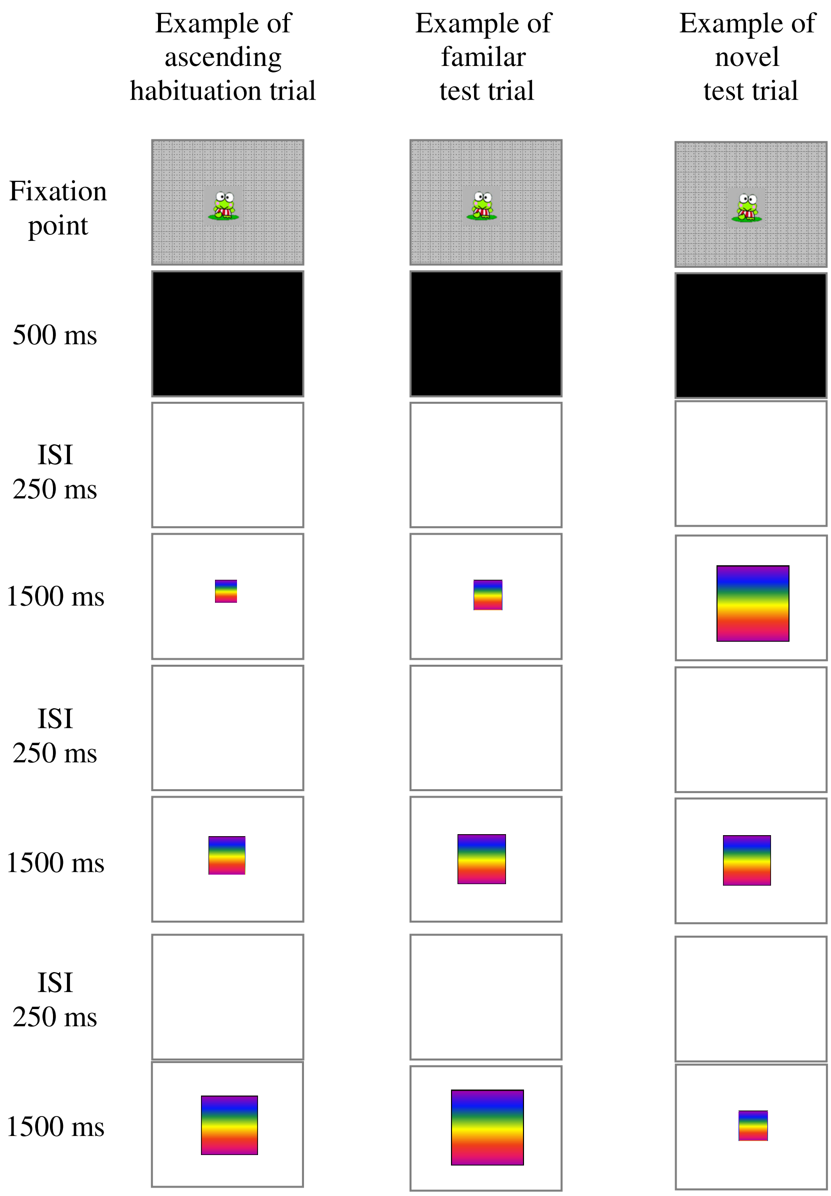


**Figure 2.3** The sequence of events in each trial: the fixation point, the ISI and the three non-numerical stimuli composing each sequence. The sequence repeated, beginning with the black screen, until specific criteria were met.

### *2.1.2 Results*

A preliminary analysis of variance (ANOVA) with *habituation condition* (ascending vs. descending) as the between-subjects factor, and *habituation trials* (first three vs. last three) as the within-subjects factor was performed in order to verify whether there were any difference in the way infants who were exposed to different order habituation conditions did reach the habituation criterion. Results revealed a significant main effect of the *habituation trials* factor $F(1,20)=44.908$, $p<.005$, $\eta p^2=.703$, due to average looking time on the first three habituation trials ($M$= 61.1 s) being significantly longer than average looking time on the last three habituation trials ($M$=20.5 s). There were no main effect nor interaction involving the factor *habituation condition*.

All infants reached the habituation criterion and, on average, habituation required 6.9 trials. A paired-samples t-test confirmed the presence of a significant decline in mean looking time from the first three ($M$=20.37 s) to the last three habituation trials ($M$=6.79 s), $t(20) = 6.857$, $p<.001$.

To determine whether, in test, infants were able to discriminate the familiar ordinal direction from the novel, reversed ordinal direction, a three-way analysis of variance (ANOVA) was performed, with *habituation condition* (ascending vs. descending) as the between-subjects factor, and *trial pair* (first vs. second vs. third) and *test trial type* (familiar vs. novel ordinal direction) as within-subjects factors. A preliminary ANOVA including also the between-subjects factor *first test trial type* (novel vs. familiar) revealed no main effect or interactions involving this factor. The three-way ANOVA revealed a significant main effect of the *test trial type*, $F(1,20)=11.864$, $p<.05$, $\eta p^2=.384$, which was qualified by a significant *test trial type* x *habituation condition* interaction, $F(1,20)=10.602$, $p<.005$, $\eta p^2=.358$. Infants who were habituated to the ascending sequences looked significantly longer to the novel ($M=25.97$ s) compared to the familiar test trials ($M=13.93$ s), $t(9)=4.386$, $p<.005$, whereas this difference was not present for infants habituated to the descending sequences (novel test trials: $M=22.01$ vs. familiar test trials: $M=22.35$; $t(10)=0.144$, $p=.888$). Successful discrimination of the novel ordinal sequences for the infants in the ascending condition was confirmed also by the examination of the data for individual infants, that showed that 10 out of 10 infants looked longer to the novel compared to the familiar test trials (10/10; Binomial test, $p=0.5$, $p<.001$). In contrast, only 7 out of the 11 infants in the descending condition looked longer to the novel compared to the familiar test trials (7/11; Binomial test, $p=0.5$, $p=.16$).

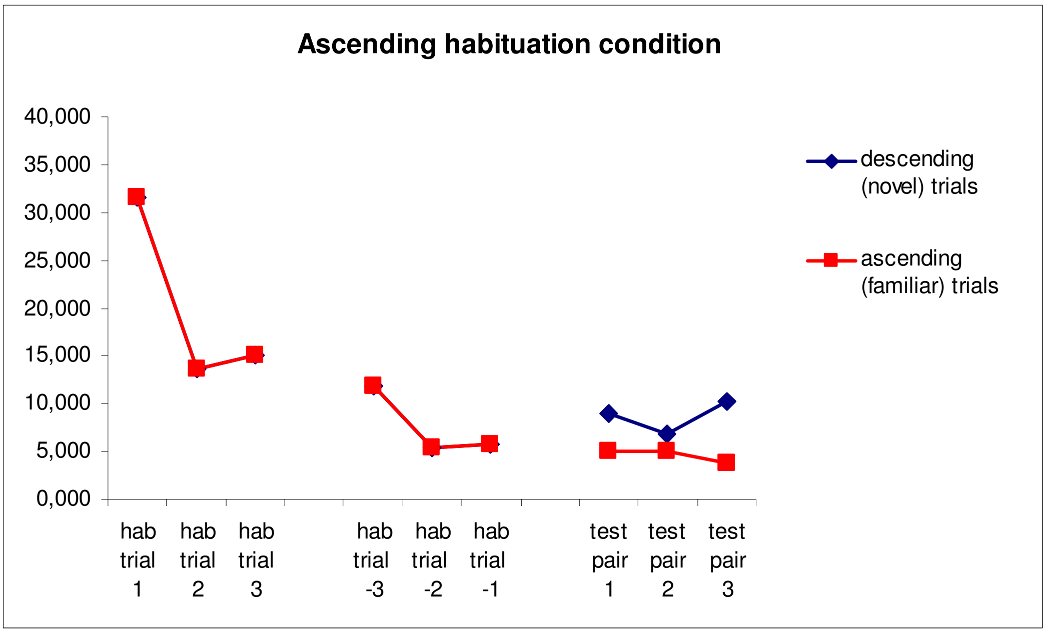


**Figure 2.4** Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of familiar and novel test trials for infants habituated to the ascending sequences (N=9).

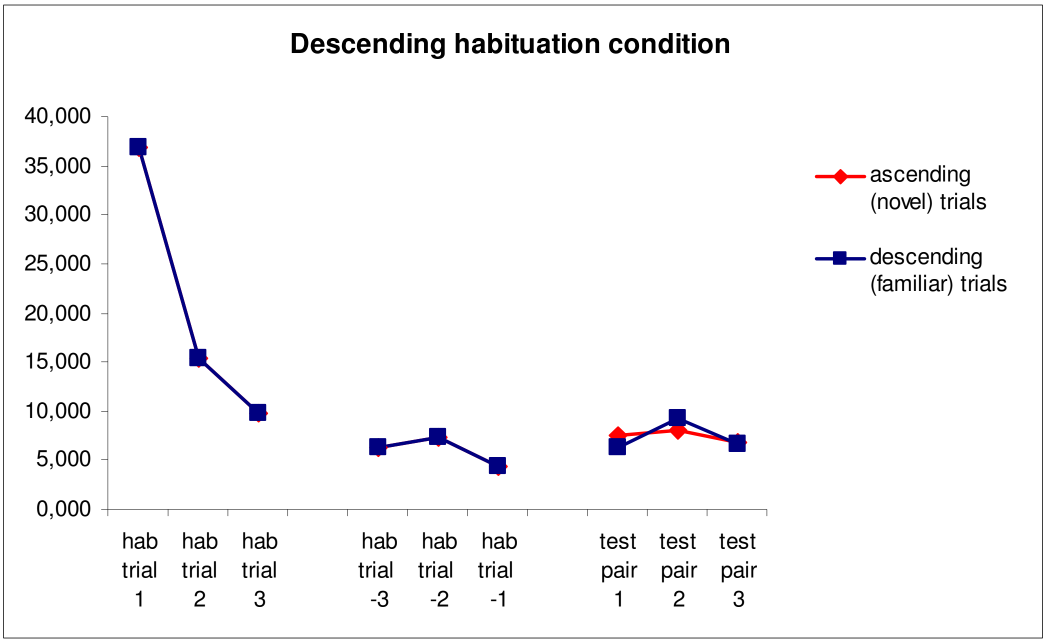


**Figure 2.5.**

Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of familiar and novel test trials for infants habituated to the descending sequences (N=11).

For infants in the ascending habituation condition, paired-samples t-tests showed a significant increase in average looking times between the last two habituation trials[1] (*M*=5.62 s) and the novel test trials (*M*=8.65 s), $t(9)=2.357$, $p<.05$, but not between the end of the habituation and the familiar test trials (*M*=4.64 s), $t(9)=1.236$, $p=.248$, demonstrating a dishabituation effect to the novel but not to the familiar test trials. This dishabituation effect was not present for infants habituated to the descending order, whose average looking time on the last two habituation trials (*M*=5.88 s) did

[1] As evident from Figure 2.4, although there is an overall steep decrement curve in looking time durations between the first three and the last three habituation trials, there is still a notable decrease between the third-from-last (*M* = 11.7 s), and the second-from-last (*M* = 5.4 s). In particular, the third-from-last trial does not differ from the third habituation trial (*M* = 15.1 s; $p = .34$) but is significantly different from the second-to-last trial ($p < .05$). Therefore, in order to capture the end of the habituation process, we calculated the dishabituation effect with respect to the last two, rather than three, habituation trials.

not differ from average looking time on the novel test trials (*M*=7.45 s, *t*(10)=1.282, *p*=.229), nor on the familiar test trials (*M*=7.34 s, *t*(10)=0.959, *p*=.360).

Overall, these results indicate that infants were able to form a size-based representation of the ordinal relations embedded in ascending sequences and discriminate the reversal in ordinal direction embedded in the novel test sequences. Infants could not discriminate between familiar and novel sequences after habituation to descending sequences.

### *2.1.3 Discussion*

The current experiment investigated whether the ability to appreciate ordinal relationships between non-numerical magnitudes is present in preverbal infants at an earlier age than previously reported (i.e. 9 months, Brannon, 2002; Suanda et al., 2008). The results demonstrate that 4-month-olds are able to detect the ordinal relationships embedded in non-numerical size-based sequences. More precisely, results showed that only infants who have been exposed to the ascending habituation condition successfully detected a reversal in the ordinal direction of size-based sequence, as evidenced by their longer looking times to descending as compared to ascending test trials. Differently, infants who were habituated to descending sequences did not discriminate between the two ordinal directions presented in test trials, as evidenced by the fact that they didn't show any preference, nor for the novel nor for the familiar test trials.

This pattern of results raised a couple of questions, which we addressed in Exp. 2 and Exp. 3. Specifically, results seemed to suggest that at 4 months of age it is easier to code and represent the ordinal information embedded in ascending ordinal sequences as compared to the ordinal information embedded in descending sequences, that is when the ordinal relationship between the elements composing the ordinal sequence is characterized by "more than" rule as compared to "less than" relationships. These unexpected findings suggested the presence of an interesting asymmetry between the two ordinal habituation conditions, which appears to be in line with evidence provided by studies conducted with non-human primates. Recent investigations that examined ordinal numerical knowledge in rhesus macaques (Macaca mulatta) demonstrated that monkeys trained to respond in descending numerical order did not generalize the descending rule to the novel values, in contrast to monkeys trained to respond in ascending order (Brannon, Cantlon, & Terrace, 2006; Brannon & Terrace, 2000). In the same way, we could hypothesize that the advantage for the ascending rule habituation arose from infants' difficulty in coding and processing the ordinal relationships embedded in descending sequences, for which a descending sequence is not perceived and processed as an ordinal sequence by human infants. To test this hypothesis, in Exp. 2 we investigated 4-month-olds' ability to discriminate the ordinal relationships embedded in descending sequences from non-ordinal relationships embedded in random, size-based sequences.

Another possible interpretation of the results emerged from Exp. 1 is that 4-month-old infants aren't in fact able to detect ordinal relationships embedded in size-based sequences, and the novelty preference manifested by infants tested in the ascending habituation condition reflected the dectection of a qualitative change, rather than an ordinal change, between the ascending and descending sequences. Despite the fact that, differently from previous studies (Brannon, 2002; Suanda et al., 2008) we presented white ISI displays before and after each of the three squares composing the sequences, because all stimuli were located at the centre of the screen ascending sequences may have achieved an approaching percept (zooming), whereas descending sequences may have yielded a retracting percept (looming). To ascertain whether infants' performance in Exp. 1 was effectively a manifestation of the ability to detect and represent ordinal relationships among non-numerical magnitudes, in Exp. 3 we aimed to replicate the results of Exp. 1 using stimuli that did not evoke any looming/zooming perceptual effect.

## 2.2 *Experiment 2: 4-month-olds' discrimination of descending vs. non-ordinal relationships within size-based sequences*

In Exp. 1, 4-month-old infants were asked to discriminate between ascending and descending ordinal sequences composed of a single element that varied in size. Therefore, they were required to detect the reversal in the ordinal direction of a size-based sequence. Results showed that infants habituated to descending sequences failed to discriminate test sequences displaying the familiar, descending, direction from test sequences that displayed the novel, ascending, direction. We hypothesized that infants' failure to manifest a novelty preference derived from their inability to encode and abstract the ordinal relationships within descending sequences, which were eventually perceived as non-ordinal. Exp. 2 was aimed to test this hypothesis, by investigating whether 4-month-olds could discriminate the difference between descending ordinal sequences composed of a single square that varied in size and non-ordered sequences composed of the same elements, but presented in a random order. We reasoned that, if infants are not able to detect ordinal relationships embedded in descending sequences, they should not discriminate descending from random sequences. Moreover, no difference should be observed in looking times during either the habituation or the test phase between the infants habituated to the descending sequences and those habituated to the random sequences.

An alternative hypothesis is that infants' encoding of ordinal relationships is just more difficult when ordinality is embedded in descending sequences as compared to ascending sequences. If this is the case, we predicted that 4-month-olds might succeed in discriminating descending ordered sequences from non-ordered sequences in which any ordinal relationships was abolished. This hypothesis finds support in the evidence provided by the study from Cooper (1984), cited in the previous chapter, in which 10- to 12-month-old infants were found to dishabituate to novel test sequences in which ordinal relationships were eliminated and not to test sequences in which ordinal relationships were reversed. These results were taken as evidence that, for younger infants, it would be easier to discriminate between ordinal sequences and non-ordinal sequences than to discriminate between ordinal sequences with opposite directions, as in the case of the task that we proposed in Exp. 1.

### *2.2.1 Method*

***Participants***

Participants were 18 healthy, full term 4-month-old infants (*M* age = 4 months, 19 days; range = 4 months, 3 days – 4 months, 29 days). Eight of the participants were female. Five additional infants were tested but exclude from the final sample due to experimenter error (N=1) or failure in reach criteria established for data analyses (N=4). Data from additional 8 infants were discarded because of fussiness (N=2) or being not cooperative (N=6), resulting in failure to complete all the test trials.

As in Exp. 1, infants were recruited via a written invitation, which was sent to parents based on birth records provided by the neighboring cities. The majority of participants were from Caucasian, middle class families. Parents gave their written informed consent before testing commenced.

***Stimuli***

The stimuli were identical to those used in Exp. 1 (see Figure 2.6).

***Design***

Infants were habituated to descending or non-ordered sequences of three displays (e.g. 24-12-6 or 24-6-12) and then tested with both descending and non-ordered sequences containing novel element sizes. Half of the infants were randomly assigned to the descending habituation condition.

Within the descending habituation condition, the three different stimulus sets were cycled in a fixed order until the infant met the habituation criterion: from largest to the smallest (i.e., 48-24-12; 36-18-9; 24-12-6). For the non-ordinal habituation condition infants were presented with one of two possible random sequences. Half of the infants were presented with a medium-largest-smallest-size sequence (i.e., 12-24-6) (see Figure 2.4, a), whereas the other half were presented with a smallest-largest-medium-size sequence (i.e., 6-24-12) (see Figure 2.4, b). Following habituation, all infants were given six test trials alternating the descending and one of the two possible non-ordered sequences. Order of presentation was counterbalanced across participants.

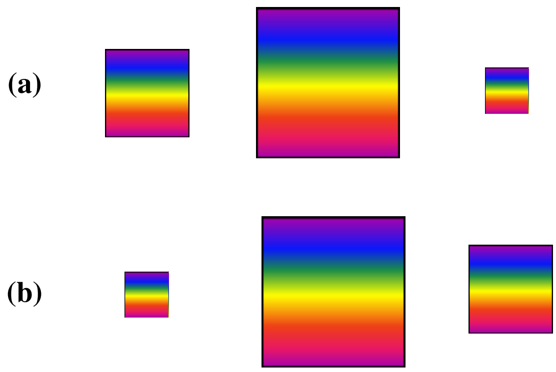


**Figure 2.6**
Example of random sequences used in Exp. 2: the medium-largest-smallest size sequence (a) and the smallest-largest-medium sequence (b)

***Apparatus and Procedure***

Same as in Exp. 1.

***Data analyses***

As in Exp.1, in order to be included in the analyses infants has to provide a minimum looking time in each test trials of 1 se. For this reason, 4 subjects were tested but excluded to the final sample. Inter-coder 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 six test trials was r = .98.

### *2.2.2 Results*

A preliminary analysis of variance (ANOVA) with *habituation condition* (descending vs. non-ordered) as the between-subjects factor, and *habituation trials* (first three vs. last three) as the within-subjects factor was performed in order to verify whether there were any difference in the way infants who were exposed to the descending sequence during habituation did reach the habituation criterion as compared to infants exposed to the random, non-ordered habituation. Results revealed a significant main effect of the *habituation trials* factor $F(1,17)=55.651$, $p<.005$, $\eta p^2=.777$, due to average looking time on the first three habituation trials ($M$=60.07 s) being significantly longer than average looking time on the last three habituation trials ($M$=18.34 s). There were no main effect nor interaction involving the factor *habituation condition*.

All infants reached the habituation criterion and an additional t-test for independent samples revealed that there were no differences in the mean number of trials infants required to habituate in the descending condition (*M*=7.2) as compared to the non-ordered sequence (*M*=6.25), $t(16)=1.437$, $p=.170$. Additional t-tests for independent samples were performed to ensure that the use of two different random sequences for infants habituated to the non-ordered random condition did not produce any difference in the habituation process.

To determine whether in test infants were able to discriminate the familiar ordinal direction from the novel, reversed ordinal direction, a three-way analysis of variance (ANOVA) was performed, with *trial pair* (first vs. second vs. third) and *test trial type* (familiar vs. novel ordinal direction) as the within-subjects factors, and *habituation condition* (descending vs. non-ordered) as the between-subjects factor. A preliminary ANOVA including also the *first test trial type* (novel vs. familiar) as a between-subjects factor revealed no main effect or interactions involving this factor. The three-way ANOVA revealed a significant main effect of the *trial pair*, $F(1,17)=7.753$, $p<.005$, $\eta p^2=.326$, and paired-sample t-test showed that, on average, infants looked significantly longer to the first trial pair (*M*=7.69 s) as compared to the second (*M*=5.1 s, $t(17)= 2.377$, $p<.05$) and the third pair (*M*=4.33 s, $t(17)= 3.953$, $p<.005$) (Bonferroni corrected).

Crucially, there were no main effect or interaction involving the factor *test trial type*. Moreover, as evident from the Figure 2.7, there were no differences in average looking time between the last two habituation trials (*M*=5.77 s) and the novel test trials (*M*=5.39 s), $t(17)= 0.359$, $p=.724$, or the familiar test trials (*M*=6.04 s), $t(17)=0.289$, $p=.776$, indicating the absence of any dishabituation effect in the test phase.

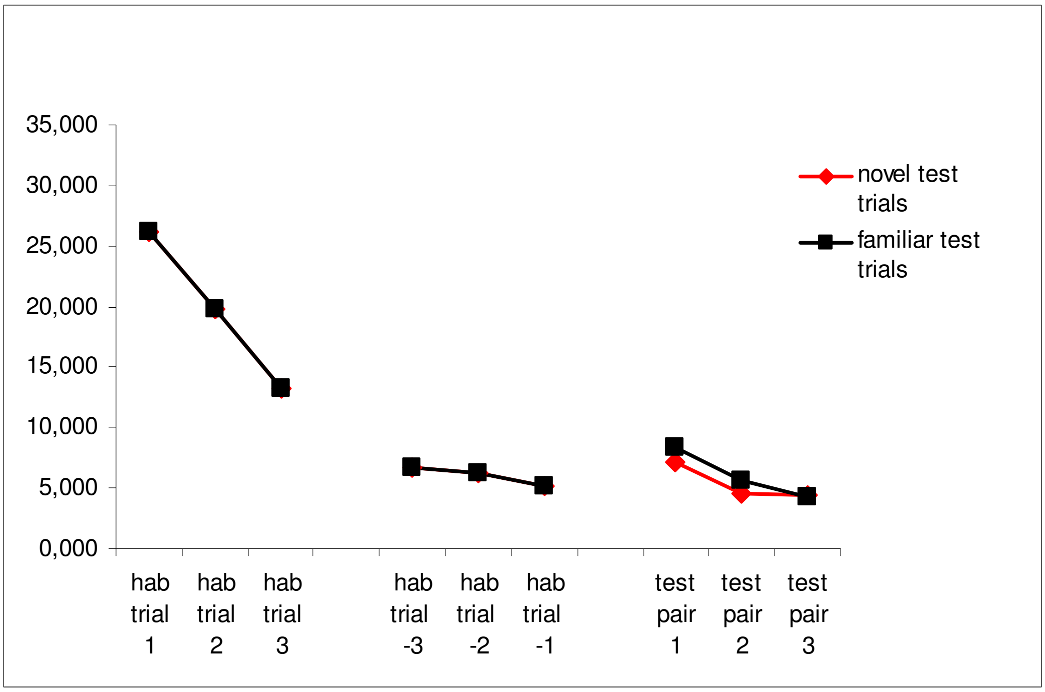


**Figure 2.7**

Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of familiar and novel test trials for all infants tested in Exp. 2

Overall, these results indicate that 4-month-old infants were not able to discriminate between ordinal descending sequences and non-ordered random sequences of squares of different size. Rather, they seemed to process descending size based as non-ordinal sequences.

### *2.2.3 Discussion*

The current experiment investigated whether 4-month-olds are able to detect the ordinal relationships embedded in descending sequences. To do so, we tested infants for their ability to discriminate size-based sequences composed of squares whose sized varied according to a descending rule, from non-ordered sequences composed of the same squares presented in a random order. Results showed that 4-

month-old infants are not able to discriminate between descending and non-ordered sequences: They did not discriminate between the familiar and novel test sequences, irrespective of the nature (descending or random) of the sequences to which they had been habituated. This finding suggests that at infants at 4 months are prevented from detecting the presence of any ordinal relationships when these relationships are embedded in descending size-based sequences. In addition, the fact that infants' looking times did not differ between the two habituation conditions, nor for the habituation phase nor for the test phase, strongly suggests that infants perceived and processed descending sequences as non-ordered, in the same way as random sequences do.

Together with the results of Exp. 1, these findings show that 4-month-old infants are able to grasp ordinal information embedded in size-based sequences only when those relationships follow an ascending direction. However, the evidence provided so far do not allow us to definitively conclude that infants at this age are really able to grasp ordinal information embedded in ascending sequences without excluding the hypothesis that successful discrimination obtained in Exp. 1 was driven by the detection of qualitative perceptual changes between the scending and descending sequences.

### 2.3 *Experiment 3: 4-month-olds' discrimination of ascending vs. descending ordinal relationships within size-based sequences controlled for perceptual looming-zooming effects*

Results from Exp. 1 and Exp.2 showed that 4-month-olds were able to represent the ordinal relations between continuous variables only when they were habituated to ascending sequences. In particular, the results of Exp. 2 confirmed the hypothesis that 4-month-old infants are not able to grasp the ordinal relationships embedded in descending sequences, and perceive and represent size-based descending sequences as non-ordered.

In Exp. 3, we tested for the hypothesis that 4-month-old infants tested in the ascending habituation condition of Exp. 1 succeeded in discriminating the novel from the familiar test sequences because they detected a qualitative perceptual change, and not a directional change in ordinal relationships. Despite the appearance of an ISI white display before and after each of the three squares composing the ordinal sequences presented in Exp. 1, the expansion in the size of the squares in the ascending sequences may have achieved an approaching percept (looming) whereas the compression of the size of the squares composing the descending sequences may have yielded a retracting percept (zooming). To disentangle the role of these perceptual effects in influencing infants' discriminative responses in the ordinal task, in Exp. 3 we tested a new group of 4-month-olds using the same exact procedure of Exp 1, with the only exception being the stimuli. To avoid any zooming/looming perceptual effects infants were presented with sequences composed of bars whose size increased or decreased accordingly to their length, but not their height.

### *2.3.1 Method*

***Participants***

Participants were 22 healthy, full term 4-month-old infants (*M* age = 4 months, 18 days; range = 4 months, 1 days – 4 months, 29 days). Nine of the participants were female. Two additional infants were tested but exclude from the final sample due to failure in reach criteria established for data analyses (N=4). Data from additional 10 infants were discarded because of fussiness (N=6) or being not cooperative (N=4), resulting in failure to complete all the test trials. Infants were recruited via a written invitation, which was sent to parents based on birth records provided by the neighboring cities. The majority of participants were from Caucasian, middle class families. Parents gave their written informed consent before testing commenced.

***Stimuli***

Stimuli were single rainbow-colored bars that varied in size (range 6-48 cm²). They were presented on a white background in the center of the computer monitor with the bars' longer side aligned to the horizontal plane There were four sets of stimuli, three for the habituation phase and one for the test phase. The first habituation set contained bars that were 6, 12, 24 cm² in total area. Stimuli within each set were created so as to have all the same height, so that for example the bar of cumulative area of 6 cm² was 2 cm wide x 3 height, while the bar of 12 cm² in total area was 4 cm wide x 3 cm height, and so on. The second set contained bars of 9, 18, 36 cm² (height kept constant at approximately 3,5 cm) and the third habituation set contained bars of 12, 24, 48 cm² (height kept constant at approximately 4 cm). The test set contained three novel bars that were 8, 16, and 32 cm², with the height of each bar kept constant at 3,2 cm. Thus, as in the previous experiments, the element sizes within each set differed always by a 1:2 ratio.

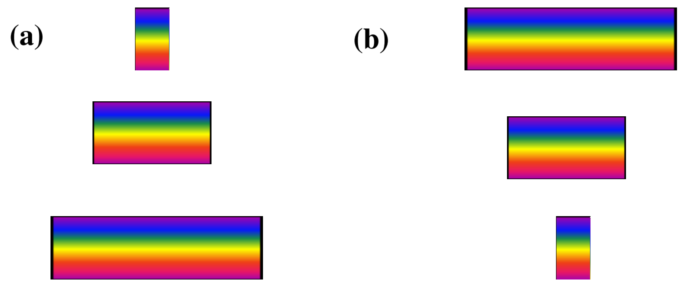


**Figure 2.8**

Example of stimuli used in Exp.3: (a) ascending sequence and (b) descending sequence

***Design, Apparatus, Procedure***

Same as in Exp.1

***Data analyses***

In order to be included in the analyses infants has to provide a minimum looking time in each test trials of 1 sec. For this reason, 2 subjects were tested but excluded to the final sample Inter-coder 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 six test trials was r = .98.

### *2.3.2 Results*

All infants reached the habituation criterion and, on average, habituation required 6.8 trials. A paired-samples t-test confirmed the presence of a significant decline in mean looking time from the first three ($M$=17.25 s) to the last three habituation trials ($M$=5.27 s), $t(21) = 11.873$, $p<.001$.

To determine whether in test infants were able to discriminate the familiar ordinal direction from the novel, reversed ordinal direction, a preliminary three-way analysis of variance (ANOVA) was performed, with *first test trial type* (novel vs. familiar) as the between-subjects factor, *trial pair* (first vs. second vs. third) and *test trial type* (familiar vs. novel ordinal direction) as within-subjects factors. The ANOVA revealed a significant main effect of *trial pair*, F(2,20)= 6.978, $p<.05$, $\eta p^2=.259$, which was qualified by a significant *trial pair* x *first test trial* x *test trial type* interaction, $F(2,20)=10.602$ , $p<.005$, $\eta p^2=.358$.

Infants who first saw a novel descending trial in test, looked significantly longer to the novel sequence ($M$=9.62 s) compared to the familiar sequence ($M$=3.59 s) in the first test trial pair, $t(12)=2.846$, $p<.05$, whereas this difference was not present for infants who first saw a familiar trial in test (novel: $M$=8.59 s vs. familiar: $M$=10.52 s; $t(8)=0.754$, $p=.472$). Nevertheless independent–samples t-test performed on the average looking time accumulated on the first pair of trials showed that the difference between the two groups was driven by the looking time accumulated on the familiar trial within the first pair ($M$=10.3 s vs. $M$=3.6 s; $t(20)=3.625$, $p<.005$), that was significantly longer for infants whose first test trials was familiar. More importantly, t-test revealed that the amount of time infants looked at the novel test trial within the first pair did not differ between groups ($M$=8.6 s vs. $M$=9.6 s; $t(20)=0.306$, $p=.763$), as evident from Figures 2.11 and 2.12. For infants who were first exposed to a novel trial in test, paired-samples t-tests showed a significant increase in average looking time between the last two habituation trials ($M$= 5.07 s) and the novel test trials ($M$=6.55 s),

$t(12)=2.635$, $p<.05$, but not between the end of the habituation and the familiar test trials ($M=4.61$ s), $t(12)=0.545$, $p=.596$, demonstrating a dishabituation effect to the novel but not to the familiar test trials.

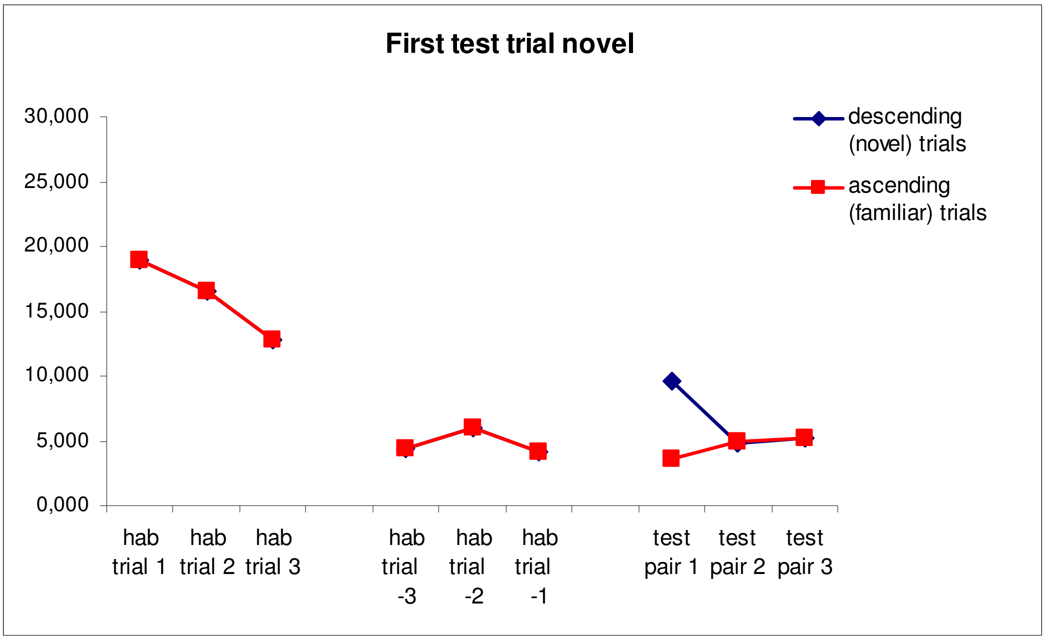


**Figure 2.9** Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of familiar and novel test trials for infants in Exp. 3 who in test first saw a novel descending trial (N=13)

This dishabituation effect was not present for infants who were first exposed to a familiar trial in test, whose average looking time on the last two habituation trials ($M=5.06$ s) did not differ from average looking time on the novel test trials ($M=6.78$ s, $t(8)=0.804$, $p=.445$), nor on the familiar test trials ($M=6.61$ s, $t(8)=0.929$, $p=.380$).

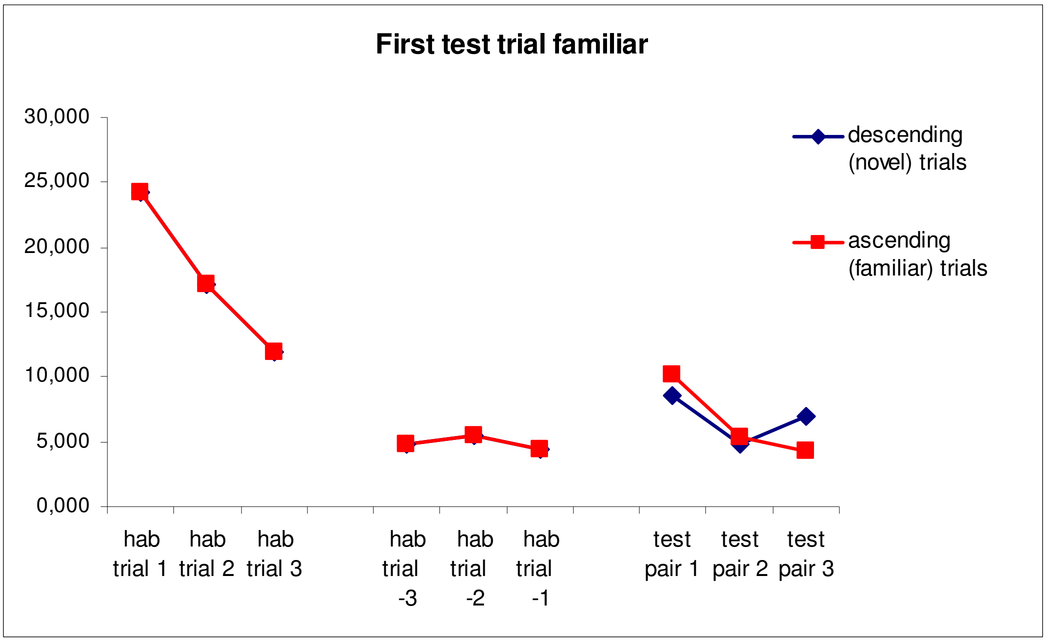


**Figure 2.10** Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of familiar and novel test trials for infants in Exp. 3 who in test first saw a familiar ascending trial (N=9)

### *2.3.3 Discussion*

The current experiment investigated whether 4-month-olds are able to represent the ordinal relations between continuous magnitudes that are controlled for zooming/looming perceptual effects, when they were habituated to ascending sequences. Results demonstrated that infants showed a novelty preference only when the reversal in the ordinal direction was presented in the first test trial. Otherwise, looking times between novel and familiar test trials did not significantly differ.

We interpreted these findings as showing that 4-month-old infants can discriminate inversions in the direction of ordinal size-based sequences, as shown by the novelty preference manifested in test pair one by infants who saw the novel sequence as the first test trial. At the same time, though, we interpreted the lack of an overall novelty preference in the current experiment as resulting from the low saliency of the stimuli used in the task, which did not carry enough salient information to keep the babies engaged in the task. As a result, novelty preference may have been obscured by the reactivation of infants' attention that followed the passage from the habituation to the test phase, which determined a generalized increase in looking times, as shown by the significant main effect of the factor pair. Importantly, though, the results showed that this generalized reactivation of infants' attention at the beginning of the test phase was more pronounced for infants who began the test phase with a novel trial than for infants who began the test phase with a familiar trial, as proven by the finding that only those infants manifested a novelty preference in test pair one.

## 2.4 General Discussion

The aim of the Experiments presented so far was to investigate whether the ability to appreciate ordinal relationships between continuous, non-numerical magnitudes could be found in infants younger than 9 months. To do so, we tested 4-month-olds' ability to discriminate an inversion in the direction of ordinal direction of size-based sequences composed of one single element varying in size.

Results from Exp. 1 demonstrate that 4-month-olds are able to do the task, but only when they had been previously habituated to ascending ordinal relationships. Infants who were habituated to descending sequences did not discriminate between the familiar and the novel ordinal directions presented in test trials, as evidenced by the fact that they didn't show any preference, nor for the novel nor for the familiar sequences.

This unexpected finding suggests the presence of an asymmetry in infants' ability to detect ordinal relationships within ascending and descending sequences. Interestingly, a similar asymmetry has been previously observed in studies on numerical cognition in non-human primates, that showed that monkeys are able to generalize the ordinal rule they learned during training to the novel numerical values only in the case of ascending ordinal relationships, and not in the case of descending order relationships (Brannon, Cantlon et al., 2006; Brannon & Terrace, 2000). The lack of discrimination between the familiar and the novel test sequences for the infants habituated to the descending ordinal relationships could originate from infants' difficulty in coding and processing the ordinal relationships between elements varying in size according to a descending rule. According to this interpretation, 4-month-old infants in Exp. 1 may have perceived descending sequences as if they were non-ordered at all. To test this hypothesis, in Exp. 2 we investigated 4-month-olds' ability to discriminate the ordinal relationships embedded in descending sequences from non-ordinal relationships embedded in random, size-based sequences. Results showed that infants were not able to discriminate between descending and non-ordered sequences because they did not discriminate between the familiar and novel test sequences, irrespective of the nature (descending or random) of the sequences to which they had been habituated. This finding provided further support to our claim that, at least in the case of size-based sequences, at 4 months infants are unable to detect the presence of any ordinal relationships when these relationships are embedded in descending sequences.

Taken together, results from Exp. 1 and Exp.2 seem to suggest that 4-month-old infants are able to grasp ordinal information embedded in size-based sequences only when those relationships follow an ascending direction, whereas they encountered some difficulties in provided processing descending sequences, as they perceived and processed them as non-ordered, in the same way as random sequences are. However, the evidence so far do not allow us to definitively conclude that 4-month-old infants are really able to grasp ordinal information embedded in ascending sequences without excluding the hypothesis that successful discrimination obtained in Exp. 1 was driven by the detection of qualitative perceptual changes between the ascending and descending sequences. In fact, another possible interpretation of the results emerged from the ascending habituation condition of Exp. 1 is that 4-month-old infants in the ascending habituation condition detected a qualitative change, rather than an ordinal change, between the ascending and descending sequences. Because all stimuli were located at the centre of the screen, ascending sequences may have achieved an approaching percept (zooming), whereas descending sequences may have yielded a retracting percept (looming). To control for this possibility, differently from previous studies (Brannon, 2002; Suanda et al., 2008), we presented white ISI displays before and after each of the three squares composing the sequences. However, to further exclude the possibility that perceptual effects may have yield to the discrimination observed in the ascending condition of Exp. 1, we replicated Exp. 1 using stimuli that did not evoke any looming/zooming perceptual effect in Exp. 3.

Results of Exp. 3 demonstrated that infants showed a novelty preference only when the reversal in the ordinal direction was presented in the first test trial. Otherwise, looking times between novel and familiar test trials did not significantly differ. We attributed the lack of an overall novelty preference as resulting from the low saliency of the stimuli used in the task, which did not carry enough salient information and, as a result, novelty preference may have been obscured by the reactivation of infants' attention that followed the passage from the habituation to the test phase, which determined a generalized increase in looking times, as shown by the significant main effect of the factor pair. It is possible that the use of stimuli that were specifically constructed in order to display a change in the size only over one out of the two dimensions, while avoiding perceptual effects, could have also impeded the detection of the size-based changes. In other words, it is possible that an increase (or descrease) in size specific to  only one dimension made the size-based change less salient.

Because discriminability depends on the ratio of the set sizes, and given that younger infants require greater ratios compared to older infants (Lipton & Spelke, 2003), 4-

month-olds may require a ratio greater than 1:2 to detect the size-based change within this set of stimuli.

Alternatively, 4-month-olds may need to be presented with stimuli with an overall greater salience in order to succeed in discrimination within the 1:2 ratio.

## CHAPTER 3: THE DISCRIMINATION OF ORDINAL RELATIONSHIPS IN TEMPORAL SEQUENCES OF NUMERICAL MAGNITUDES

This chapter presents 3 different experiments in which 7-month-old infants were tested using an infant-controlled habituation paradigm for their ability to discriminate inversions in the direction of ordinal sequences of numerical, discrete, magnitudes. As already mentioned in the 1st chapter, this ability has been previously reported in 11-month-old infants (Brannon, 2002; Suanda et al., 2008). The aim of our research project was to investigate whether the ability to appreciate ordinal relationships embedded in numerical sequences could be found in infants younger than 11 months, when multiple sources of information (i.e. color and shape) and redundant cues to ordinality are provided throughout the task. Additionally, in light of recent evidence on the existence of an early developing predisposition to relate representations of numerical magnitudes and spatial length in 8 month-old infants (de Hevia & Spelke, in press, see chapter 1), we tested 7 month-olds also for the presence of a basic mapping of space to number.

Available evidence from research on the development of temporal sequences learning indicates that the ability to associate different stimuli on the basis of spatiotemporal information, which is based on temporal and/or spatial proximity, remains constant across development, after its first appearance in the first months of life (Kirkham et al., 2002). Most crucially, recent work conducted by Kirkham and colleagues (Kirkham et al., 2007) on infants' learning of spatiotemporal sequences - event sequences defined by time and location statistics- demonstrated that, at 8 months, learning can be facilitated when the events within the sequence are specified by multiple sources of information (color and shape). Kirkham et al. (2007) found that 5- and 8-month-old infants failed to learn the statistic of spatiotemporal sequences composed of a single colored shape, and that 8-month-olds, but not 5-month-olds, succeeded in the same task when the objects composing the sequences differed in both color and shape.

Overall, available evidence suggests that a mechanism capable of detecting and learning simple temporal patterns is available early in development, and that in older infants, at 8 months of age, (Kirkham et al., 2007) integration of multiple sources of information plays an important role in supporting the extraction of structure from the sequence and in strengthening the representation of the sequence pattern, at least when location-based associations have to be extracted.

In the present study, we adopted the logic of research on sequence learning and multiple cue integration to investigate whether, in absence of quantitative cues but in the presence of multiple visual features, infants would manifest the ability to detect ordinal numerical relationships within temporal sequences at an earlier age than what was previously found (i.e., 11 months, Brannon, 2002; Suanda et al., 2008). In particular, we tested whether 7-month-old infants can extract the ascending or descending ordinal relationships among numerical displays when multiple visual features are available both within (shape) and between (colour) the ordinal sequences, and thus succeed in detecting a reversal in the sequences' ordinal direction even when quantitative cues are not available.

As in Brannon (2002) and Suanda et al. (2008), infants were habituated to ascending or descending repeated dynamic sequences of three sets of numerical displays, and then tested with a new set of numerical displays presented in both the familiar and reversed ordinal direction. However, we departed from past studies by introducing the following methodological manipulations. First, in the current study the numerical displays were composed of coloured bars. Importantly, in order to highlight the distinctiveness of each numerical sequence, the bars varied in colour between the sequences. With this manipulation we provided infants with a means to cluster the sequences, thus favouring the abstraction and learning of the ordinal rule.

Second, by controlling the overall contour length of the numerical displays within each sequence, in addition to the total surface area, single items in the habituation trials varied in shape, as the result of a variable ratio between width and height. More precisely, the variation was such that the shape of the bars embedded in each display correlated with the numerosity of the display: higher bars for smaller numbers, medium-high bars for medium numbers, and shorter bars for larger numbers. Although the physical size of the bars was inversely related to number, we reasoned that the variation in the shape of the bars would have emphasized the distinctiveness of each display within the sequences, possibly drawing infants' attention to the numerical magnitude embedded in the display. In particular, by associating the smaller, medium and larger numerical display within each sequence to a specific shape, we provided infants with an additional cue of ordinal relationships, in that infants could use the items' shape, in addition to the items' number, to individuate the constituent displays of each ordinal sequence.

A further relevant feature that differentiates the current study from previous research is the size of the numbers presented. In earlier studies by Brannon (2002) and Suanda et al. (2008), ordinal sequences contained both small (< 4) and large (> 3) numbers, whereas in the present study only large numerical values were presented (range 4-48). This choice was based on the premise that, according to the well-known two-systems model of infants' numerical representation proposed by Feigenson and collagues (Feigenson et al., 2004), infants' quantitative competence are subserved by two distinct representational systems, one for representing large, approximate numerical magnitude, and the second for the precise representation of small numbers of individual objects. Within this theoretical framework, the representations resulting from the appreciation of the cardinal value of small and large numbers are difficult to compare, as suggested by the finding that 6- and 7-month-olds fail to make 1:2 numerosity discriminations when one set is small and the other is large (Xu, 2003), while they succeed when given a fourfold change in number (Cordes & Brannon, 2009). Thus, to avoid the possibility that the engagement of the two core systems would hinder the appreciation of ordinal relationships among the numerical values included in the sequences, we presented infants with numerosities larger than 3 (range 4-48).

Finally, the presentation time of each numerical display was increased, relative to past studies with older infants (Brannon, 2002; Suanda et al., 2008). Although in Suanda et al.'s (2008) study an increase in time exposure did not allow 9-month-old infants to detect reversals in a purely numerical ordinal sequence, we introduced this manipulation in order to adapt the information processing demands of the task to the age of the participants (Wood & Spelke, 2005).

In Exp. 5 we added spatial cues to the ordinal task used in Exp. 4 in order to investigate whether a basic mapping of space to number is present in 7-month-old infants, given the recent evidence provided by de Hevia & Spelke (in press) that showed 8-month-old infants' predisposition to relate representations of numerical magnitudes to spatial length. More precisely, in Exp. 5 we tested whether infants are able to link oriented left-to-right spatial codes to representations of numerical magnitudes.

## *3.1 Experiment 4: 7-month-olds' detection of ordinal numerical relationships within temporal sequences*

### *3.1.1 Method*

***Participants***

Participants were 16 healthy, full term 7-month-old infants (*M* age = 7 months, 19 days; range = 7 months, 5 days – 7 months, 27 days). Eight of the participants were female. Twelve additional infants were tested but excluded from the final sample due to experimenter error (N=3), fussiness (N=3) or being not cooperative (N=6), resulting in failure to complete all the test trials. Infants were recruited via a written invitation, which was sent to parents based on birth records provided by the neighboring cities. The majority of participants were from Caucasian, middle class families. Parents gave their written informed consent before testing commenced.

***Stimuli***

Stimuli were arrays of colored rectangular-shaped items presented on a white background, randomly arranged, with the item's shorter side aligned with the horizontal plane. Stimuli were created using E-Prime 1.0 software. There were four sets of stimuli, three for the habituation phase and one for the test phase. The first habituation set contained 6,12, and 24 items; the second contained 9,18, and 36 items;

and the third contained 12, 24, and 48 items. The test stimulus set contained 4, 8, and 16 items. Each stimulus set was presented in a different color: “blue” (R.G.B.: 0, 0, 255) for the 6-12-24 set, “red” (R.G.B.: 255, 0, 0) for the 9-18-36 set, “green” (R.G.B.: 6, 141, 6) for the 12-24-48 set, and “purple” (R.G.B.: 201, 28, 195) for the 4-8-16 test set (see Figure 3.1). Thus, the numerosities within each set differed by a 1:2 ratio, well within the limits of 7-month-old infants’ numerical discrimination abilities (Xu & Spelke, 2000). For each stimulus set, three different exemplars that differed in item configuration were generated.

To ensure that non-numerical, continuous variables did not provide any cue to the ordinal relations during habituation, cumulative surface area and contour length were kept constant by varying item size and shape inversely to number. Thus, the height of the single items for the smaller, medium, and larger displays were, respectively, 3.3 cm, 1.5 cm, and 0.6 cm, with the width constant at 0.3 cm. In addition, the size of each habituation display was held constant at 176.04 $cm^2$ (16.3 cm x 10.8 cm), so that number covaried with density. For test displays, the cumulative surface area and contour length were positively correlated with number: the item size and shape were kept constant at 1.4 cm x 0.5 cm. In addition, the display size varied, such that density was held constant at 0.06 elements per $cm^2$. Therefore, the continuous variables that varied in habituation trials were held constant in test trials, and vice-versa (see Figure 3.1).

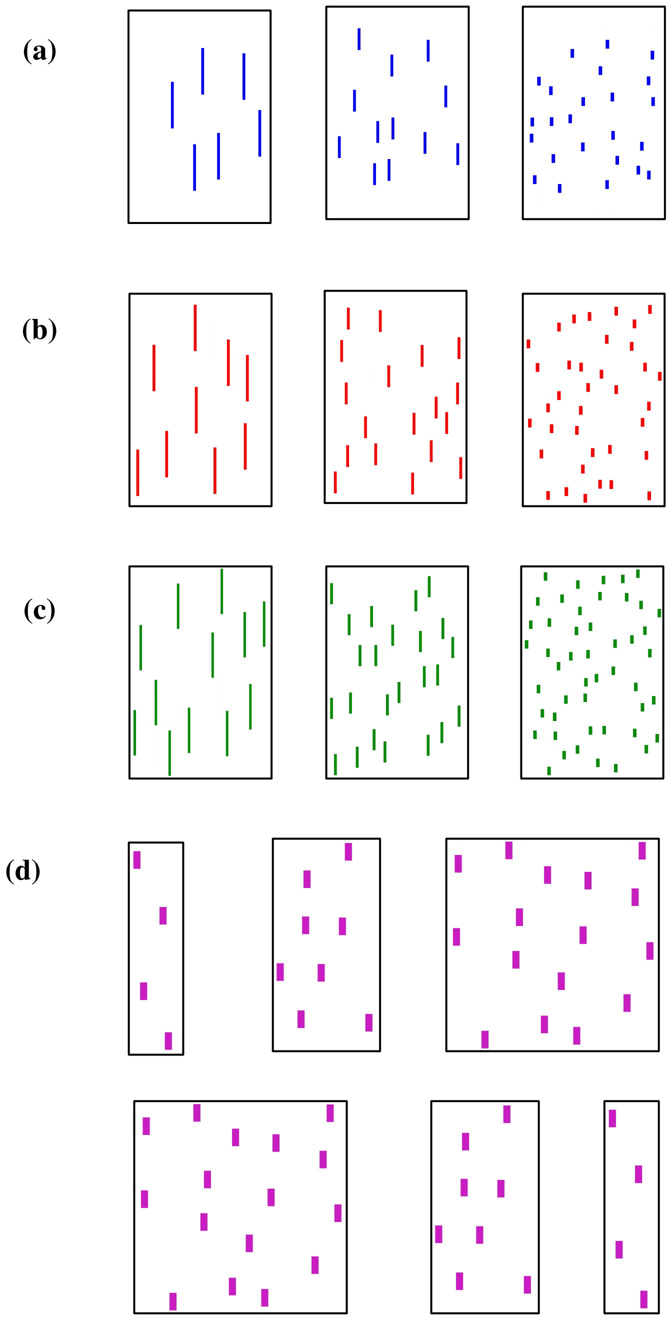


**Figure 3.1** The four set of stimuli used in Exp. 1. The first three lines (a), (b), (c) represent the stimulus sets presented in the ascending habituation; the last two lines (d), represent the stimulus set presented in the familiar and novel test trials. The first habituation set (a) contained 6,12, and 24 blue items, the second (b) 9-18-36 red items, and the third (c) 12-24-48 green items. The test set (d) contained 4-8-16 items presented in purple.

***Design***

Infants were habituated to ascending or descending sequences of three numerical displays (e.g. 6-12-24 or 24-12-6) and then tested with both ascending and descending sequences containing novel numerical values. Half of the infants were randomly assigned to the ascending habituation condition.

Within each habituation condition, the three different stimulus sets were cycled in a fixed order until the infant met the habituation criterion: from the smallest to the largest numerical display for the ascending condition (i.e., 6-12-24; 9-18-36; 12-24-48), and from largest to the smallest for the descending condition (i.e., 48-24-12; 36-18-9; 24-12-6). Following habituation, all infants were given six test trials alternating the ascending and descending sequences. Order of presentation was counterbalanced across participants. The use of a consistent fixed order of presentation of the numerical displays across trials for each of the two habituation conditions was intended to provide infants with additional redundant cues to ordinality between, as well as within, trials. Although there is no direct evidence that infants are able to extract the average number from different numerical values, this possibility finds partial support in the finding that 9-month-olds can compute the addition of two numerical arrays and compare the result to a third array (McCrink & Wynn, 2004, 2009). If, in the current study, infants were capable to average the three numerical values included in any habituation set and compare the result to another averaged set, then they would have been helped in the abstraction and learning of the ordinal rule embedded within the habituation trials by the redundant information of increasing or decreasing magnitude embedded between at least 2/3 of the trials.

***Apparatus***

Each infant was tested while sitting in an infant seat approximately 60 cm from the monitor where the stimuli were presented. A curtain separated the participant from the experimenter at all times. Parents were asked to remain on the experimenter's side of the curtain, so as to not distract the infant, but were free to go to the infant at any time should he or she show signs of distress. 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 TV monitor to allow the online coding of the infant's looking times by the experimenter, who was blind to the habituation condition to which the infant was assigned. Looking behavior was recorded by holding a button down when the infant was looking at the computer monitor and letting it go when the infant looked away. The button input was fed into an E-Prime program, which automatically computed the parameters that determined the end of each trial, and when the habituation criterion was met. The live image of the infant's face was also recorded via a Mini-Dv digital recorder, and for half of the infants in each habituation condition data were subsequently coded offline.

***Procedure***

A cartoon animated image associated to a varying sound served as attention catcher before the trial began. When the infant looked in the direction of the animated fixation point, the experimenter started the trial. Each trial consisted in a repeating cycle (5750 ms in total) that began with a black screen (500 ms) followed by the three numerical displays. The displays were consecutively presented on a white background for 1750 ms each. 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 stimulus sets were presented in a fixed order and repeated until the infant either was given a maximum of 14 trials or met the habituation criterion, which was defined as a 50% decline in looking time on three consecutive trials, relative to the total looking time on the first three trials that summed to at least 12 s. Following habituation, infants were given 6 test trials, in which novel (ascending for infants habituated to descending sequences and vice-versa) and familiar ordinal sequences appeared in alternation with half of the infants seeing the novel test sequence first.

***Data analyses***

Inter-coder 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 six test trials was $r = .99$.

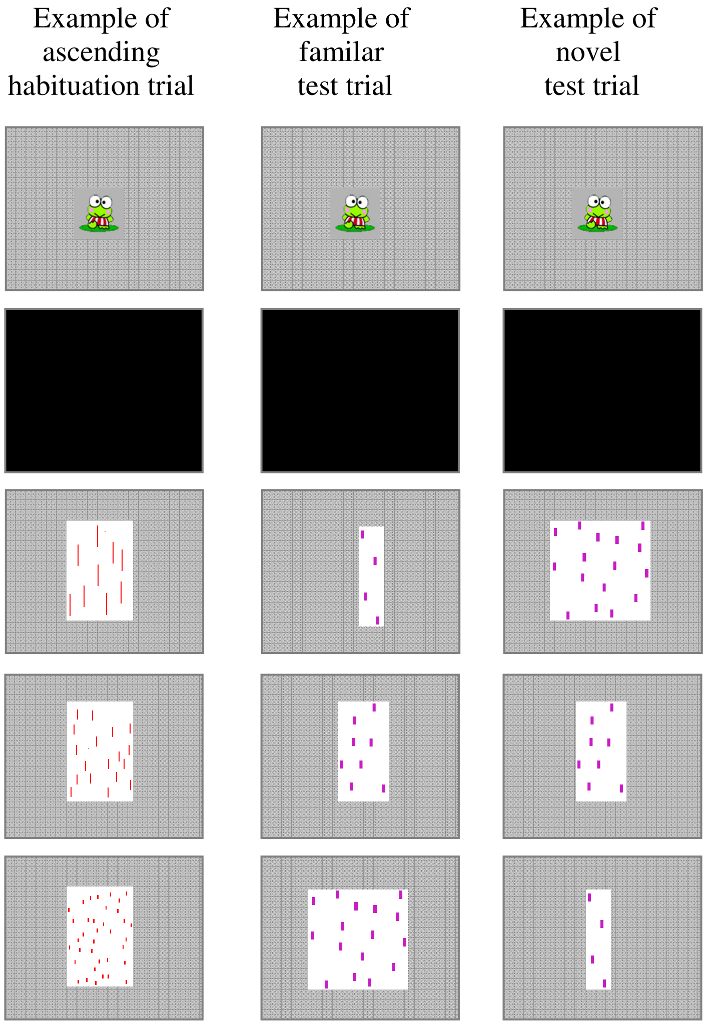


**Figure 3.2** The sequence of events in each trial for Exp. 4: the fixation point and the three numerical displays composing each sequence. The sequence repeated, beginning with the black screen, until specific criteria were met. 1

### *3.1.2 Results*

A preliminary analysis of variance (ANOVA) with *habituation condition* (ascending vs. descending) as the between-subjects factor, and *habituation trials* (first three vs. last three) as the within-subjects factor was performed in order to verify whether there were any difference in the way infants who were exposed to different order habituation conditions reached the habituation criterion. Results revealed a significant main effect of the *habituation trials* factor $F(1,15)=36.147$, $p<.005$, $\eta p^2=.721$, due to average looking time on the first three habituation trials ($M$= 68.2 s) being significantly longer than average looking time on the last three habituation trials ($M$=27 s). There were no main effect nor interaction involving the factor *habituation condition*. All infants reached the habituation criterion and, on average, habituation required 7.7 trials.

To determine whether in test infants were able to discriminate the familiar ordinal direction from the novel, reversed ordinal direction, a four-way analysis of variance (ANOVA) was performed, with *habituation condition* (ascending vs. descending) and *first test trial* (novel vs. familiar) 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. The analysis revealed a significant *first test trial* x *trial pair* interaction, $F(1,14)=4.95$, $p<.05$, $\eta_p^2=.29$, but all follow-up comparisons failed to reach significance ($p$s > .2, Bonferroni corrected). Most crucially, there was a main effect of *test trial type*, $F(1,15)=9.06$, $p<.02$, $\eta_p^2=.43$, with no interactions involving this factor. As evident from Figure 2, across the three pair presentations infants looked longer to the novel ($M$=10.7 s) compared to the familiar test trials ($M$=7.8 s), thus showing a successful discrimination of the novel ordinal sequence.

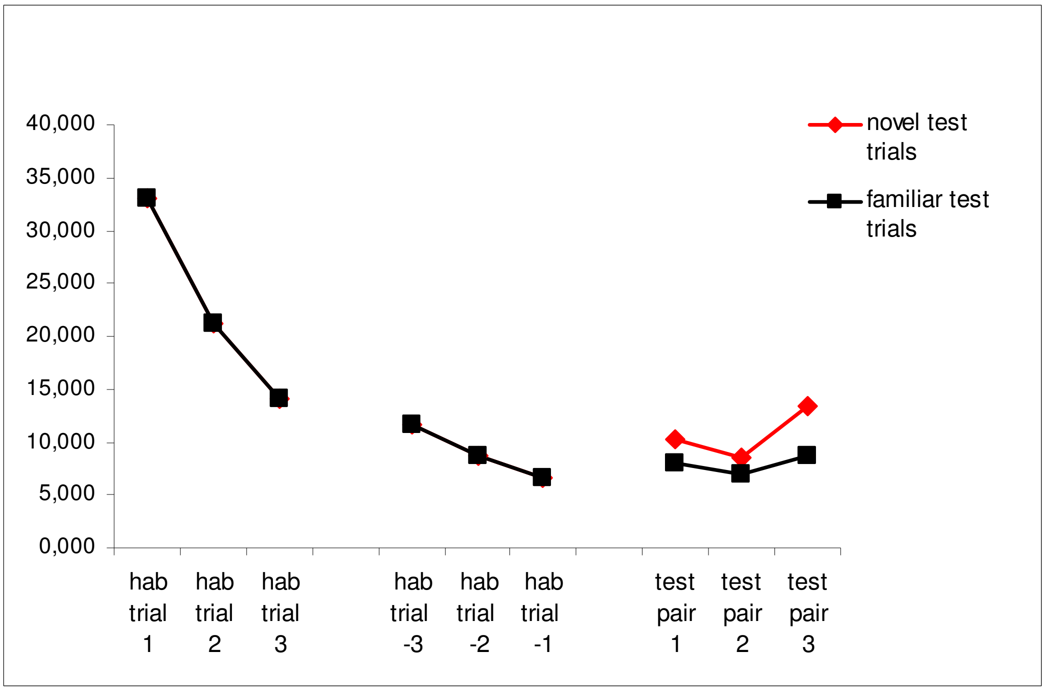


**Figure 3.3**

Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of familiar and novel test trials for infants in Exp. 4

Additional analyses confirmed the evidence of sensitivity to numerical ordinal relations in the tested group of infants. First, examination of the data for individual infants revealed that 14 out of 16 infants (Binomial test, $p<.001$) looked longer to the novel compared to the familiar test trials. Second, paired-samples *t*-tests showed a significant increase in average looking time between the last two habituation trials[2] ($M=7.7$ s) and the novel test trials, $t(15)=2.43$, $p<.05$, but not the familiar test trials, $t<1$, n.s., demonstrating a dishabituation effect to the novel but not to the familiar test trials.

[2] As evident from Figure 3.3, although there is an overall steep decrement curve in looking time durations between the first three and the last three habituation trials, there is still a notable decrease between the third-from-last ($M = 11.7$ s), the second-from-last ($M = 8.7$ s) and the last habituation trial ($M = 6.6$ s). In particular, the third-from-last trial does not differ from the third habituation trial ($M = 14.0$ s; $p = .18$) but is marginally different from the second-to-last trial ($p = .06$). Therefore, in order to capture the end of the habituation process, we calculated the dishabituation effect with respect to the last two, rather than three, habituation trials.

Overall, these results indicate that infants were able to form a number-based representation of the ordinal relations embedded in the numerical sequences during habituation and discriminate the reversal in ordinal direction embedded in the novel test sequences.

### *3.1.3 Discussion*

The experiment investigated whether the ability to appreciate ordinal relationships between numerical magnitudes is present in preverbal infants at an earlier age than previously reported (Brannon, 2002; Suanda et al., 2008), when multiple featural information and redundant cues to ordinality are provided throughout the task. The results demonstrate that, under these conditions, 7-month-old infants can represent numerical ordinal relations and detect reversals in ordinal direction. With respect to the available literature on ordinal numerical cognition in infancy, the contribution of the current study concerns the impact of featural information and multiple cue integration on infants' proneness to detect number-based patterns of ordinal regularities across changes in non-numerical dimensions. Suanda et al. (2008) showed that 9-month-old infants succeeded at appreciating ordinal relations when such relations were specified by multiple quantitative cues (e.g., number, item size, total surface area), but failed when only numerical cues were available in the face of conflicting non-numerical cues. In the current study, 7-month-old infants succeeded at detecting and representing ordinal relations relying solely on number, with non-numerical quantitative cues displaying non-monotonic changes. In fact, of the four considered continuous dimensions (i.e., cumulative surface area, item size, contour length, and density), only one (density) co-varied with number in habituation, whereas the other three were either constant (surface area and contour length) or inversely related to number (element size). In test, the two dimensions that were constant in habituation did co-vary with number, but the two that varied in habituation were kept constant. Therefore, the most important implication of these results is the demonstration that not only numerical cues are sufficient for 7-month-olds to appreciate ordinal relations, but also that ordinal relations between numbers were salient enough in our experimental design as to allow infants to filter out conflicting cues provided by changes in the three non-numerical quantitative dimensions. When considered together with Suanda et al.'s (2008) results, these findings provide strong indication that redundant information and multiple featural cues can help infants to discern the ordinal pattern embedded in temporal sequences of numerical displays across a wide range of input, thus bolstering their sensitivity to ordinal relations.

### *3.2 Experiment 5: 7-month-olds' detection of ordinal numerical relationships within spatio-temporal sequences*

The current experiment was aimed to investigate the presence of a mapping of space to number by testing whether infants are able to link oriented spatial codes to representations of numerical magnitudes. It is well known that in adults a spontaneous use of space occurs in numerical processing in the form of a left-to-right oriented number line (Dehaene, 1992), for that adults link small numbers to "left" and large numbers to "right" (Dehaene et al., 1993). Recent evidence has demonstrated that preliterate children manifest an intuition for the left-to-right organization of numerical magnitude, which the authors interpret as deriving from experience in counting (Opfer & Thompson, 2006), suggesting that the directional mapping of numbers onto space is not entirely triggered by reading performance. These findings suggest that aspects of the spatial representation of number are influenced by experience, culture or instruction, but they do not reveal whether humans have an unlearned, automatic, and non-directional mapping of number to space. However, given that an early developing predisposition to relate representations of numerical magnitude and spatial length have been recently found in 8-month-olds (de Hevia & Spelke, in press), one could hypothesized that a basic mapping of space to number may exist from the very beginning, but its direction may be fixed by experience. Therefore, in the current study we investigated whether an oriented spatial-numerical link is present in 7-month-old infants. More specifically, using the same stimuli and procedure used in Exp.4, we tested whether infants' ability to encode the ordinal relationships embedded in the numerical sequences would be enhances when the numerical displays composing the sequences were presented in a different but contiguous spatial position from left to right along the horizontal axis, and whether this would happen selectively for ascending as compared to descending sequences. In other words, by presenting the numerical displays from left to right we tested whether 7-month-olds are facilitated in the encoding of the ordinal relationship when the direction of these relationships are congruent with the direction of the mental number line. Infants were habituated to ascending *or* descending ordinal sequences and tested with familiar *and* novel sequences. In both the habituation and test trials the first display of each ordinal sequence was displayed on the left side of the screen, the second was presented at the centre and the third one on the right side of the screen, so that infants could make an association between the spatial position of the numerical array and its relative magnitude within the sequence. Thus, for ascending sequences the direction was congruent with the mental number line, whereas for descending sequences it was incongruent with the direction of the adults' spatial representation of number. A preference for the novel trials in test would provide evidence for the presence of an early spontaneous mapping of number to space and would demonstrate that infants were able to link oriented spatial information to ordinal numerical information. Nevertheless, if the results revealed a novelty preference only for infants habituated to the ascending sequences but not for infants habituated to the descending sequences, this would indicate that the congruency between the direction of the ascending ordinal relationships and the left-to-right orientation of the spatial cues provided throughout the experiment played a crucial role in infants' abstraction of the ordinal rule and thus in the discrimination between familiar and novel trials. This finding would provide evidence against the hypothesis that the left-to-right direction of the mapping of space to number is the emerging product of learned, cultural factors.

### *3.2.1 Method*

***Participants***

Participants were 14 healthy, full term 7-month-old infants (*M* age = 7 months, 21 days; range = 7 months, 8 days – 8 months, 0 days). Nine of the participants were female. Twenty additional infants were tested but excluded from the final sample due to experimenter error (N=5), fussiness (N=5) or being not cooperative (N=10), resulting in failure to complete all the test trials. Infants were recruited via a written invitation, which was sent to parents based on birth records provided by the neighboring cities. The majority of participants were from Caucasian, middle class families. Parents gave their written informed consent before testing commenced.

***Stimuli, Design, Apparatus and Procedure***

The Stimuli (see figure 3.1), Design, Apparatus and Procedure were the same as in Exp. 5. The only difference was that the three numerical displays were consecutively presented (for 1750 ms each) on a grey background in three different spatial positions. The first display appeared always on the left part of the screen, (an area that goes 7 cm from the left edge of the screen and 36,5 cm from the right edge of the screen), the second display appeared within the central area of the screen (22 cm halfway between the edges) and the third display appeared on the right part of the screen (36.5 cm from the left edge of the screen and 7 cm from the right edge of the screen) (Figure 3.4).

To familiarize infants with the spatial task and calibrate the infants' gaze, infants were presented with a cartoon-animated image associated to a sound, which appeared sequentially on the left and on the right positions on the screen and served as attention catchers. The animated image was first presented on the left part of the screen, and as soon as the infant looked in the direction of the image, the experimenter presented the same image on the right side of the screen. This calibration was made to help the experimenter in the subsequent coding of the infant looking behaviour from left to right and to help the infant in focusing the attention on the different spatial positions were the stimuli appeared during the habituation task.

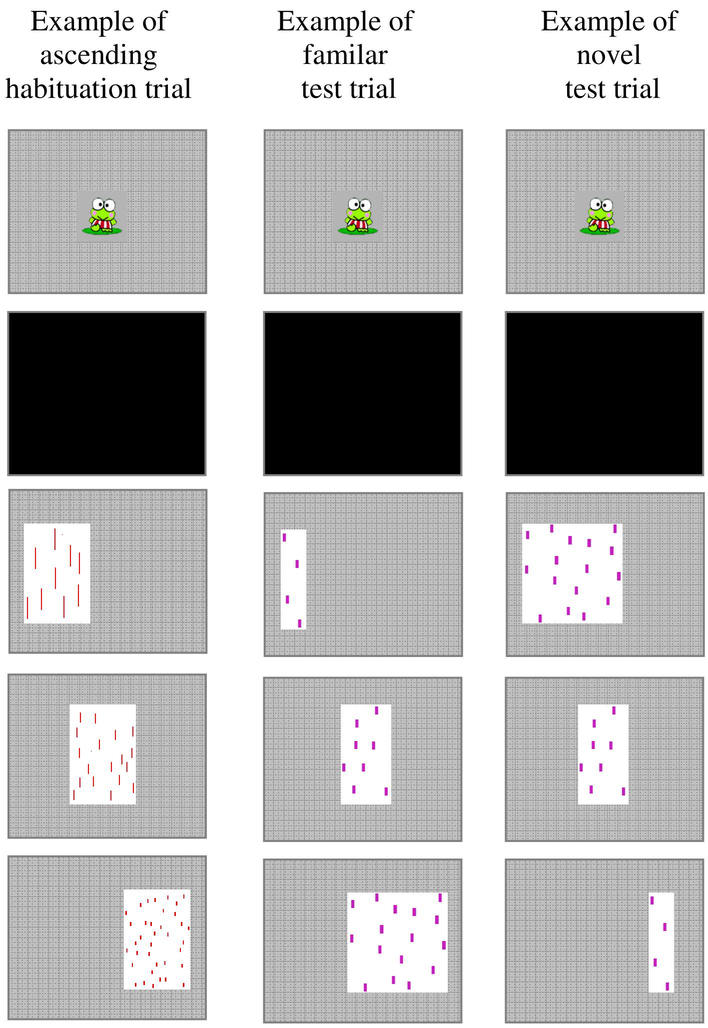


**Figure 3.4.**

The sequence of events in each trial for Exp. 5: the fixation point and the three numerical displays composing each sequence. The sequence repeated, beginning with the black screen, until specific criteria were met.

### *Data analyses*

Inter-coder 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 six test trials was r = .99.

### 3.2.2 Results

A preliminary analysis of variance (ANOVA) with *habituation condition* (ascending vs. descending) as the between-subjects factor, and *habituation trials* (first three vs. last three) as the within-subjects factor was performed in order to verify whether there were any difference in the way infants who were exposed to the two habituation conditions reached the habituation criterion. Results revealed a significant main effect of the *habituation trials* factor $F(1,13)=33.312$, $p<.005$, $\eta p^2=.735$, due to average looking time on the first three habituation trials ($M=62.34$ s) being significantly longer than average looking time on the last three habituation trials ($M=24.37$ s). There were no main effect or interaction involving the factor *habituation condition*. All infants reached the habituation criterion and, on average, habituation required 7.9 trials.

To determine whether in test infants were able to discriminate the familiar ordinal direction from the novel, reversed ordinal direction, a three-way analysis of variance (ANOVA) was performed, with *habituation condition* (ascending vs. descending) as between-subjects factor, and *trial pair* (first vs. second vs. third) and *test trial type* (familiar vs. novel ordinal direction) as within-subjects factors. A preliminary ANOVA including *first test trial type* (novel vs. familiar) as a between-subjects factor revealed no main effect or interactions involving this factor, therefore in subsequently analysis data were collapsed across first test trial type factor. The three-way ANOVA revealed a significant main effect of *trial pair*, $F(1,13)=7.046$, $p<.005$, $\eta_p^2=.370$, due to the fact that infants looked longer in the first pair of trials ($M=14.71$ s) as compared to the second ($M=10.56$ s, $t(13)=2.583$, $p<.05$) or to the third pair ($M=8.3$ s, $t(13)=3.721$, $p<.005$). The ANOVA also revealed a significant *test trial type* x *habituation condition* interaction, $F(1,13)=13.974$, $p<.005$, $\eta_p^2=.538$, which we followed-up through separate ANOVAs, one for each habituation condition. The ANOVA performed on infants habituated to the descending habituation condition revealed a significant *test* main effect, $F(1,6)=7.275$, $p<.05$, $\eta_p^2=.548$, due to longer looking times to the novel, ascending, test trials ($M$=43.03 s) than to the familiar test trials ($M$=28.08 s).

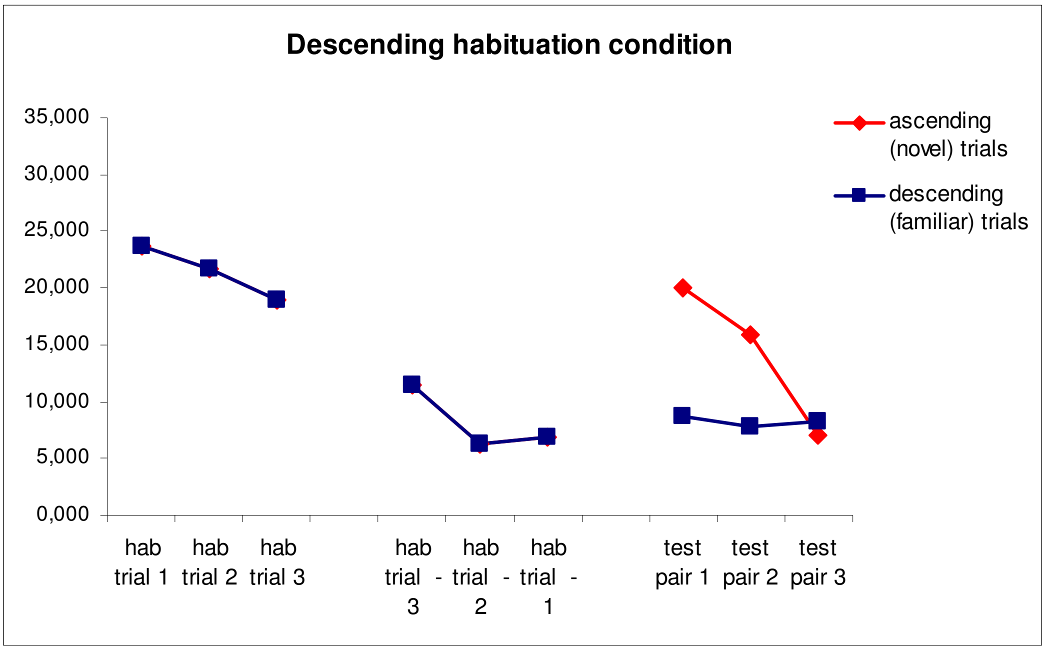


**Figure 3.6**

Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of familiar and novel test trials for infants habituated to descending sequences in Exp. 5

Although the same *test* main effect was present also in the ANOVA performed on infants tested in the ascending condition, $F(1,6)=8.581$, $p<.05$, $\eta_p^2=.589$, for this group the effect was due to longer to the ascending, familiar, test trials (*M*=38.3 s) as compared to the novel, descending trials (*M*=23.13 s).

As evident from the Figure 3.6, paired-samples t-tests performed on infants in the descending habituation condition showed a significant increase in average looking time between the last three habituation trials (*M*=8.19 s) and the novel test trials (*M*=13.4s), $t(6)=4.227$, $p<.05$, but not between the end of the habituation and the familiar test trials (*M*=8.27 s), $t(6)=0.083$, $p=.937$, demonstrating a dishabituation effect to the novel but not to the familiar test trials. In the same way, infants habituated to the ascending condition showed a significant increase in average looking time between the last three habituation trials (*M*=8.05 s) and the familiar test trials (*M*=12.77 s), $t(6)=4.634$, $p<.005$, but not between the end of the habituation and the novel test trials (*M*=9.37 s), $t(6)=1.301$, $p=.241$, demonstrating thus a dishabituation effect to the familiar but not to the novel test trials.

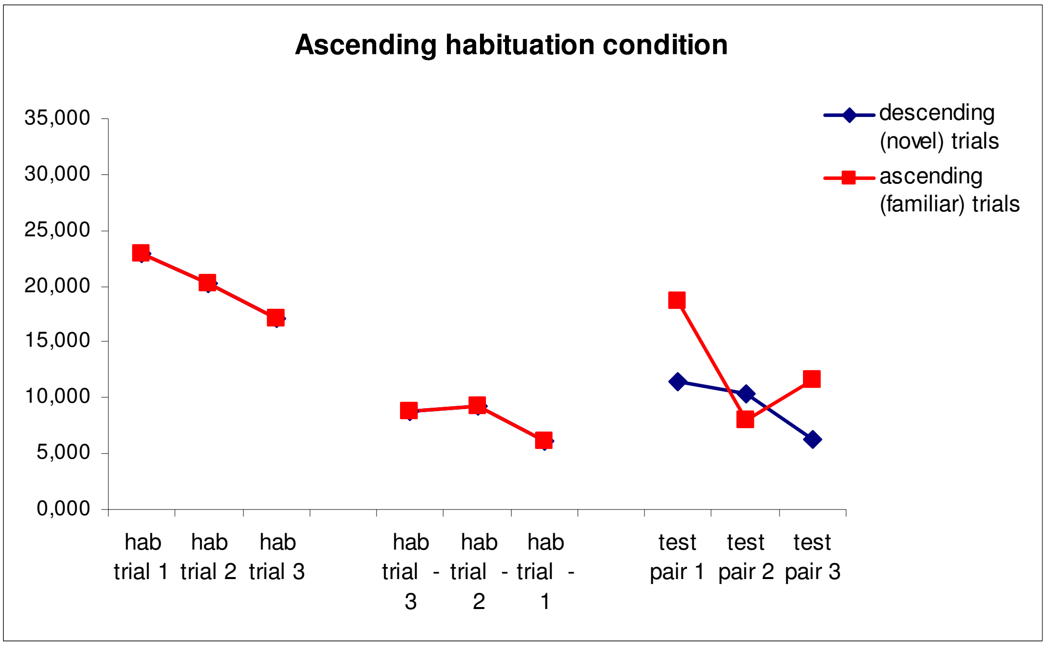


**Figure 3.7.**

Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of familiar and novel test trials for infants habituated to ascending sequences in Exp. 5

Overall, these results indicate that infants were able to discriminate between novel and familiar test trials. However, the results revealed an asymmetry in infants' performance – a novelty preference for infants in the descending habituation condition and a familiarity preference for infants tested in the ascending condition.

### *3.2.3 Discussion*

The aim of the Exp. 5 was to provide further evidence for the presence of a mapping of space to number by testing whether infants are able to link oriented spatial codes to representations of numerical magnitudes.

Results demonstrate that when spatial information related to the location of each single element of the sequence was provided, 7-month-old infants successfully discriminated between ascending and descending sequences. However, during the test phase infants looked significantly longer to ascending test sequences, independently from the habituation condition to which infants were previously exposed. This asymmetry in infants' performance is compatible with the presence of a spontaneous preference for the ascending, left-to-right oriented sequences, that is for the sequences in which the smallest numbers appear on the left and the largest numbers appear on the right, congruently with the orientation of the adult mental number line.

To ascertain whether infants' performance in Exp. 5 was effectively a manifestation of a spontaneous preference for ordinal relationships that are presented according to the direction of the mental number line, we performed a further experiment (Exp. 6), in which we used the same exact procedure used in Exp. 5, with the only exception that ordinal information was removed from the habituation phase of the experiment by equating the numerical values composing the habituation sequences.

### 3.3 *Experiment 6: 7-month-olds' preference for ascending left-to-right number-based sequences*

The current experiment was aimed at verify whether 7-month-old infants manifest a spontaneous preference for ascending ordinal relationships that are presented according to the direction of the mental number line, that is from left to right. Infants were presented with the same test trials presented in Exp.5, preceded by an habituation phase in which spatiotemporal information and featural cues (i.e. colours) were provided, but not ordinal information. Specifically, during habituation infants were presented with left-to-right sequences of different colors in which ordinal relationships were eliminated by equating the numerical values, in that all numerical displays contained 8 items. Under these experimental conditions, longer looking times to the ascending test sequences would demonstrate the presence of a spontaneous preference for numerical ordered sequences in which the ordinal relationships are congruent with he orientation of the adult number line.

#### 3.3.1 *Method*

***Participants***

Participants were 16 healthy, full term 7-month-old infants (*M* age = 7 months, 15 days; range = 7 months, 3 days – 8 months, 2 days). Seven of the participants were female. One additional infant were tested but exclude from the final sample due to failure in reach criteria established for data analyses. Data from additional 10 infants were discarded because of fussiness (N=4) or being not cooperative (N=6), resulting in failure to complete all the test trials. Infants were recruited via a written invitation, which was sent to parents based on birth records provided by the neighboring cities. The majority of participants were from Caucasian, middle class families. Parents gave their written informed consent before testing commenced.

***Stimuli***

Stimuli were created in the same manner of those used in Exp. 4 e 5. There were four sets of stimuli, three for the habituation phase and one for the test phase. The habituation sets contained always 8 items, arranged in different configurations, and they were presented in different color according to the habituation trials, as in Exp. 4 e 5. The colors were again “blue” (R.G.B.: 0, 0, 255), “red” (R.G.B.: 255, 0, 0) and , “green” (R.G.B.: 6, 141, 6). The test set was the same of Exp. 4 e 5.

We chose to use the numerosity 8 for habituation trials because 8 was halfway from both the numerosities showed in the test trials (4 and 16), so that each set differed by a 1:2 ratio, well within the limits of 7-month-old infants' numerical discrimination abilities (Xu & Spelke, 2000). Each item composing the 8 display measured 2 cm in height and 0.4 cm in width. The size of each habituation display was 16.3 cm x 8 cm, and the density was held constant according to the density of test displays, in which the cumulative surface area and contour length were positively correlated with number and the item size and shape were kept constant at 1.4 cm x 0.5 cm.

Infants were habituated to the presentation of the three numerical displays all with the same numerosity (8). For half of the infants in the first trial items were blue, in the second they were red and in the third they were green. For the other half in the first trial items were green, in the second they were red and in the third they were blue. After habituation infants were then tested with both ascending and descending sequences containing novel numerical values (i.e., 4, 8, 16). Half of the infants were presented with ascending test sequence first, half with the descending first.

***Apparatus and Procedure***

Same as in Exp. 5.

***Data analyses***

In order to be included in the analyses infants has to provide a minimum looking time in each test trials of 1 sec. For this reason 1 subject wase tested but excluded to the final sample. Inter-coder 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 six test trials was r = . 99.

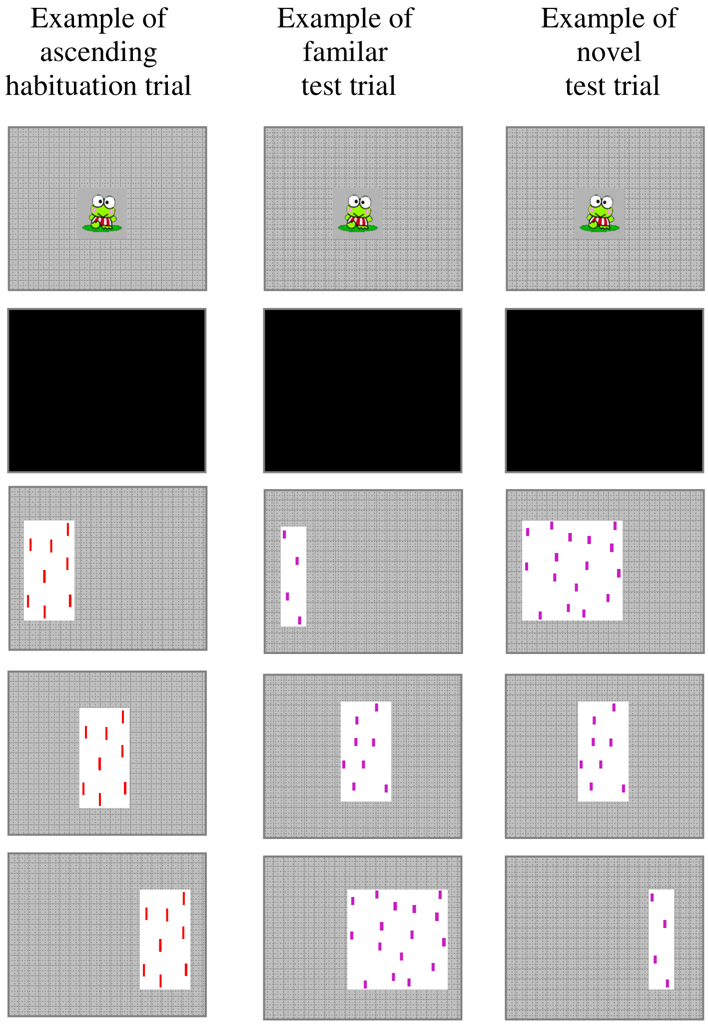


**Figure 3.8** The sequence of events in each trial in Exp. 6: the fixation point and the three numerical displays composing each sequence. The sequence repeated, beginning with the black screen, until specific criteria were met.

### *3.3.2 Results*

All infants reached the habituation criterion and, on average, habituation required 7.6 trials. A paired-samples *t*-test confirmed the presence of a significant decline in mean looking time from the first three ($M$=22.56 s) to the last three habituation trials ($M$=8.12 s), $t(15)=9.970$, $p<.001$.

To determine whether in test infants showed a preference for one out of the two test sequences, a preliminary three-way analysis of variance (ANOVA) was performed, with the *first test trial type* (novel vs. familiar) as between-subjects factor and *trial pair* (first vs. second vs. third) and *order direction* (ascending vs. descending) as within-subjects factors. The three-way ANOVA revealed a significant main effect of *trial pair*, $F(1,15)=3.802$, $p<.05$, $\eta_p^2=.214$, which was due to longer looking times to the first pair ($M=14.26$ s) as compared to the third test trials pair ($M=8.03$ s, $t(15)=2.730$, p<.05, Bonferroni corrected). There was also a significant main effect of *first test trial type*, $F(1,15)=8.193$, $p<.05$, $\eta_p^2=.369$, which was due to looking times being longer for infants who first saw an ascending trial at test than for infants who were first exposed to a descending trial at test ($M=14.6$ s vs. $M=7.93$ s).

To further explore the effects of the factor *first test trial type*, we performed two separate ANOVAs with *trial pair* (first vs. second vs. third) and *order direction* (ascending vs. descending) as within-subjects factors. The ANOVA performed on the infants who first saw the ascending sequence in test showed a marginally significant main effect of the *trial pair* factor, $F(1,8)=3.430$, $p=.058$, $\eta_p^2=.300$. Paired-samples - test showed that overall infants accumulated a significantly longer total looking time on the second pair of trials ($M=34.87$ s) as compared to the third pair ($M=19.38$ s), $t(8)=2.550$, $p<.05$, whereas the total looking time accumulated on the first pair ($M=33.38$ s) did not differ from the looking time accumulated during the second pair, $t(8)=0.208$, $p=.841$, but was marginally different from the third, $t(8)=2.245$, $p=.055$ (Bonferroni corrected).

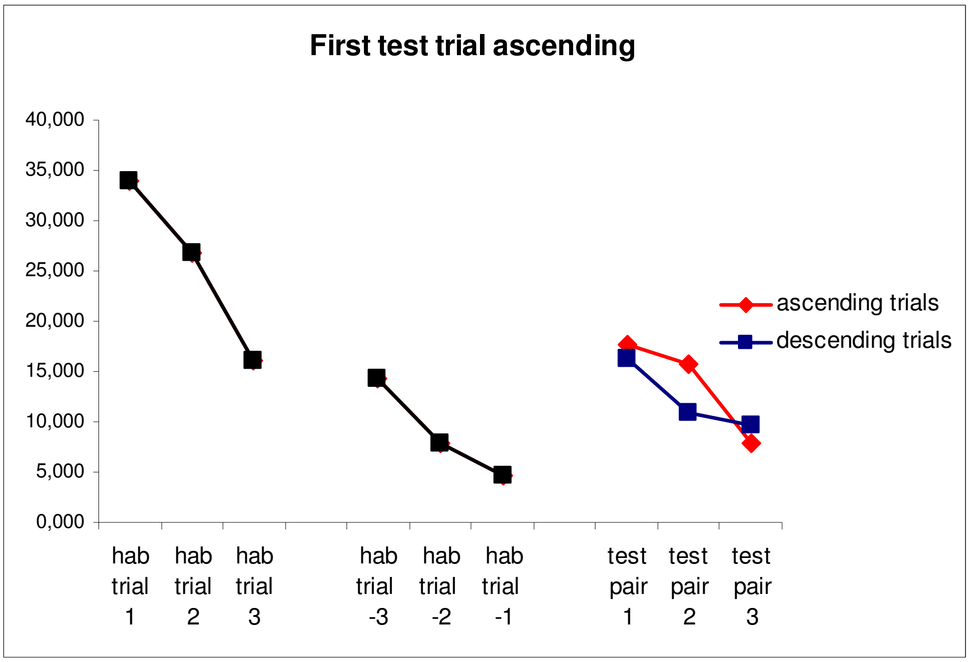


**Figure 3.9**

Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of ascending and descending test trials for infants who first saw an ascending trial in Exp. 6

Crucially, there was no significant main effect or interaction involving the factor *order direction*. The two-way ANOVA performed on the group of infants who first saw the descending sequence at test did not reveal any significant effect.

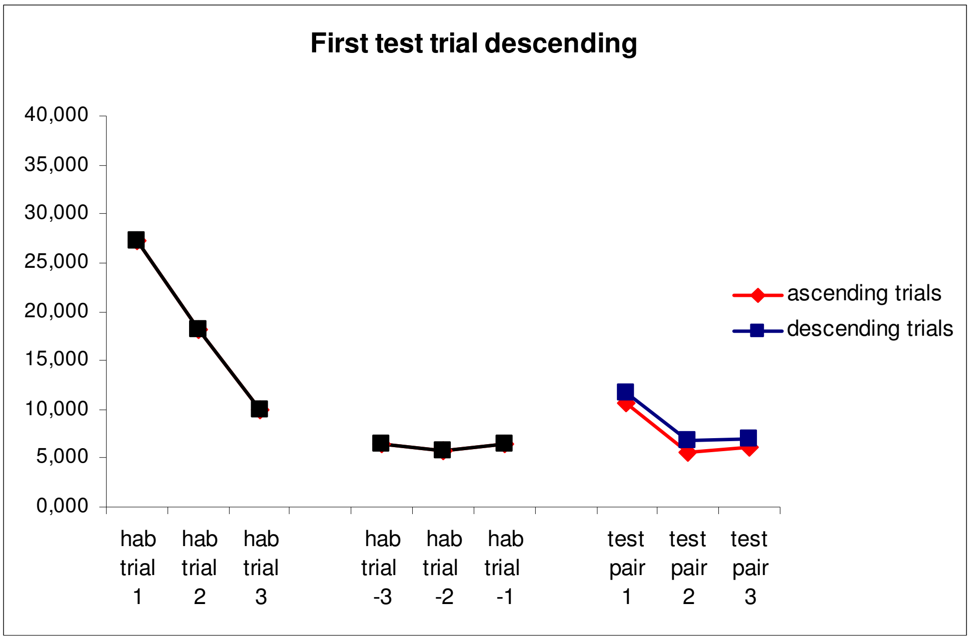


**Figure 3.10** Mean total looking times for each of the first three and the last three habituation trials and for each of the three pairs of ascending and descending test trials for infants who first saw an ascending trial in Exp. 6

### *3.3.3 Discussion*

The aim of the Exp. 6 was to investigate whether 7-month-old infants manifest a spontaneous preference for ascending ordinal relationships that are presented according to the direction of the mental number line, that is from left to right. To do so, infants were habituated with to left-to-right temporal sequences in which ordinal relationships were eliminated by equating the numerical values within each sequence. After habituation, infants were presented with 6 left-to-right test trials alternating ascending and descending order. Results did not reveal any difference in the looking time to the two ordinal sequences in test, and thus failed to provide evidence for the existence of a spontaneous preference for left-to-right oriented ascending order sequences.

This pattern of results do not support the hypothesis according to which, in Exp. 5, infants' novelty preferences interacted with the spontaneous preference for the ascending sequence, in accordance with small-left and large-right. However, these findings seem to put in prospective the importance of the ordinal cues provided throughout habituation in Exp. 5, which probably played a crucial role in infants' discrimination between ordinal relationships. In fact, it is possible that the mapping of number to space found in Exp. 5 could occur at a representational level, for that ordinal information provided through the habituation phase was indeed essential. In other words it is possible that infants in Exp. 5 needed to attend to different examples of the ordinal rule displayed during habituation in order to link numerical and spatial information. Once they had the chance to abstract the ordinal rule from multiple examples provided in ascending or descending habituation trials, they looked longer to ascending left-to-right sequences in test. Therefore, the absence of any preferential response in in Exp. 6 could be interpreted as resulting from the fact that infants did not have the chance to form any representation of the two orders during habituation phase. However, further investigation is needed to answer the question about what mechanisms underlie the preference for ascending left-to-right oriented sequences manifested by infants in Exp. 5.

### 3.4 *General Discussion*

The aim of the Experiments presented in the current chapter was to investigate whether the ability to appreciate ordinal relationships embedded in numerical sequences could be found in infants younger than 11 months, when infants are provided by multiple sources of information and redundant cues to ordinality.

Results from Exp. 4 demonstrated that, when featural cues such as colour and shape are provided, and redundant cues to ordinality are provided throughout the task, 7-month-old infants can represent numerical ordinal relations and detect reversals in ordinal direction. Available literature on ordinal numerical cognition in infancy has demonstrated that 9-month-old infants succeeded at appreciating ordinal relations when such relations were specified by multiple quantitative cues (e.g., number, item size, total surface area), but failed when only numerical cues were available in the face of conflicting non-numerical cues (Suanda et al., 2008). With respect to previous research, the contribution of the current study concerns the impact of featural information and multiple cue integration on infants' proneness to detect number-based patterns of ordinal regularities across changes in non-numerical dimensions. More specifically, the most important implication of these results is the demonstration that not only numerical cues are sufficient for 7-month-olds to appreciate ordinal relations, but also that ordinal relations between numbers were salient enough in our experimental design as to allow infants to filter out conflicting cues provided by changes in the three non-numerical quantitative dimensions.

Another aim of the reported research was to test the presence of an early mapping of space to number, by testing whether 7-month-old infants are able to discriminate between ascending and descending sequences when they are given spatial information, in the form of a dislocation of each element composing the ordinal sequence in a different but contiguous spatial position along the horizontal axis, following a left-to-right direction. Thus in Exp. 5 we investigated the possibility that an oriented spatial-numerical link could be found in infants as young as 7 months, and tested whether the direction of the spatial information provided throughout the task, that was congruent with the direction of the mental number line, will influence the encoding of numerical information within ordinal sequences.

Results showed that 7-month-old infants successfully discriminated between ascending and descending sequences, thus demonstrating infants' ability to link oriented spatial codes to representations of numerical magnitudes. Moreover, since results showed that during test phase infants looked significantly longer to ascending test sequences, independently from the habituation condition to which infants were previously exposed, we demonstrated that the direction of the spatial information provided throughout the task will influence the encoding of numerical information within ordinal sequences. This interesting finding suggests that 7-month-olds are able to link ordinal and spatial information although they do not need a congruency between the direction of the two. The pattern of results obtained, in fact, suggests that the successfully discrimination between the two ordinal directions seems to be driven by a sort of spontaneous preference for the series of numerical arrays with the smallest number on the left and the largest on the right.

To ascertain whether infants' performance in Exp. 5 was effectively a manifestation of a spontaneous preference for ordinal relationships that are presented according to the direction of the mental number line, Exp. 6 was aimed at investigate this preference by presenting infants ascending and descending numerical sequences, from left-to-right, with previous habituation to a left-to-right sequence in which ordinal relationships were eliminated by equating the numerical values. However, results from Exp. 6 did not revealed any difference in the looking time spent on the two ordinal sequences in test, suggesting that 7-month-old infants did not show a spontaneous preference for ascending sequences that are displayed following the direction of the mental number line, in accordance with small-left and large-right. This pattern of results did not answer the question raised by result from Exp. 5 about the presence of a spontaneous preference for the ascending sequence, in accordance with small-left and large-right, in Exp. 5.

However, a comparison between findings from Exp. 5 and 6 put in prospective the importance of the ordinal cues provided throughout habituation in Exp. 5, which probably played a crucial role in discrimination between ordinal relationships. Our interpretation for that in Exp. 6 infants did not show any preference for one out of the two ordinal sequences presented is that the mapping of number to space found in Exp. 5 could occur at a representational level, for that ordinal information provided through the habituation phase was indeed essential. In other words it is possible that infants in Exp. 5 needed to attend to different examples of the ordinal rule displayed during habituation in order to link numerical and spatial information and only after the abstraction of the ordinal rule from multiple examples provided through habituation trials, they showed to look longer to ascending test sequences, that are presented according to the left-to-right orientation. In Exp.6 infants did not have the chance to form any representation of the two order during habituation phase, therefore they did not display any spontaneous preference. Further investigation is needed to answer the question about whether infants spontaneously prefer ordinal relationships that are presented according to the direction of the mental number line.

# CHAPTER 4: GENERAL DISCUSSION & CONCLUSIONS

The results of the present research provide various contributions to the study of the organization of numerical knowledge in infancy and, in particular, to the study of the development of the ability to detect ordinal relationships embedded in sequences of non-numerical and numerical magnitudes. First and foremost, in our series of experiments, we demonstrated that the ability to extract ordinal relationships among magnitudes is present in preverbal infants at an earlier age than previously reported (Brannon, 2002; Suanda et al., 2008).

Results from Exp. 1 demonstrated that 4-month-old infants who had been exposed to the ascending habituation condition successfully detected a reversal in the ordinal direction of size-based sequence, whereas infants who were habituated to descending sequences did not discriminate between the familiar and the novel trials presented in test. We hypothesized that infants' failure to manifest a novelty preference in the descending habituation condition derived from their inability to encode and abstract the ordinal relationships embedded within descending sequences, which were eventually perceived as non-ordinal.

This interpretation was confirmed by the results of Exp. 2, which demonstrated that infants were not able to discriminate between descending and non-ordered sequences, irrespective of the nature (descending or random) of the sequences to which they had been habituated. This finding provided further support to our claim that, at least in the case of size-based sequences, at 4 months infants are unable to detect the presence of any ordinal relationships when these relationships are embedded in descending sequences.

A possible explanation for the asymmetry in our results could be due to more general limits on infants' memory. When infants looked at ascending sequences they were found to be able to keep trace of the increasing size of the element, whereas they failed in keeping trace of the progressive decreasing in descending sequences. This suggests that size-based information is easy to be coded and stored in memory when the starting point of the sequence carried less information as compared to information embedded in subsequent stimuli. It is possible that, in contrast, when the first stimulus carried more information as compared to the next in the sequence, in order to compare the two sizes, infants had to store in memory an amount of information (size 1 + size 2) that exceed their limits, thus resulting in failure to complete and succeed the comparison.

In other words we hypothesized that 4-month-olds may be able to grasp ordinal information embedded in ascending size-based sequences because the amount of information provided is more easily computed an compared with respect to descending sequences.

However, the evidence so far do not allow us to definitively conclude that 4-month-old infants are really able to grasp ordinal information embedded in ascending sequences without excluding the hypothesis that successful discrimination obtained in Exp. 1 was driven by the detection of qualitative perceptual changes between the ascending and descending sequences. Because all stimuli were located at the centre of the screen, ascending sequences may have achieved an approaching percept (zooming), whereas descending sequences may have yielded a retracting percept (looming), infants could have react to the qualitative changes perceived instead of to the reversal in the ordinal direction. To control for this possibility, we replicated Exp.

1 using stimuli that did not evoke any looming/zooming perceptual effect in Exp. 3. However, results of Exp. 3 demonstrated that infants showed a novelty preference only when the reversal in the ordinal direction was presented in the first test trial. Otherwise, looking times between novel and familiar test trials did not significantly differ. We attributed the lack of an overall novelty preference as resulting from the low saliency of the stimuli used in the task, which did not carry enough salient information and, as a result, novelty preference may have been obscured by the reactivation of infants' attention that followed the passage from the habituation to the test phase.

We argued that maybe the use of stimuli that were specifically constructed in order to display a change in the size only over one out of the two dimensions, while avoiding perceptual effects, may have impeded the detection of the changes in the elements' size. In other words, it is possible that an increase (or descrease) in size along only the horizontal direction made the size-based change less salient. Because discriminability depends on the ratio of the set sizes, and given that younger infants require greater ratios compared to older infants (Lipton & Spelke, 2003), 4-month-olds may require a ratio greater than 1:2 to detect the size-based change within this set of stimuli.

Moreover, according to the contribution of Exp.4, that provide evidence for the influence of featural information and multiple cue integration on infants' proneness to detect number-based patterns of ordinal regularities, 4-month-olds may need to be presented with stimuli with an overall greater salience in order to succeed in discrimination within the 1:2 ratio.

In fact, results from Exp. 4 demonstrate that when multiple featural information and redundant cues to ordinality are provided throughout the task, 7-month-old infants can represent numerical ordinal relations and detect reversals in ordinal direction. Moreover, our findings showed that infants succeeded at detecting and representing ordinal relations relying solely on number, with non-numerical quantitative cues displaying non-monotonic changes. In fact, of the four considered continuous dimensions (i.e., cumulative surface area, item size, contour length, and density), only one (density) co-varied with number in habituation, whereas the other three were either constant (surface area and contour length) or inversely related to number (element size). In test, the two dimensions that were constant in habituation did co-vary with number, but the two that varied in habituation were kept constant. Therefore, the most important implication of these results is the demonstration that not only numerical cues are sufficient for 7-month-olds to appreciate ordinal relations, but also that ordinal relations between numbers were salient enough in our experimental design as to allow infants to filter out conflicting cues provided by changes in the three non-numerical quantitative dimensions.

Another important aim of the present research project was to test whether within the same task, 7-month-olds are able to discriminate between ascending and descending sequences when they were given spatial information, in the form of a dislocation of each element composing the ordinal sequence in a different but contiguous spatial position along the horizontal axis, following a left-to-right direction. Thus in Exp. 5, while testing for the presence of a mapping of space to number, we investigate the possibility that an oriented spatial-numerical link could be found in infants as young as 7 months, verifying whether the direction of the spatial information provided throughout the task, that was congruent with the direction of the mental number line, will influence the encoding of numerical information within ordinal sequences. Results showed that 7-month-old infants successfully discriminated between ascending and descending sequences, thus demonstrating infants' ability to link oriented spatial codes to representations of numerical magnitudes. Moreover, since results showed that during test phase infants looked significantly longer to ascending test sequences, independently from the habituation condition to which infants were previously exposed, we demonstrated that the direction of the spatial information provided throughout the task will influence the encoding of numerical information within ordinal sequences.

This interesting findings suggest that 7-month-olds are able to link ordinal and spatial information although they do not need a congruency between the direction of the two. In fact, even those infants who were habituated to descending sequences presented from left to right, discriminated between familiar and novel test trials.

It is important to note that while results from Exp. 1 and 2 have shown that 4 month-olds are not able to code and grasp ordinal information embedded in descending sequences of size-based squares, results from Exp. 4 and 5 provided evidence for 7-mont-olds' ability to represent descending ordinal relationships between sequences of numerical magnitudes, even with spatial dislocation of elements.

The pattern of results obtained from Exp. 5 suggests that the successfully discrimination between the two ordinal directions could be explained by the presence of a spontaneous preference for series of numerical arrays with the smallest number on the left and the largest on the right. This hypothesis was the focus of the Exp. 6, in infants were presented ascending and descending numerical sequences, from left-to-right, with previous habituation to a left-to-right sequence in which ordinal relationships were eliminated by equating the numerical values. Results did not revealed any difference in the looking time spent on the two ordinal sequences in test, suggesting that 7-month-old infants did not show a spontaneous preference for ascending sequences that are displayed following the direction of the mental number line, in accordance with small-left and large-right. However, a comparison between findings from Exp. 5 and 6 put in prospective the importance of the ordinal cues provided throughout habituation in Exp. 5, which probably had played a crucial role in discrimination between ordinal relationships. Our interpretation for that in Exp. 6 infants did not show any preference for one out of the two ordinal sequences presented is that the mapping of number to space found in Exp. 5 could occur at a representational level, for that ordinal information provided through the habituation phase was indeed essential. In Exp.6 infants did not have the chance to form any representation of the two order during habituation phase, therefore they did not display any spontaneous preference.

Further investigation is needed to answer the question about whether infants spontaneously prefer ordinal relationships that are presented according to the direction of the mental number line.

## REFERENCES


Antell, S. E., & Keating, D. P. (1983). Perception of numerical invariance in neonates. *Child Development, 54*(3), 695-701.

Bachtold, D., Baumuller, M., & Brugger, P. (1998). Stimulus-response compatibility in representational space. *Neuropsychologia, 36*(8), 731-735.

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*(4), 286-308.

Bijeljac-Babic, R., Bertoncini, J., & Mehler, J. (1991). How do four-day-old infants categorize multisyllabic utterances. *Developmental Psychology, 29*, 711-721.

Brannon, E. M. (2002). The development of ordinal numerical knowledge in infancy. *Cognition, 83*(3), 223-240.

Brannon, E. M., Abbott, S., & Lutz, D. J. (2004). Number bias for the discrimination of large visual sets in infancy. *Cognition, 93*(2), B59-68.

Brannon, E. M., Cantlon, J. F., & Terrace, H. S. (2006). The role of reference points in ordinal numerical comparisons by rhesus macaques (Macaca mulatta). *Journal of Experimental Psychology: Animal Behavior Processes, 32*(2), 120-134.

Brannon, E. M., Lutz, D., & Cordes, S. (2006). The development of area discrimination and its implications for number representation in infancy. *Developmental Science, 9*(6), F59-64.

Brannon, E. M., Suanda, S., & Libertus, K. (2007). Temporal discrimination increases in precision over development and parallels the development of numerosity discrimination. *Developmental Science, 10*(6), 770-777.

Brannon, E. M., & Terrace, H. S. (2000). Representation of the numerosities 1-9 by rhesus macaques (Macaca mulatta). *Journal of Experimental Psychology: Animal Behavior Processes, 26*(1), 31-49.

Brysbaert, M. (1995). Arabic number reading: On the nature of the numerical scale and the origin of phonological recoding. *Journal of Experimental Psychology: General, 124*, 434–452.

Buckley, P. B., & Gillman, C. B. (1974a). Comparisons of digits and dot patterns. *Journal of Experimental Psychology, 103*(6), 1131-1136.

Buckley, P. B., & Gillman, C. B. (1974b). Comparisons of digits and dot patterns. *J Exp Psychol, 103*(6), 1131-1136.

Cantlon, J., Fink, R., Safford, K., & Brannon, E. M. (2007). Heterogeneity impairs numerical matching but not numerical ordering in preschool children. *Developmental Science, 10*(4), 431-440.

Church, R. M., & Meck, W. H. (1984). The numerical attribute of stimuli. In B. T. G. Roitblat H. L., Terrace H. S. (Ed.), *Animal Cognition* (pp. 445-464). Hillsdale, N.J.: Lawrence Erlbaum Associates, Inc.

Clearfield, M. W., & Mix, K. S. (1999). Number versus contour length in infants' discrimination of small visual sets. *Psychological Science, 10*, 408-411.

Cooper, R. G., Jr. (1984). Early number development: Discovering number space with addition and subtraction. In C. Sophian (Ed.), *Origins of cognitive skills* (pp. 157-192). Hillsdale, N.J.: Lawrence Erlbaum Associates, Inc.

Cordes, S., & Brannon, E. M. (2009). The relative salience of discrete and continuous quantity in young infants. *Developmental Science, 12*(3), 453-463.

de Hevia, M. D., Girelli, L., Bricolo, E., & Vallar, G. (2008). The representational space of numerical magnitude: illusions of length. *Quarterly Journal of Experimental Psychology, 61*(10), 1496-1514.

de Hevia, M. D., Girelli, L., & Vallar, G. (2006). Numbers and space: a cognitive illusion? *Experimental Brain Research, 168*(1-2), 254-264.

de Hevia, M. D., & Spelke, E. S. (2009). Spontaneous mapping of number and space in adults and young children. *Cognition, 110*(2), 198-207.

de Hevia, M. D., & Spelke, E. S. (in press). Number-space mapping in human infants. *Psychological Science*.

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*(1-2), 1-42.

Dehaene, S. (1996). The organization of brain activations in number comparison: Event related potentials and the additive-factors methods. *Journal of Cognitive Neuroscience, 8*, 47-68.

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

Dehaene, S. (2001). Précis of the number sense. *Mind and Language, 16*(1), 16-36.

Dehaene, S., & Akhavein, R. (1995). Attention, automaticity, and levels of representation in number processing. *Journal of Experimental Psychology: Learning, Memory & Cognition, 21*(2), 314-326.

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

Dehaene, S., & Changeux, J. P. (1993). Development of elementary numerical abilities: A neuronal model. *Journal of Cognitive Neuroscience, 5*, 340-407.

Dehaene, S., & Cohen, L. (1994). Dissociable mechanisms of subitizing and counting: neuropsychological evidence from simultanagnosic patients. *Journal of Experimental Psychology: Human Perception & Performance, 20*(5), 958-975.

Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract representations of numbers in the animal and human brain. *Trends in Neurosciences, 21*(8), 355-361.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception & Performance, 16*(3), 626-641.

Dehaene, S., Izard, V., Spelke, E., & Pica, P. (2008). Log or linear? Distinct intuitions of the number scale in Western and Amazonian indigene cultures. *Science, 320*(5880), 1217-1220.

Dehaene, S., Sergent, C., & Changeux, J. P. (2003). A neuronal network model linking subjective reports and objective physiological data during conscious perception. *Proceedings of the National Academy of Sciences of the United States of America, 100*(14), 8520-8525.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science, 284*(5416), 970-974.

den Heyer, K., & Briand, K. (1986). Priming single digit numbers: Automatic spreading activation dissipates as a function of semantic distance. *American Journal of Psychology, 99*, 315–340.

Feigenson, L. (2005). A double-dissociation in infants' representations of object arrays. *Cognition, 95*(3), B37-48.

Feigenson, L., & Carey, S. (2003). Tracking individuals via object-files: evidence from infants' manual search. *Developmental Science 6*(5), 568–584.

Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: object files versus analog magnitudes. *Psychological Science, 13*(2), 150-156.

Feigenson, L., Carey, S., & Spelke, E. (2002). Infants' discrimination of number vs. continuous extent. *Cognitive Psychology, 44*(1), 33-66.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences, 8*(7), 307-314.

Fischer, M. H. (2001). Number processing induces spatial performance biases. *Neurology, 57*(5), 822-826.

Gallistel, C. R. (1990). *The organization of learning.*: MIT Press.

Gallistel, C. R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition, 44*(1-2), 43-74.

Gevers, W., Reynvoet, B., & Fias, W. (2003). The mental representation of ordinal sequences is spatially organized. *Cognition, 87*(3), B87-95.

Gevers, W., Reynvoet, B., & Fias, W. (2004). The mental representation of ordinal sequences is spatially organized: evidence from days of the week. *Cortex, 40*(1), 171-172.

Huntley-Fenner, G., & Cannon, E. (2000). Preschoolers' magnitude comparisons are mediated by a preverbal analog mechanism. *Psychological Science, 11*(2), 147-152.

Ito, Y., & Hatta, T. (2004). Spatial structure of quantitative representation of numbers: evidence from the SNARC effect. *Memory & Cognition, 32*(4), 662-673.

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*.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: object-specific integration of information. *Cognitive Psychology, 24*(2), 175-219.

Kanwisher, N. (2000). Domain specificity in face perception. *Nature Neuroscience, 3*(8), 759-763.

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: evidence for a domain general learning mechanism. *Cognition, 83*(2), B35-42.

Kirkham, N. Z., Slemmer, J. A., Richardson, D. C., & Johnson, S. P. (2007). Location, location, location: development of spatiotemporal sequence learning in infancy. *Child Development, 78*(5), 1559-1571.

Koechlin, E., Naccache, L., Block, E., & Dehaene, S. (1999). Primed numbers: Exploring the modularity of numerical representations with masked and unmasked semantic priming. *Journal of Experimental Psychology: Human Perception & Performance, 25*, 1882-1905.

Lewkowicz, D. J. (2004). Perception of serial order in infants. *Developmental Science, 7*(2), 175-184.

Lipton, J. S., & Spelke, E. S. (2003). Origins of number sense. Large-number discrimination in human infants. *Psychological Science, 14*(5), 396-401.

Mandler, G., & Shebo, B. J. (1982). Subitizing: an analysis of its component processes. *Journal of Experimental Psychology: General, 111*(1), 1-22.

McCrink, K., & Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychological Science, 15*(11), 776-781.

McCrink, K., & Wynn, K. (2009). Operational momentum in large-number addition and subtraction by 9-month-olds. *Journal of Experimental Child Psychology, 103*(4), 400-408.

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature, 215*(5109), 1519-1520.

Naatanen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Iivonen, A., et al. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature, 385*(6615), 432-434.

Opfer, J. E., & Thompson, C. A. (2006). Even early representations of numerical magnitude are spatially organized: Evidence for a directional mapping bias in pre-reading preschoolers. . In R. Sun & N. Miyake (Eds.), *Proceedings of the 28th annual conference of the Cognitive Science Society* (pp. 639-644). Vancouver, British Columbia, Cognitive Science Society.

Pepperberg, I. M. (1987). Evidence for conceptual quantitative abilities in the African grey parrot: labeling of cardinal sets. *Ethology, 75*, 37-61.

Pica, P., Lemer, C., Izard, V., & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Science, 306*(5695), 499-503.

Restle, F. (1970). Speed of adding and comparing numbers. . *Journal of Experimental Psychology 83*.

Rilling, M., & McDiarmid, C. (1965). Signal Detection in Fixed-Ratio Schedules. *Science, 148*, 526-527.

Rossetti, Y., Jacquin-Courtois, S., Rode, G., Ota, H., Michel, C., & Boisson, D. (2004). Does action make the link between number and space representation? Visuo-manual adaptation improves number bisection in unilateral neglect. *Psychological Science, 15*(6), 426-430.

Rousselle, L., Palmers, E., & Noel, M. P. (2004). Magnitude comparison in preschoolers: what counts? Influence of perceptual variables. *Journal of Experimental Child Psychology, 87*(1), 57-84.

Scholl, B. J., & Leslie, A. M. (1999). Explaining the infant's object concept: beyond the perception/cognition dichotomy. In E. Lepore & Z. Pylyshyn (Eds.), *What is Cognitive Science* (pp. 26-73): Blackwell.

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review, 16*(2), 328-331.

Simon, T. J. (1997). Reconceptualizing the origins of number knowledge: A 'non-numerical' account. *Cognitive Development, 12*, 349–372.

Spelke, E., & Dehaene, S. (1999). Biological foundations of numerical thinkingResponse to T.J. Simon (1999). *Trends in Cognitive Sciences, 3*(10), 365-366.

Starkey, P., & Cooper, R. G., Jr. (1980). Perception of numbers by human infants. *Science, 210*(4473), 1033-1035.

Strauss, M., & Curtis, L. (1981). Infant perception of numerosity. *Child development, 52*, 1146-1152.

Suanda, S., Tompson, W., & Brannon, E. M. (2008). Changes in the ability to detect ordinal numerical relationships between 9 and 11 months of age. *Infancy, 13*(4), 308-337.

Thomas, R. K., & Chase, L. (1980). Relative numerousness judgements by squirrel monkeys. *Bulletin of the Psychonomic Society, 16*, 79-82.

Trick, L. M., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Review, 101*(1), 80-102.

Uller, C., Carey, S., Huntley-Fenner, G., & Klatt, L. (1999). What representations might underlie infant numerical knowledge. *Cognitive Development, 14*(1), 1-36.

van Loosbroek, E., & Smitsman, A. (1990). Visual perception of numerosity in infancy. *Developmental Psychology, 26*, 916-922.

van Galen, M. S., & Reitsma, P. (2008). Developing access to number magnitude: a study of the SNARC effect in 7- to 9-year-olds. *Journal of Experimental Child Psychology, 101*(2), 99-113.

van Oeffelen, M. P., & Vos, P. G. (1982). A probabilistic model for the discrimination of visual number. *Perception & Psychophysics, 32*, 163-170.

vanMarle, K., & Wynn, K. (2006). Six-month-old infants use analog magnitudes to represent duration. *Developmental Science, 9*(5), F41-49.

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*(11), 483-488.

Wood, J. N., & Spelke, E. S. (2005). Chronometric studies of numerical cognition in five-month-old infants. *Cognition, 97*(1), 23-39.

Wynn, K. (1998). Psychological foundations of number: numerical competence in human infants. *Trends in Cognitive Sciences, 2*(8), 296-303.

Wynn, K., Bloom, P., & Chiang, W. C. (2002). Enumeration of collective entities by 5-month-old infants. *Cognition, 83*(3), B55-62.

Xu, F. (2003). Numerosity discrimination in infants: evidence for two systems of representations. *Cognition, 89*(1), B15-25.

Xu, F., & Arriaga, R. I. (2007). Number discrimination in 10-month-old infants. . *British Journal of Developmental Psychology, 25*, 103-108.

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition, 74*(1), B1-B11.

Xu, F., Spelke, E. S., & Goddard, S. (2005). Number sense in human infants. *Developmental Science, 8*(1), 88-101.

Zebian, S. (2005). Linkages between number concepts, spatial thinking, and directionality of writing: The SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. *Journal of Cognition and Culture 5*, 165-190.

Zorzi, M., Priftis, K., & Umilta, C. (2002). Brain damage: neglect disrupts the mental number line. *Nature, 417*(6885), 138-139.