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THE FOUNDATIONS OF NUMERICAL KNOWLEDGE IN THE FIRST MONTHS OF LIFE

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DATA CONSEGNA TESI

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Riassunto

Il mondo visivo del neonato è molto diverso, e notevolmente impoverito, rispetto a quello dell'adulto: l'acuità, la sensibilità al contrasto e la sensibilità al colore sono infatti estremamente ridotte (Slater & Johnson, 1998). Ciononostante, gli studi condotti negli ultimi 30 anni dai ricercatori interessati ad indagare l'ontogensi della cognizione hanno dimostrato che, fin dalla nascita, il bambino possiede alcune sofisticate capacità attentive (Farroni, Simion, Umiltà & Dalla Barba, 1999; Simion, Valenza & Umiltà, 1995; Valenza, Simion & Umiltà, 1994) e percettive (Farroni, Valenza, Simion & Umiltà, 2000; Macchi Cassia, Simion, Milani & Umilta`, 2002; Valenza, Leo, Gava & Simion, 2006; Valenza & Bulf, 2007) che gli consentono di elaborare e rappresentare differenti tipi di informazioni.

In accordo con questo quadro teorico questa tesi di dottorato vuole essere un contributo allo studio delle origini della conoscenza numerica e si articola in due parti.

Nella prima parte, ho descritto i processi e i sistemi rappresentativi che permettono agli adulti di elaborare le informazioni numeriche, indipendentemente dal linguaggio (Capitolo 1). Successivamente, sono stati riportati alcuni studi, condotti in ambito evolutivo, che dimostrano una precoce abilità nel rappresentare informazioni numeriche, sia ordinali che cardinali (Capitolo 2). Infine, sono stati descritti i principali modelli teorici che postulano l'esistenza di due sistemi innati implicati nelle prestazioni numeriche (Capitolo 3): un sistema di rappresentazione dell'oggetto deputato all'elaborazione esatta di piccole quantità numeriche (n < 4), detto Object-file system (e.g., Carey, 1998; Uller, et al., 1999) ed un sistema numerico per l'elaborazione approssimativa di grandi quantità, detto Analog magnitude system (e.g., Dehaene & Changeux, 1993). Recentemente, un nuovo modello, chiamato ATOM, ha in parte modificato il modello dell'Analog magnitude, proponendo che la conoscenza numerica si sviluppa a partire da un generale sistema di rappresentazione delle grandezze presente fino dalla nascita che elabora tutte le variabili, continue e numeriche, che possono essere percepite come "minore di" o "maggiore di" (Walsh, 2003). Mentre l'Object-file system è deputato all'elaborazione e alla rappresentazione degli

oggetti e solo in seguito estrae implicitamente le informazioni numeriche, l'Analog mangitude system è un sistema direttamente implicato nell'elaborazione dell'informazione quantitativa e risulta modulato dal rapporto numerico tra i valori confrontati.

Nonostante l'assunzione che entrambi questi sistemi siano innati, sorprendentemente nessuno studio ha esplorato la loro presenza alla nascita. Nella seconda parte della presente tesi vengono riportate tre distinte ricerche empiriche condotte al fine di studiare l'origine delle abilità numeriche.

Un primo obiettivo è stato di verificare la presenza alla nascita delle abilità necessarie all'Object-file system. In specifico, lo scopo dello Studio 1 (Capitolo 4) e' stato di indagare se nei primi giorni di vita sia presente la capacità di formare rappresentazioni categoriali delle relazioni spaziali tra due oggetti visivi. Per mezzo della tecnica dell'abituazione e della familiarizzazione visiva, in cinque differenti esperimenti è stato dimostrato che non solo i neonati sono in grado di discriminare la posizione di un oggetto rispetto ad un oggetto di riferimento (Esperimento 1, 2, e 5), ma sono anche in grado di riconoscere una relazione spaziale destra/sinistra invariante sia in condizioni di bassa (Esperimento 3) che di alta variabilità percettiva (Esperimento 4). I dati ottenuti nello Studio 1 dimostrano che, dalla nascita, i bambini sono in grado di elaborare categorialmente le relazioni spaziali tra gli oggetti, almeno quando la relazione spaziale coinvolge due oggetti facilmente discriminabili.

Lo Studio 2 (Capitolo 5) conferma ed estende questi risultati dimostrando che già alla nascita è presente la capacità di cogliere sequenze ordinate di tre elementi, organizzata in base alla relazione spaziale destra/sinistra. In specifico, utilizzando la tecnica della familiarizzazione visiva, i risultati dell'Esperimento 6 e 7 dimostrano che i neonati sono in grado di cogliere una sequenza spaziale in base alle relazioni spaziali tra gli elementi, in assenza di informazioni temporali.

Nell'insieme i risultati ottenuti nello Studio 1 e 2 suggeriscono che dai primi giorni di vita il sistema cognitivo umano percepisce, elabora e rappresenta gli oggetti sulla base delle loro caratteristiche visuo-spaziali, avvalorando l'ipotesi dell'esistenza di un precoce sistema generale, automatico di rappresentazione dell'oggetto, basato sull'elaborazione visuo-spaziale e presente già alla nascita (e.g., Scholl & Leslie, 1999; Simon, 1997; Uller, et al., 1999).

Il secondo obiettivo di questa tesi è stato di indagare la presenza nei primi mesi di vita di competenze ordinali, implicate da un generale sistema di rappresentazione delle quantità (Walsh, 2003). A tal fine, sono state indagate la presenza e le caratteristiche di un sistema di rappresentazione ordinale di grandezze continue alla nascita e a tre mesi di vita.

I risultati dello Studio 3 (Capitolo 6) dimostrano che a 3 mesi di vita (Esperimento 9) i bambini sono in grado di discriminare tra una sequenza ordinale ed una sequenza casuale di grandezze. Al contrario, i neoanti non hanno manifestato questa competenza (Esperimento 8), sebbene essi siano stati in grado di riconoscere una sequenza ordinale di grandezze, in condizioni di bassa variabilità percettiva (Esperimento 10).

Nel complesso, i dati del terzo studio hanno dimostrato che l'emergere della capacità di cogliere una sequenza ordinale di grandezze continue avviene nei primi mesi di vita, indicando che tale abilità si manifesta molto più precocemente di quanto riportato in letteratura (Brannon, 2002).

In conclusione, i dati ottenuti sembrano suggerire che, alla nascita, il sistema cognitivo umano sia in grado di elaborare gli oggetti, mentre l'abilità di elaborare le quantità appare molto più immatura. Di conseguenza, se la capacità di elaborare gli oggetti precede l'abilità di elaborare le informazioni quantitative, è ipotizzabile che nei primi giorni di vita, i bambini possiedano le competenze necessarie per elaborare le piccole numerosità, per mezzo dell'Object-file system, e che solo successivamente si sviluppi l'abilità di elaborare le informazioni quantitative.

Summary

Many studies carried out over the last 30 years lead to the suggestion that flexible skills and belief systems that adults employ to process objects, agents, space and numbers might gradually emerge as the results of the interaction between the structure of the input provided by the species-typical environment and initial, innately specified constraints (de Schonen, 2002; Elman et al., 1996; Karmiloff-Smith, 1992, Nelson 2001; Simion, Macchi Cassia, Turati, & Valenza, 2001). Indeed, despite newborns' poor visual acuity, investigators of the earliest beginnings of cognition have come to recognize that from birth, newborns possess very sophisticated attentive (Farroni, Simion, Umiltà & Dalla Barba, 1999; Simion, Valenza & Umiltà, 1995; Valenza, Simion & Umiltà, 1994) and perceptual abilities (Farroni, Valenza, Simion & Umiltà, 2000; Macchi Cassia, Simion, Milani & Umilta`, 2002; Valenza, Leo, Gava & Simion, 2006; Valenza & Bulf, 2007) that allow them to process and represent different kinds of information.

In line with this theoretical framework the present study has addressed to investigate the origin of numerical knowledge

My study begins reporting the language-independent processes and representation systems that allow adults to elaborate numerical information (Chapter 1). Subsequently, the documentation of studies demonstrating that very early infants are able to represent cardinal as well as ordinal numerical information is reported (Chapter 2). Finally, the two predominant models of the development and structure of numerical knowledge in the first year and months of life are described (Chapter 3). Both these models posit the existence of an inborn system implied in numerical performance: An object-tracking system for object representation, called Object-file system (e.g., Carey, 1998; Uller, et al., 1999), and a numerical estimation system, called Analog magnitude system (e.g., Dehaene & Changeux, 1993). Recently, a new theory (i.e., ATOM model) has extended the application of analog magnitude system to continuous as well as numerical quantities, based on ordinal knowledge (Walsh, 2003). Whereas the Object-file system detects and represents objects with their spatio-temporal features and only subsequently extracts numerosity information; Analog magnitude system is

specifically implied in the elaboration of quantity information, and its application is modulated by the numerical ratio of the values compared (i.e., ratio effects).

Strikingly, despite the assumption that both of these systems are innate, no studies have explored if the specific abilities required for object representation by Object-file system (e.g., Simon, 1999) and for quantity elaboration by Analog magnitude system (e.g., Gelman & Gallistel, 1978; Walsh, 2003) are present in early life (but see, Antell & Keating, 1983).

Starting from this lack, I tried to investigate the origin of numerical knowledge running three studies aimed at two main goals. The first aim has been to verify the presence of the abilities required by the Object-file system at birth. Specifically, Study 1 (Chapter 4) is aimed to investigate whether in the first days of life the capacity to form categorical representations of spatial relationships between visual objects is present. Using the visual habituation or familiarization technique five different experiments have demonstrated that newborns not only are able to discriminate an object’s position with respect to a landmark (Experiment 1, 2, and 5), but they are also able to recognize a perceptual invariance between left/right spatial relations in condition of low (Experiment 3) and high-perceptual variability (Experiment 4) of the object. Altogether, evidence from Study 1 reveals that from birth, infants are able to treat spatial relationship between objects in a categorical manner, at least when the spatial relationship involves only two objects and they are easily discriminable from each other.

Study 2 (Chapter 5) supports and extends these results showing that newborns are able to detect spatial ordered sequences of three objects, arranged in accordance with left/right spatial-relation principles. Specifically, using the familiarization technique, Experiments 6 and 7 have shown that 3-day-old infants are able to detect a spatial order sequence based on the spatial relations between three elements at least when temporal information are not available.

Altogether, the findings obtained in Study 1 and 2 suggest that from birth human cognitive system detects, processes and represents object based on their visuo-spatial features supporting the hypothesis of the existence of an early general and automatic attentive system of object tracking based on visuo-spatial processing (e.g., Scholl & Leslie, 1999; Simon, 1997; Uller, et al., 1999).

The second main goal of the present research is to investigate the presence, in the first months of life, of ordinal representational competencies implied by a general representational system of magnitude (i.e., ATOM; Walsh, 2003). To this end, the presence and the features of a representational system of ordinal magnitudes at birth and at 3 months of life have been tested.

Specifically, Study 3 (Chapter 6) has ascertained when the ability to detect ordered sequence of continuous magnitudes arises. Collected data have demonstrated that 3-month-old infants (Experiment 9) were able to discriminate between a monotonic continuous magnitude ordinal sequence (e.g., going from the smallest magnitudes to the largest) and a non-monotonic sequence (i.e., random order). Conversely, newborns did not show this ability (see Experiment 8), even if they have showed the ability to recognize a spatial ordinal magnitude sequence when they are required to discriminate a monotonic from a non-monotonic sequence, in conditions of lower perceptual variability (Experiment 10).

Altogether, the data from Study 3 have demonstrated the abilities of detecting ordinal continuous magnitude arise even in the first months of life, earlier than evidenced in literature (Brannon, 2002). Moreover, these data allow outlining the developmental trend of ordinal knowledge in the first months of life, highlighting that ordinal competences develop in the first 3 months of life, at least for continuous magnitudes.

In conclusion, these data seem suggest that, at birth, the human cognitive system elaborates objects, whereas the ability to elaborate quantities appears very fragile. Consequently if the capacity for objects processing develops before quantity processing, it is arguable that from the first days of life, infants posses the abilities necessary to elaborate small numerosities, yielded by an Object-file system, and that subsequently the ability to elaborate analog magnitudes develops.

Introduction

One central issue in developmental cognitive science is the exploration of how knowledge of specific domains seen in adults develops during early life.

Many studies carried out over the last 30 years lead to the suggestion that flexible skills and belief systems that adults employ to process objects, agents, space and numbers might gradually emerge as the results of the interaction between the structure of the input provided by the species-typical environment and initial, innately specified constraints (de Schonen, 2002; Elman et al., 1996; Karmiloff-Smith, 1992, Nelson 2001; Simion, Macchi Cassia, Turati, & Valenza, 2001). Indeed, despite newborns' poor visual acuity, investigators of the earliest beginnings of cognition have come to recognize that from birth, newborns possess very sophisticated attentive (Farroni, Simion, Umiltà & Dalla Barba, 1999; Simion, Valenza & Umiltà, 1995; Valenza, Simion & Umiltà, 1994) and perceptual abilities (Farroni, Valenza, Simion & Umiltà, 2000; Macchi Cassia, Simion, Milani & Umiltà, 2002; Valenza, Leo, Gava & Simion, 2006; Valenza & Bulf, 2007) that allow them to process and represent different kinds of information. Such work has provoked a re-conceptualization of the infant as an active, organized information processor rather than a collection of passive and disorganized sensory receptors. However, in most of these studies newborns were tested only with a narrow range of stimuli. For instance, many studies have been focused on investigating how faces (Farroni, Pividori, Simion, Massaccesi & Johnson, 2004; Farroni, Johnson, Menon, Zulian, Faraguna & Csibra, 2005; Macchi Cassia,, Simion & Umiltà, 2001; Macchi Cassia, Turati & Simion, 2004; Simion, et al., 2001; Turati, Simion, Milani & Umiltá, 2002; Valenza, Simion, Macchi Cassia & Umiltà, 1996; Gava, Valenza, Turati, de Schonen in press) or objects (Slater, 2001; Valenza et al., 2006; Valenza & Bulf, 2007) are processed.

Conversely, although in our daily lives most of our activities are related to and affected by numbers (from the important ability to comprehend the value of money to the more recreational ability to understand the score of our favorite football team) only one study has explored whether newborns possess the ability to abstract numerical invariance from a set of visual array (Antell & Keating, 1983).

In my studies, I have recognized this paucity of research and starting from this lack I have tried to examine the origins of numerical knowledge. In other words, given that the ability to use numbers is one of the most complex cognitive abilities that humans posses and is often held up as a defining feature of the human mind, a crucial issue in studying human cognition concerns the origins of the capacity to mentally represent and manipulate numbers.

The present research is intended to contribute to the study of numerical abilities' origins, and it is set out in two parts.

The first part will start reporting the language independent processes and representation systems that allow adults to elaborate numerical information (Chapter 1). Subsequently, Chapter 2 will contain documentation of studies demonstrating that very early infants are able to represent cardinal as well as ordinal numerical information. Finally, I will describe the predominant models of the development and structure of numerical knowledge in the first year and months of life (Chapter 3). In particular two different numerical systems will be described: An object-tracking system activated by small numerosities (n<4) and based on continuous variables elaboration, called *object-file* system (e.g., Carey, 1998; Hauser & Carey, 1998; Uller, et al., 1999), and a numerical estimation system activated by large numerosities and based on quantities elaboration, called analog *magnitude system*, (e.g., Church & Meck, 1984; Dehaene & Changeux, 1993). It will be also stressed that, recently it has been posited that the analog magnitude system might arise from a general system of magnitudes representations, based on ordinal knowledge (Walsh, 2003).

In the second part, I will report my research of the last few years. These studies are aimed at two main goals. The first aim is to verify the presence of the abilities required by the Object-file system at birth. Specifically, Study 1 is aimed to investigate whether in the first days of life the capacity to form categorical representations of spatial relationships between visual objects is present. Using the visual habituation or familiarization technique five different experiments will be carried out to investigate whether newborns are able to discriminate and categorize a spatial relation that is defined by the left/right spatial position of an object-target with respect to a landmark. Newborns' ability to discriminate an object's position with respect to a landmark (Experiment 1, 2, and 5) and to recognize a perceptual invariance between left/right spatial relations in conditions of low (Experiment 3) and high-perceptual variability (Experiment 4) of the object's positions will be tested. Study 2 has addressed the presence at birth of the ability to detect ordered sequences. Specifically, using the familiarization technique, Experiments 6 and 7 will investigate whether newborns are able to detect a spatial sequence of three objects, arranged in accordance with left/right spatial-relation principles.

The second main goal of the present research is to investigate the presence of ordinal representational competencies implied by a general representational system of magnitude (Walsh, 2003) in the first months of life. To this end, the presence and the features of a representational system of ordinal magnitudes at birth and at 3 months of life will be tested. Specifically, Study 3 is designed to ascertain when the ability to detect ordered sequence of continuous magnitudes (i.e., area) arises. For this purpose, three experiments will be carried out with newborns and 3-month-old infants. Experiments 8 and 9 will investigate whether newborns (Exp.8) and 3-month-olds' (Exp.9) are able to discriminate between a monotonic continuous magnitude ordinal sequence (e.g. going from the smallest magnitudes to the largest) and a non-monotonic sequence (i.e., random sequences). Furthermore, newborns' discrimination of ordinal sequences will be tested using habituation technique (Experiment 10).

Altogether, this series of studies contribute to verify whether some visuo-spatial abilities are already present at birth, supporting the theoretical hypothesis that posits that human cognitive system is endowed with an inborn object representational system implied in numerical abilities.

Moreover, the obtained results allow outlining the developmental trend of ordinal knowledge in the first months of life, supporting the hypothesis of the existence of an early and general representational system of non-numerical magnitudes.

Chapter 1

Numerical knowledge

Number is a property of sets of elements in the external world. To escape the ambiguity of the world "number", the term *numerosity* is used to refer specifically to a measurable numerical quantity (Gelman & Gallistel, 1978). The term *numerosity* concerns the unique property of a set of elements that does not change when the characteristics of the elements vary. In other words, we recognize different sets with the same number of items as equivalent, regardless the variation of perceptual variables as shape, color, spatial disposition or sensor modality of presentation (e.g., visual, auditory).

In the present chapter, two different aspects of the concept of "numerosity" will be described: the processes that permit adults to grasp numerosity and the theoretical models proposed to explain the nature of numerical representation in adulthood.

1 Number processes

The process that allows grasping the numerosity of a perceived set and access to the corresponding mental representation of numerosity (i.e., *token* or *numeron*) is called *quantification*.

A classic task for testing quantification processes is timed numerosity judgments, in which human adult subjects are asked to determine, as quickly and accurately as possible, how many items are presented in a display. Numerosity judgment latencies increase linearly with the numerosity of the display only over the range 4-6. For numerosities 1-3, response times is fast and increases only moderately with the number of items. For numerosities larger than 7, responses time is approximately constant, but accuracy drops severely (Mandler & Shebo, 1982). On the basis of the performance patterns obtained in timed numerosity judgments tasks, three different kinds of quantification have been postulated: *subitizing*, for processing small numerosities (range 1-3) , *counting*, for processing of a set in a range of 4-6 elements, and *estimation*, for processing large numerosities (larger than 7). Subitizing concerns a perceptive and attentive phenomenon that allows the immediate and accurate processing of small numerosities (Durgin, 1995; Kaufamn, Lord, Reese, e Volkmann, 1949). Differently, number judgments for larger set-sizes were referred to either as counting, the mathematical action of repeatedly adding (or subtracting) one, usually to find out exactly how many objects there are, or estimating, an approximation of a result which is usable even if input data may be incomplete, uncertain, or noisy. The main difference between counting and estimation depend on the number of elements present within the display, and the time given to observers in which to respond (i.e., estimation occurs if insufficient time is available for observers to accurately count all the items present).

Many studies suggest that these processes for grasping numerosity are available to a non-verbal representational level. For instance, a broad variety of animal species, such as rats (e.g., Meck and Church, 1983; Davis, MacKenzie, Morrison, 1989), birds (e.g., Emmerton, Lohmann, Niemann, 1997; Xia, Siemann e Delius, 2000), monkeys (e.g., Olthof, Iden & Roberts, 1997; Brannon & Terrace, 1998; Jordan, MacLean & Brannon, submitted), non-human primates (e.g., Matsuzawa, 1985; Biro & Matsuzawa, 2001; Kawai, 2001; Tomonaga &

Matsuzawa, 2002), fishes (e.g., Agrillo, Dadda, & Bisazza, 2007) and even insects (Chittka & Geiger, 1995) show the ability to subitize and estimate numerosities

2 Numerical representation systems

Several theoretical models have been proposed to explain the nature of the numerical representation system (e.g., Dehaene, 1997; Trick & Pylyshyn, 1994). The main commonality between these different hypotheses concerns the assumption that numerical knowledge could be coded in a language-independent way. The *triple code model* proposed by Stanislas Dehaene (1992) is the most widely accepted and empirically demonstrated theoretical concept of human adults' numerical system. This model proposes that adults are sensitive to meaningful numerical quantities. Any numerical activity solicits an "approximate mode" in which we access and manipulate a mental model of approximate quantities (e.g., Dehaene, 1997; Gallistel & Gelman, 1992). To enter into this putative approximate mode, Arabic and verbal numerals are first translated from their digital or verbal code into a quantity code. The input modality is then neglected, and numerical quantities are represented and processed in the same way as other physical magnitudes, such as length or luminosity. This kind of numerical representation is called an analog magnitude representation system.

2.1 Analog numerical representation system: the mental number line

The existence and characteristics of an abstract and pre-verbal numerical representation in human beings have been investigated since the XIX century. In 1880, Francis Galton surveyed a group of people about how they mentally represent numbers. Many people described the use of a mental image in which numbers, sometimes colored, are along a continuous line oriented from left to right, with smaller numbers on the left end. Galton (1880) named this mental representation of numbers *mental number line* (Figure 1).

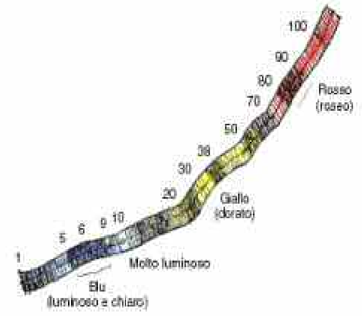

Figure 1: Instance of mental line [Source: Galton (1980)]

Recently, several lines of psychophysical and neuropsychological evidence have emerged in support of this mental pre-verbal representation of numbers in human adults. (e.g., Dehaene, Bossini, & Giraux, 1993; Zorzi, Priftis, & Umiltà, 2002). Dehaene's *triple-code model* (1992) suggests that the human cognitive system is endowed with a specific representational domain for numerical knowledge in which numerical information is recoded several times between different strictly interconnected representational formats (interactive model). Moreover, each numerical procedure is constrained to one and only one code of input-output (modular model). The *triple-code model* proposes three representational modules of numerical knowledge: A numerical visual Arabic code, in which numbers are represented as strings of digits (e.g., 28); a verbal representational format, in which numbers are represented as strings of words (e.g., twenty-eight); an analog quantity representation, in which numbers are represented as a distribution of activation along a mental number line ("mental number line") (Figure 2).

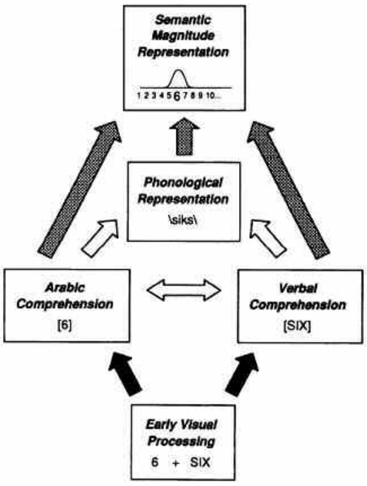

Figure 2: Schematic representation of the putative number processing pathways in a number matching task [source: Dehaene & Akhvein (1995)]

Dehaene's hypothesis is that number sense qualifies as a biologically determined category of knowledge. The foundations of arithmetic lie in our ability to mentally represent and manipulate numerosities on a mental "number line", the analogical representation of number, and that this representation has a long evolutionary history and a specific cerebral substrate (Dehaene, 1997).

The *mental number line* corresponds to an inborn preverbal analog representational of numerical quantities characterized by spatial relations, along a continuum from left to right (based on the origin culture), distributed as a scalar variability (Dehaene, 1997; Dehaene, et al., 1993; Dehaene, Piazza, Pinel, e Cohen, 2003). Specifically, the *triple code* model proposes that the mental representation format of the mental number line is involved in all the processes of pre-verbal arithmetic reasoning. Moreover, it is posited that the mental number line is at the basis of development of all numerical abilities dependent on language, thus the abilities dependent on the "Visual Arabic Code" and on the verbal code.

The existence of a mental number line and its characteristics have been widely documented in adults tested with a Number Comparison task. In this task, two numbers are simultaneously showed on the screen. The subjects are required to decide which number is the larger. The response is given by pressing one of two buttons. The dependent variable is the reaction time, thus the time elapsing between the appearance of the two numbers on the screen and the beginning of the correct manual response. Resulting data indicate that the responses are faster and more accurate as the difference between the two numbers becomes larger (e.g., reaction time for the comparison 51-65 is shorter than the reaction time for the comparison 59-65) (Figure 3). This phenomenon is called the *distance effect*: the necessary time to decide which number is the larger varies inversely with the distance between the numbers along the mental number line (Buckley & Gillman, 1974; Dehaene, 1989; Moyer & Landauer, 1967). This confirmed that the mental number line has a spatial extension. Distance effects have been reported with various animal species whenever the animal must identify the larger of two numerical quantities or decide whether two numerical quantities are the same or not (Gallistel & Gelman, 1992), suggesting phylogenetic origins of this representational system (Dehaene, Dehaene-Lambertz & Cohen, 1998)).

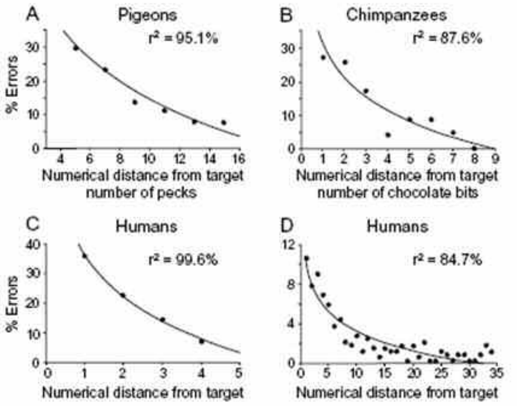

Figure 3: Results obtained in magnitude comparison tasks confirming the distance effect in different species. In all species, error rates in various number comparison tasks decrease monotonically as an approximately logarithmic function of the numerical distance between the numbers to be compared. [Source: Dehaene, Dehaene-Lambertz e Cohen (1998)].

In the same magnitudes comparison task another phenomenon arises: The *size effect* (Buckley & Gillman, 1974; Dehaene, 1989). In this case, between equidistant numbers, the responses are slower with the increasing absolute size of numbers to be compared (e.g., reaction time on 2-4 comparison is shorter than reaction time on 52-54 comparison). The interpretation of this phenomenon is that the mental number line is logarithmically compressed: The quantities represented are closer as the numbers become larger. In other words, two numbers such as 52 and 54 are closer to each other on the mental number line than 2 and 4 are (Figure 4).

Figure 4: schematic representation of size effect along mental number line

In conclusion, distance effect and size effect depend on the ratio between the compared magnitudes: Larger is the ratio, easier is the discrimination (obeying the Weber's law). For this reason, they are also named *ratio effects* (e.g., Dehaene 1992).

An important attribute of the mental number line concerns its spatial extension. This characteristic is supported by some studies that, using the Parity Judgment task, demonstrated that the mental number line has a specific orientation. Subjects were presented with Arabic digits in the range 0-9 and were asked to press one response key if the target was even and another response key if the target was odd. Collected data showed that the larger the target, the faster the response on the right-hand side relative to the response on the left-hand side. Left-hand responses were faster than right-hand responses for small numbers, and the converse was true for large numbers. Thus, large numbers are associated with right and small with left (Dehaene, et al., 1993). This association is called the *SNARC effect*– Spatial Numerical Association of Response Codes (Figure 5).

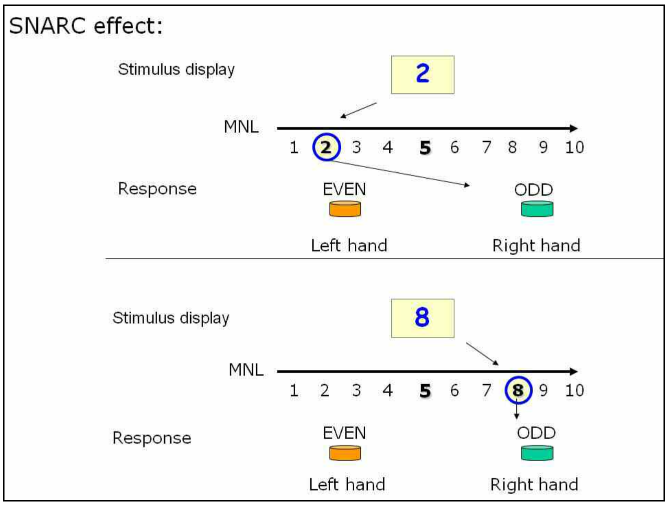

Figure 5: schema of SNARC effect in a Parity Judgment Task.

Dehaene, et al. (1993) have interpreted the SNARC effect as a possible demonstration that numbers are along a line with a specific spatial orientation from left to right. The smaller quantities are represented on the left side, with respect to the left hand, and the smaller ones are represented on the right side, with respect to the right hand. As is well-known, responses are faster when stimulus and answer are on the same side of the median line of the body rather than when they are on opposite sides. Moreover, Dehaene (Dehaene, et al., 1993) proposes that the appearance of the number automatically activates the corresponding representation on the mental number line.

Further evidence of numerical representations' spatial properties arise from a study carried out with patients affected by *hemispatial neglect* (Zorzi, et al., 2002). Hemispatial neglect is a neurological disorder characterized by a failure to represent information appearing in the hemifield contralateral to a brain lesion.

Specifically, this syndrome is characterized by a difficulty in the exploring of, attending to, and detection of stimuli when operating in the controlateral hemifield to the lesion, when these difficulties are not due to a sensorial or primary motors disturbance (e.g., Heilman, 1979). One task that demonstrates the characteristics of this syndrome is the line bisection task, in which subjects is required to mark the middle point of a drawn line. Neglect patients fail in line bisection tasks, since they shift the line midpoint as a function of line length (Halligan & Marshall, 1988) (Figure 6).

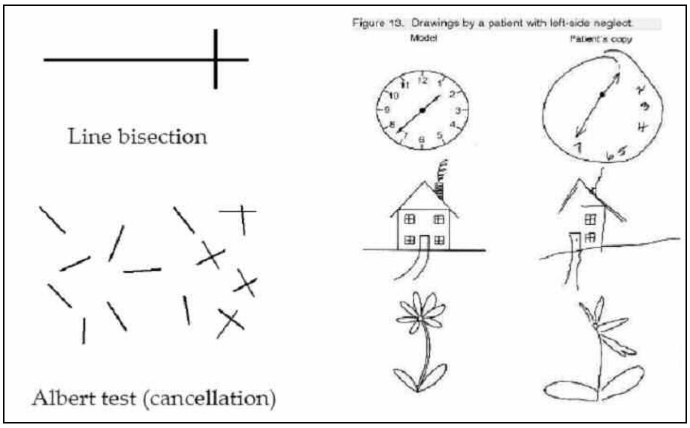

Figure 6: Instances of performances obtained by a patient affected by *hemispatial neglect*. This patient does not perceive the left hemifields due to an insult to the right hemisphere

Zorzi, Priftis and Umiltà (2002) have demonstrated that hemispatial neglect patients disrupt the mental number line in a manner similar to visually presented lines. These data demonstrate that the mental number line has a spatial nature that renders it functionally isomorphic to real physical lines. This suggests that the notion of a mental number line is much more than a metaphor (Zorzi et al, 2002).

In light of the above-reviewed data, it is widely accepted that human adults' numerical knowledge takes root in a language-independent analog representation system of magnitudes, affected by ratio effects. Moreover, animal evidence suggests that numerical processing (i.e., counting, subitizing, and estimation) does not have to be verbal (e.g., Matsuzawa, 1985; Chittka & Geiger, 1995). Consequently, it seems that some human and animal numerical abilities do not depend on language competency, but require access to an analog representation of numerical quantities.

2.2 Controversial aspects on analog magnitude representations

Although the bulk of evidence has supported the existence of an analog magnitude model of adults' and animals' mental architecture of numerical representation systems (e.g., Dehaene, 1997), analog representation systems seem to possess some significant characteristics that limit their possible applications (e.g., Carey, 2001). Specifically, their main objections pertain to the analog representations' inability to justify the performance obtained with small numerosities. As is reported above, adults' performance with small set of elements presents a specific pattern, in which the response time is fast, increases only moderately with the number of items, and is not affected by ratio effects.

Further concerns include that proposed processes for constructing analog magnitude representations include nothing that corresponds to the operation of "adding one". Rather, all analog magnitude systems positively obscure this operation: since numerical values are compared by computing a ratio, the difference between 1 and 2 is experienced as different from that between 2 and 3, which is again experienced as different from that between 3 and 4. In addition, of course, the difference between 7 and 8 is not experienced at all, since 7 and 8, as with any higher successive numerical values, cannot be discriminated. Consequently, the analog magnitude representation systems do not support any computations of addition or multiplication that build on the operation of “adding one” (Carey, 2001).

Dehaene’s reply to these comments is that the processing of numerosities up to 4 elements is attributable to the perceptive and attentive process of *subitizing* that implements marginally the magnitude analog representation system (Dehaene, 1992).

In order to resolve these questions some models have proposed that a different system replaces the magnitude analog representation system in numerical processing of both small and large numerosities (e.g., Scholl & Leslie, 1999; Simon, 1997; Uller, Carey, Huntley-Fenner & Klatt, 1999). This alternative system is at the base of the *subitizing* phenomenon and allows for building parallel representations of small sets of elements. As already reported above, subitizing concerns a perceptive and attentive phenomenon that allows the immediate and accurate processing of small numerosities (Kaufamn, et al., 1949). In accordance with an independent-language view, these numerical processing models have also proposed that numerical abilities lie in pre-verbal cognitive mechanisms. Conversely, to the numerical inborn knowledge position, these models suggest that numerical discrimination arises from perceptive and attentive mechanisms (e.g., Uller, et al., 1999).

2.3 <u>An alternative system of number representation: Parallel individuation of the small set</u>

As an alternative to the analog magnitude system proposal, numerous researchers (e.g., Kahneman & Treisman, 1984; Lesile, Xu, Tremoulet & Scholl, 1998; Trick & Pylyshyn, 1994) have suggested that a very different representation system might support the pre-verbal representations of number. Several theories of object selection and tracking have led to hypotheses of the enumeration process, such as Kahneman and Treisman's (1984) Object-file Theory of Visual Indexing, Trick and Pylyshyn's (1994) Visual Indexing Theory (or FINST Theory) or Lesile, Xu, Tremoulet e Scholl's (1998) Object-indexing Model. In these alternative representational systems, number is only implicitly encoded; there are no symbols for number at all, not even analog magnitude ones for representing numbers. This class of mental representation produces a symbol (*object token*) for each element within the perceived set. Since these representations consist of one symbol (file) for each individual (usually object) represented, they are called "object-file" representations.

One of the more important indexing models to include a mechanism directly implied in the *subitizing* phenomenon and in the counting process is the FINST Theory proposed by Lana M. Trick e Zenon W. Pylyshyn (1994).

2.3.1 The visual indexing theory (FINST Theory)

One of the experimental paradigms of choice for studying both initial and continuing object-based selection is the Multiple Object Tracking (MOT) task developed by Pylyshyn and Storm (1988). The MOT task has been used widely in the study of attention and particularly in the study of sustained attention to multiple loci-of-attention. In MOT, a set of simple identical objects (typically 8 circles) is presented on a computer screen. A subset of them ("targets") is made visually distinct, typically by flashing them on and off for a brief period of time. Then, all objects move about in an unpredictable manner and the task is to keep track of the now-identical objects and to identify the targets at the end of a short trial. Observers can do this under a variety of conditions at better than 90% accuracy.

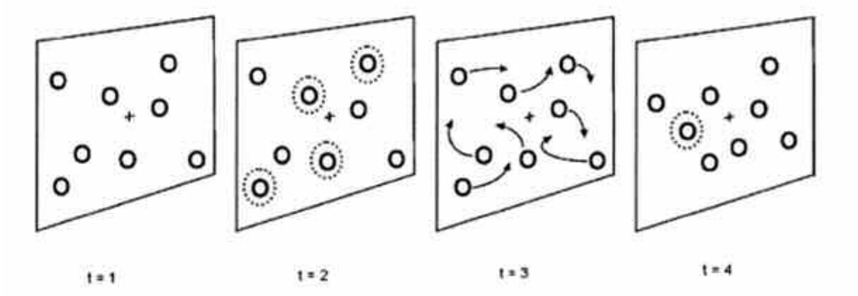

Figure 6: Illustration of a typical MOT experiment. A number of identical objects are shown (t = 1) and a subset is selected by flashing them (t=2), after which the objects move in unpredictable ways. At the end of the trial the observer has to pick out all the targets (t=4).

Pylyshyn and Trick (Pylyshyn, 2001; Trick & Pylyshyn, 1994) has developed the Visual Indexing (or FINST) Theory to account for these capacities. Pylyshyn and Trick have hypothesized the existence of primitive indexing mechanisms that individuate and index, or keep track of about four or five individual objects in the visual field. The FINST mechanism was hypothesized to fill a need for selecting and keeping track of token elements independently of encoding any of their properties (Pylyshyn, 2001). Several reasons are given for why we need such a mechanism to individuate and track distinct objects in the world. One is that early vision must pick out and compute the relationships among several individual objects while ignoring their properties. Another is that incrementally computing and updating representations of a dynamic scene requires keeping track of token individuals despite changes in their properties or locations. A mechanism meeting these requirements has been proposed in order to account for a number of disparate phenomena, including *subitizing* (Pylyshyn, 2001)

The Visual Indexing (or FINST) Theory argues that *subitizing* exploits a limited-capacity pre-attentive mechanism for individuating a small number of feature clusters, the FINST mechanism (Pylyshyn, 1989). The aim of the FINST mechanism is to individuate elements in the visual space, assigning each a reference symbol (*tokens*) that allows the human cognitive system to individuate objects explicitly. *Tokens* are attributed to the elements present in the visual field on the basis of Gestalt's spatio-temporal principles of proximity, similarity, good continuation and common fate. In Trick and Pylyshyn's model, *tokens* are called FINST by *finger of INSTantiation* and their function is to discriminate between objects in terms of spatial position. For instance, when an object partly occludes one other object, the FINST mechanism allows us to individuate where one object begins and where the other object ends. We individuate feature clusters by assigning reference tokens (i.e., FINSTs) which act as pointer variables (Pylyshyn, 1989). FINSTs provide a way of saying "that one" without explicitly stating properties.

Trick and Pylyshyn (1994) have argued that the *subitizing* phenomenon is a partial effect of the coordination of the different phases of visual processing. The FINST model claims that visual processing is made up of different phases along a continuum from a pre-attentive first stage to a final one of object recognition. The *subitizing* phenomenon springs from the switch from the pre-attentive phase of parallel individuation of the elements in a space to the subsequent attentive phase of object recognition. The first, spatially parallel, preattentive stage has two parts: *Feature registration* and *grouping*. In the feature registration processes, object properties such as color, brightness, orientation, curvature, and so forth, can be used to define the edges of an object. This process involves finding the locations of the feature discontinuities in the image and assigning place tokens (Marr, 1982). This process is thought to be spatially parallel; analyses occur at every point in the image at the same time. Consequently, items that differ from other items for a single feature can be detected in a time independent of the number of items in the display in question (*pop*-out phenomenon; Treisman & Gelade, 1980). Next, through the pre-attentive grouping processes, the different visual features detected are grouped to form visual objects, on the basis of Gestalt's spatio-temporal principles (e.g., *texture segregation* phenomenon; Beck, 1982). The next stage involves visual routines that compute number and spatial relations such as "inside" and "connected", tasks that by their nature require spatially serial processing (Minsky & Papert, 1969). In the final stage of visual analysis, the structural descriptions created in the earlier stages of analysis are matched to memory representations for particular objects or classes of objects. If a match is found, then the item can be named or categorized.

FINSTs are assigned after the pre-attentive operations of feature detection and grouping, but before the operation of spatial attention. Technically, this stage is pre-attentive because it operates before active attention and before spatially serial analyses.

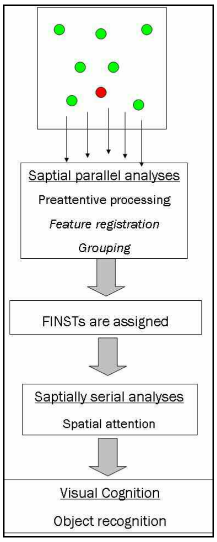

Figure 7: The FINST mechanism in visual processing

The FINST model proposes that *subitizing* occurs when people enumerate items in the visual field, and the number of items is less than the total number of internal reference tokens or FINSTs. In turn, *subitizing* processes consist of two stages. The first stage involves variable binding: One FINST is assigned to each item in the display. This first stage is pre-numeric, because at this stage we are only conscious of “some” items in the display; number recognition has not yet occurred. Pre-numeric individuating information must be available to the system before the attentional processor is moved to an item to check its identity. Otherwise, the system would not “know” when to start indexing or know when to stop. The second stage of subitizing is number recognition, in which a person can use the information about assigned reference tokens to access a number name. Number recognition must involve matching each individuated item with a number name stored in short-term memory. Specifically, the authors propose that the number of elements that could be processed through *subitizing* is due to a constraint due to the number of objects that can be individuated in a visual scene, rather than the amount of information that can be held in short-term memory.

Authors suggest that the velocity and the accuracy of subitizing are owed to the specific properties of underlying attentional processes. Subitizing is fast because it is a simple process involving two stages, one of which may be parallel. Subitizing is very accurate because there are few memory requirements. The FINSTs put more stress on the attentional requirements of particular visual displays and tasks. FINSTs can be assigned to objects in the visual field regardless of their spatial contiguity with the following restriction: the architecture of the visual system provides only about four FINSTs (Pylyshyn, 1989).

This model also proposed a counting process based on the subitizing phenomenon. In accordance with the FINSTs model, counting arises after it becomes apparent that all the tokens are assigned, that is, once we learn that the display cannot be subitized (e.g., Mandler & Shebo, 1982; Trick & Pylyshyn, 1994). Successively, the items are grouped into cluster of 2-4 items, subitizing each group, adding the result into a running total, marking the cluster and then moving the attentional focus to the next group. This process has been called the group-and-add process of enumeration (e.g., Trick & Pylyshyn, 1994). In line with FINSTs model, counting is slow because it involves many stages, some of which take longer as the number of items in the display increases. Moreover, in contrast with subitizing, counting is an approximate process as memory requirements make it error-prone; it is possible to forget the subtotal, or forget the addition table. There are simply more things to go wrong when counting than subitizing.

In conclusion, FINST Theory proposes a theory of enumeration that could be incorporated into a theory of vision. This theory with respect to the other enumeration theories has the benefit that it is based on the vision requirements of the visual process and so it is based on the necessity to select elements in the visual field. This enumeration process requires attention processing only because it is necessary to select the items. However, this theory is based on the spatial properties of the objects, so it cannot explain event enumeration, the enumeration of items defined across time (e.g., successive tones).

The FINST Theory has been confirmed by a large number of empirical evidences (e.g., Scholl, Pylyshyn, & Feldman, 2001; Viswanathan & Mingolla, 2001, for a review see Scholl, 2001), beginning with the studies of Pylyshyn and Storm (1988), that have shown that observers can track up to five independently moving targets within a field of ten identical items.

3 Conclusions

In the present chapter, two different topics concerning numerosity have been explored: the processes that allow grasping numerosity, and the theoretical models posited to explain the structure of numerosity representation in adulthood.

Quantification is the term for the process that allows detection and representation of the numerosity of a perceived set. Three processes of quantification have been postulated: subitizing, estimation and counting. Since subitizing and estimation are accessible to many species of animals, an important attribute of these processes is that they are language-independent.

Furthermore, in the last twenty years, a body of evidence confirms that numerical knowledge of human adults is based on two language-independent systems: The analog magnitude system and the object-file model.

The analog magnitude system proposal assumes that adults’ numerical knowledge arise from a pre-verbal numerical representational system, shared with other animals, that provides a mental model of approximate quantities (e.g., Dehaene, 1997; Gallistel & Gelman, 1992). In the *Triple Code Model*, claimed by Dehaene (1997), it is posited that the cognitive system is endowed with a representation of numerical quantities similar to a number line. This representational format is characterized by spatial relations, distributed as a scalar variability along a continuum from left to right (based on the origin culture) (Dehaene, 1997; Dehaene, et al., 1993; Dehaene, et al., 2002). In this representational system, numerical quantities are represented and processed in the same way as other physical magnitudes, like length or luminosity (Dehaene, 1997). Moreover, the quantities representations are affected by ratio effects (i.e., size effect and distance effect).

Alternatively, the object-file model proposes that numerical knowledge has its roots in perceptive and attentional mechanisms. The main common characteristic of the different indexing models that support a numerical processing theory is the supposition that numerical processing is based on a non-numeric process on the basis of Gestalt spatio-temporal principles of visual perception, that give rise to the *subitizing* phenomenon. Moreover, it is hypothesized that this system is subjected to a limit on the number of objects simultaneously attended and tracked of about four elements. The FINST Theory, proposed by Trick and Pylyshyn (1994), proposes that the ability to detect numerical information is due to the mechanism of subitizing the elements present in the visual field. The human cognitive system is endowed with 4 or 5 reference symbols (i.e., FINSTs) that can be automatically assigned to the perceived items, in a first pre-numeric individuation stage. Next, in the following number recognition stage, each individuated item is matched with a number name and stored in short-term memory system. Trick and Pylyshyn (1994) propose that the counting process is also based on the subitizing mechanism.

The evidence present in the literature seems to confirm Dehaene’s position that adult numerical knowledge system is endowed with two different representational systems, one that elaborates approximate quantities in an analog representational way and one that elaborates small quantities by the perceptual and attentive mechanism of subitizing.

An important characteristic of both of these representational systems is that they are based on pre-verbal representational systems of quantities, and thus are language-independent. Consequently, studies concerning the origins of numerical knowledge have been oriented toward two comparative contexts of investigation: The study of numerical abilities in animals and the study of numerical abilities in infants before language development.

This thesis is an attempt to investigate this latter research area and in the next chapters will be reported the data on numerical abilities in the first months of life (Chapter 2) and the main theoretical models posited to explain the origins and development of these competencies (Chapter 3).

Chapter 2

Evidence of pre-verbal numerical knowledge in infancy

As extensively reported in the previous chapter, a growing number of studies suggest that human adults posses two language-independent representational systems both implied in the numerical abilities: An analog magnitude system for approximate large numerosities and a tracking object system for precise small numerosities (e.g., Dehaene, et al., 1998; Gallistel & Gelman, 1992). In order to understand the origins and the development of pre-verbal numerical knowledge, in the last decades many studies have been carried out. In this chapter will be describe some studies that suggest that very early in the development infants show the ability to represent both cardinal and ordinal information (e.g., Brannon, 2002; Xu & Spelke, 2000).

Mainly three different procedures were used in assessing sensitivity to number in pre-verbal infants: Habituation-dishabituation of looking time, violation of expectation and manual search task paradigms (e.g. Antell & Keating, 1983; Bijeljac-Babic, et al., 1991; Feigenson, Carey, & Hauser, 2002; Koechlin, Dehaene, & Mehler, 1998; Simon, Hespos, & Rochat, 1995; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981; Treiber & Wilcox, 1984; Uller, Huntley-Fenner, Carey, & Klatt, 1999; van Loosbroek & Smitsman,1990; Wynn, 1992; Xu & Spelke, 2000, but see Clearfield & Mix, 1999, Feigenson & Carey, 2005).

Most of the researches on infants' numerical knowledge have used the *habituation-dishabituation paradigm*, since this procedure permits to avoid the infants’ immature motor abilities even in the earlier months of life. Usually the procedure adopted in these studies consists to present repeatedly to each infant some arrays containing a certain number of items, until the infant’s looking time to the arrays decreases to a pre-specified criterion (typically to half of her or his initial levels of looking). At this point, the infant is considered to be habituated to the stimuli. Following habituation, the infant is presented with new displays, some containing the original number of items and some containing a new number of items. It is well known that infants tend to look longer at stimuli that are new to them (Fagan, 1977) therefore, a preference for the display containing the new number of items is interpreted as proof of the infant’s ability to distinguish between the two numbers(Figure 1).

The *violation of expectation paradigm* was developed by Baillargeon, Spelke and Wasserman (1985) for exploring object representation in 5-month-old infants. In general, babies are familiarized to a series of events, repeated a number of times. For instance, a doll is put behind a screen, and then the screen is removed showing the doll on the stage. Infants are presented to these habituation events until bored. Successively, during test phase, infants see one of dishabituation events: A new expected possible event, (e.g., when the screen is removed the baby can see the doll), and an unexpected impossible event (e.g., when the screen is removed the baby can see two dolls). A preference for the event judged as impossible is normally interpreted as a proof of infant’s ability to distinguish between the two events (Figure1).

In the *manual search task* paradigm (Van de Walle, Carey, & Prevor, 2000), the experimenter inserts one or two balls in an opaque box and the infants are required to retrieve the ball from the box. After the balls were inserted, the experimenter hold one of them at the back of the box, hence the numbers of balls that the infants saw is different from the numbers of ball that he can reach from the ball. The dependent measurable is the duration of infants' searching when the box was expected to be empty, rather when the box should be expected to contain more objects (Figure 1).

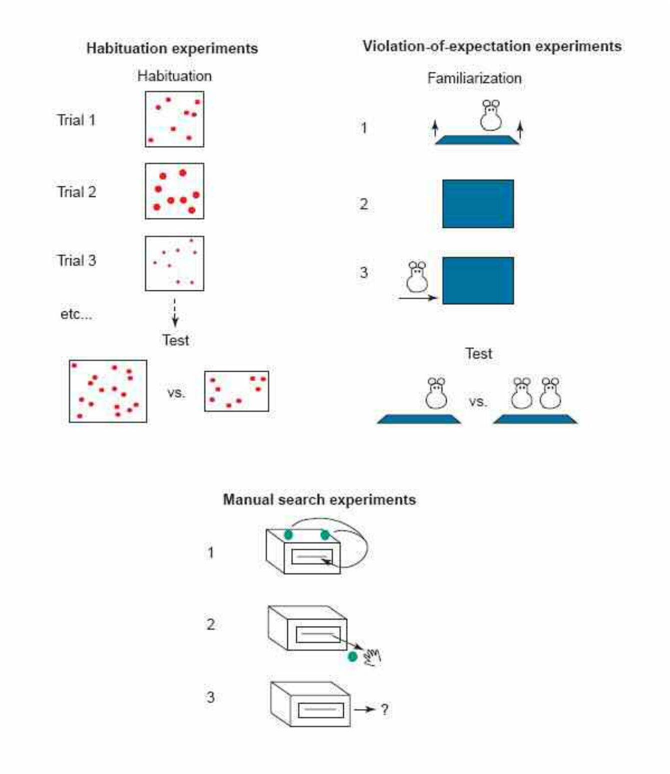

Figure 8: Three types of tasks used to test infants' quantity representations [source: Feigenson, Dehaene, & Spelke, 2004].

1 Number representation in infancy: small numerosities discrimination

Many studies suggest that since the first months of life, even in the first days of life, infants are able to discriminate small quantities of simple dots (Antell & Keating, 1983; Starkey & Cooper, 2002), moving objects and collection of objects (van Loosbroek & Smitsman, 1990; Wynn, Bloom & Chiang, 2002), syllables of words of human speech (Bijeljac–Babic, Bertoncini & Mehler, 1993; van Marle & Wynn, 2006) and events such as puppet jumps (Wynn, 1996).

Antell and Keating (1983) conducted one of the first studies to assess numerical abilities in infants with *habituation-dishabituation paradigm*. In this study, the Authors have reproduced with newborns the procedure and the results of the pioneering study of Starkey and Cooper (1980) with 5-month-old infants. Antell and Keating study was aimed to assess newborns' ability to recognize the number of some dots in a visual set. Newborns were habituated to two displays with the same number of dots (i.e., 2, or 3, or 4, or 6), but which varied in terms of the length of the line or density between the dots. After reaching criterion, during the post-habituation phase, the infants were presented to a third display, in which each stimulus contained a novel number of dots (2 vs. 3, 3 vs. 2, 4 vs. 6, or 6 vs. 4), but which maintained the line length of one of the habituation arrays and the dot density of the other (Figure 2).

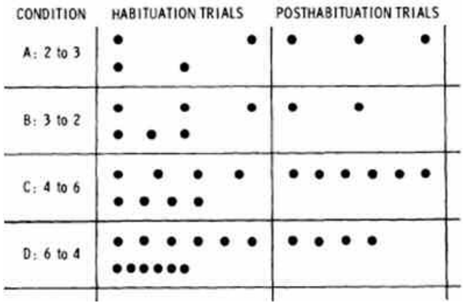

Figure 9: Stimuli used in Antell and Keating (1983) study [source: Antell & Keating (1983)].

Newborns looked longer to the stimulus with a novel number of items only when small numerosities were presented, thus they discriminate only 2 dots from 3. This did not occur in the large-number condition, with 4 and 6 dots. This data demonstrated that neonates are able to detect numerical difference in arrays consisting of small numbers of discrete stimuli, but that they fail when the set becomes too large.

In another *habituation-dishabituation* study, Wynn (1996) examined 6-month-old infants' ability to individuate and enumerate physical actions: the sequential jumps of a puppet. Examining infants' enumeration of actions addresses a different issue respect the studies described above. The individuation of actions is likely to more complex because actions are not definable purely in terms of objective properties. In this task, during habituation phase, infants were showed to a puppet that produced a specific sequence of jumps (e.g., 2 jumps). Then, in test phase, two sequences of jumps were presented one with the familiar number of jumps (e.g., 2 jumps) and the other with a new number of jumps (e.g., 3 jumps). The old-number test jump sequence was always different from the habituation sequence in both tempo and total duration. The novel-number test jump sequence was always the same as the habituation sequence on one of these dimensions. Infants successfully discriminated only 2-jumps from 3-jumps sequences. These data confirm the results obtained with static visual array (e.g., Starkey & Cooper, 1983) thus infants can discriminate only small numerosities (i.e., up till 4 elements).

Using the *violation of expectation paradigm*, Wynn (1992) showed that 5-month-olds are able to engage in numerical reasoning with small numerosities. In her experiments, infants are shown a small collection of objects, which then has an object added to or removed from it. The resulting number of objects shown to infants was either numerically consistent, or inconsistent with the events (Figure 3). Since infants look longer at outcomes that violate their expectations, the authors interpret these finding as the proof that infants anticipate the number of objects that should result, and for this reason they look longer at the inconsistent outcomes than the consistent ones.

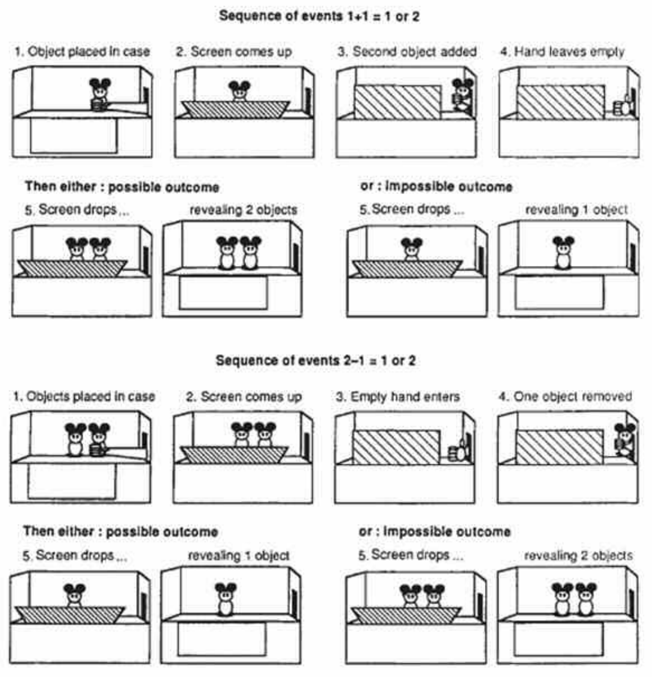

Figure 10: One of the sequences of events shown in Wynn (1992) [source: Wynn (1992)].

Moreover, these results suggest that 5-month-old infants not only know that there should be a change as a result of the operation, but exactly what the final outcome should be. From these data, Wynn has deduced that 5-month-olds are sensitive to numerical relationships between small numbers of objects (Wynn, 1995).

Feigenson and Carey (2005) used the *manual search task* (Van de Walle, et al., 2000; Feigenson & Carey, 2003, 2005) to explore the limits of 12-month-old infants' quantification of small object arrays (Figure 4). The comparisons tested were 1 vs. 2, 1 vs. 3, 1 vs. 4, 2 vs. 3.

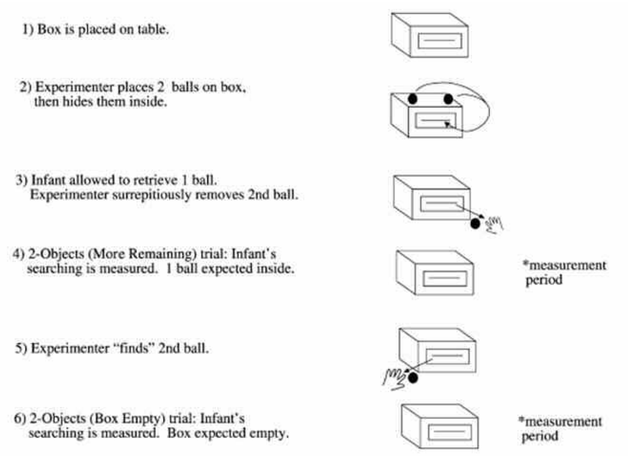

Figure 11: Procedure used in Feigenson and Carey (2005) study [source: Feigenson & Carey (2005)].

Only under the condition with small numerosities (i.e., 1 vs. 2, 1 vs. 3, 2 vs. 3) all infants successfully retrieved the correct number of balls.

The findings above reported converge with studies using cross-modal stimuli (e.g., Starkey, Spelke & Gelman, 1983; Kobayashi, Hiraki & Hasegawa, 2005; Jordan & Brennon, 2006). Starkey, Spelke and Gelman (1983) provided evidence that 6- to 8-month-old infants are able to match the number of elements present in a visual display with the number of sounds in a temporal sequence. Using a preferential looking procedure, infants were presented to two displays with 2 and 3 elements each one. While infants were looking to these displays, a sequence of 2 (or 3) tones was presented. The infants attended longer to the display of items that matches in number the sequence of sounds. Since infants showed a looking preference for the numerically corresponding display rather than for the non-corresponding display, the Authors deduced that they are able to detect the number of items both in visible and audible display (Starkey, et al., 1983).

This result was confirmed by a study by Kobayashi and colleagues (Kobayashi, *et al.*, 2005) in which they reported that 6-month-old infants represented the numerical equivalence between objects and sounds in a violation of expectation procedure. Infants were first familiarized with a 2 and 3 Mickey Mouse-like object sequentially impacting a surface, with each object emitting a tone at impact. Infants were then tested during trials in which an occluder blocked the infants' view, but the infants heard 2 or 3 of the tones from familiarization (varied in rate and total sequence duration). When the occluder was removed, 2 or 3 of the Mickey Mouse-like objects were revealed. Infants looked significantly longer at the numerically non-equivalent events, suggesting that they had formed an expectation of how many objects they should see based on how many sounds they had heard and were surprised that this expectation was violated.

The infants' ability to match cross-modal information on the basis of number in a natural situation is recently confirmed also by Jordan and Brannon (2006) study, yielding evidence that 7-month-olds preferentially attend to dynamic visual displays of 2 or 3 women that numerically match the number of voices they hear simultaneously speaking a word. In this study, infants were exposed to two movies presented side by side: one video showed 2 women and one video showed 3 women, mouthing the word ''look''. While the babies were looking at the displays, they heard 2 or 3 women concurrently saying ''look''. As in the previous study reported, infants prefer to look longer the display that matched the number of voices with the number of faces. This result not only confirms the cross-modal numerical abilities previously demonstrated by Starkey *et al.* (1983) but also extends these abilities to a situation more ecologically relevant and meaningful to the infant.

The fact that infant can enumerate entities with quite distinct properties, presented in different perceptual modalities, might suggest that infants possess abstract, generalizable representations of small numbers, and that these representations are independent of the perceptual properties of specific arrays (Wynn, 1995).

1.1 Continuous dimensions confound

The early studies describe above exposed themselves to criticism. Indeed often these studies did not adequately address alternative continuous variables that may have affected infants' behavior, especially when visual processing is implied (e.g., Antell & Keating, 1983; Feigenson & Carey, 2005; Wynn, 1992). In addition, some studies suggest that in some contexts infants may keep track of continuous dimensions such total contour length rather than number (Clearfield and Mix, 1999, 2001; Feigenson, et al., 2002).

For example, Clearfield and Mix (1999) demonstrated that 6- to 8- month-old infants discriminate between visual stimuli on the basis of contour length or some other continuous variable that correlates with it, rather than on number. In this study, infants were habituated to stimuli composed by a constant number of items (i.e., 2 or 3) with a constant contour length (Figure 5). The items in the arrays varied in position in each habituation trials (Starkey, et al., 1990). Following the habituation trials, infants were presented with test stimuli that alternated between changes in number and changes in contour length. The infants dishabituated to change in contour length when number remained constant, but did not dishabituated when contour length remained constant. The Authors have concluded that when number and continuous variables are separated, infants attend to continuous variables (i.e., contour length), rather than number, to discriminate between sets. Since contour length is correlated with total area, brightness and size, it could be any or all of these variables that affect infants' looking behavior.

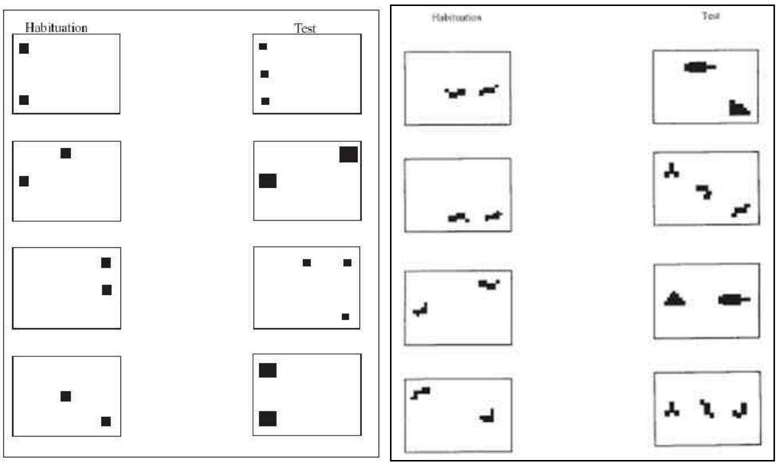

Figure 12: Sample habitation and test stimuli used in Clearfield and Mix (1999) study (left panel) and in Clearfield and Mix (2001) study, in which contour length was held constant across habituation and test trials (right panel) [source: Clearfield & Mix (1999) and Clearfield & Mix (2001)].

This conclusion was reinforced in a following study, in which Clearfield and Mix (2001) investigated which specific measure of spatial extent infants use to discriminate small sets of items. In this study the Authors extended the results of Clearfield and Mix (1999) by separating area from contour length to determine whether infants could use either feature alone to discriminate quantity. This research investigated whether infants respond to a change in area when contour length is controlled across habituation and test trials, and vice versa. Hence, in one variation, infants were habituated to two abstract shapes of a same total area (e.g., 16 cm^2). The test trials were three shapes with a same total area and two shapes with a new total area value (e.g., 24 cm^2). In the contour-length variation, infants were shown test trials that alternated between changes in contour length and changes in number, whereas area remained constant across habituation and test trials. Infants detected changes in area when contour length remained constant, and they detected changes in contour length when area remained constant. In no case infants detected changes in number when both contour length and area remained constant. Thus, it appears that infants detect changes in quantity based on either area or contour length.

Clearfield and Mix's findings suggest that continuous dimensions must be more carefully controlled in studies of numerical cognition. Such studies also highlight a need for a more exhaustive investigation of the perception of both number and continuous dimensions in infancy.

2 Number representation in infancy: Large numerosities discrimination

Only recently, a growing number of studies have investigated the ability to discriminate large number of elements in the first months of life. Using the visual habituation method, Xu and Spelke (2000) demonstrated that 6-month-olds are able to discriminate between large numbers of items on the basis of numerosity, even if the continuous variables are hold controlled. In this study, the stimuli presented during the habituation phase contained 8 (or 16) dots, which varied the total surface area, the average size of each items and the average brightness. During the test phase, two stimuli were presented to the babies, one of them with the familiar number (e.g., 8) and the other one with a novel number of dots (e.g., 16). The test stimuli presented an equivalent density and both of them contained the same size dots, so the test display with 16 dots had twice the area as the display with 8 dots. However, the total areas of the two test displays were equidistant from the average area of the habituation displays (Figure 6).

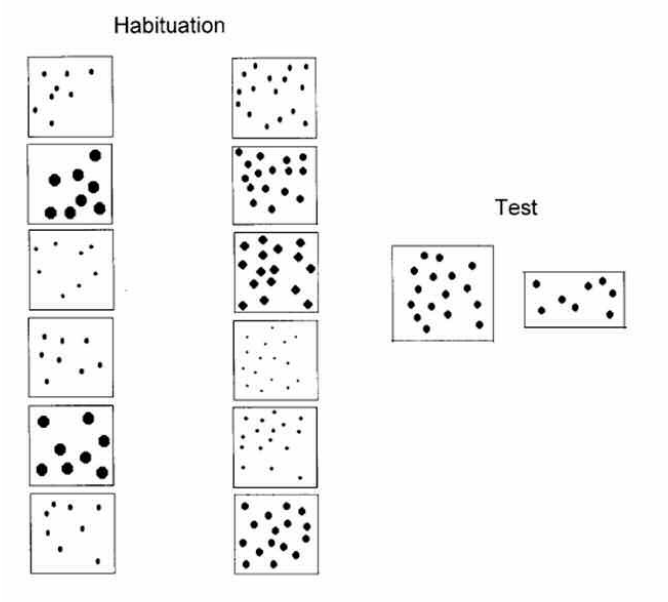

Figure 13: Schematic representation of the stimuli and the procedure used in Xu and Spelke (2000) study [adapted form Xu & Spelke (2000)]

Collected data shows that 6-month-olds are able to distinguish between 8- and 16- element displays, but not between 8- and 12-element display, when variables such as density, surface area and brightness were controlled. Infants at 6 months of age show the ability to discriminate large numerosities on the basis of numerical information, when the ratio difference between them is sufficiently large (i.e., ratio effects).

However, Mix, Huttenlocher and Levine (2002) have partly criticized the result of this study. These Authors have highlighted a possible confound in Xu and Spelke (2000) study that might undermine the conclusion. Area and contour length do not change linearly with respect to each other when the size of the individual items in the displays changes. This means that although Xu and Spelke's (2000) procedure may have controlled for area, it did not control for contour length. In fact, the difference between the mean contour length during habituation and the contour lengths at test is always greater for the novel number displays than it is for the familiar number displays. This might be enough for justifying the infants' abilities to discriminate between 8 and 16 elements. This confounds of contour length and number is not as strong in the 8 versus 12 conditions. Thus, both the novel and familiar test displays were relatively close in contour length to the habituation displays. This may account for Xu and Spelke's (2000) failure to obtain a significant looking time difference in this condition.

Others recent studies have replicated and extended the pioneering experiments of Xu and Spelke (2000), suggesting that from 6-months of age infants discriminate a wild range of values that differ by a 1: 2 ratio (e.g., Xu, Spelke et al., 2005; Xu & Arriga, 2007).

For example, Xu, Spelke and Goddard (2005) have demonstrated that 6-month-old infants succeed in discriminating large numerosities with larger ratio, when they are required to discriminate larger numerosities (16 vs. 32; 16 vs. 24) with respect to the previous study, but the ratio was held the same (1:2; 2:3).

Similarly, Xu and Arriga (2007), using a similar procedure, have demonstrated that since 10 months of age infants are able to discriminate numerosities that differ by a ratio of 2:3, but not those differ by a ratio of 4:5.

Altogether these data suggest that at 6 months infants are able to discriminate only large numerosities with a ratio of 1:2 between them and at 9 months a smaller ratio of 2:3, regardless the cardinal values of the numerosities. It seems that number discrimination improves in precision during the first year outlining a specific developmental trend in discriminating numerosities settled by the ratio between them.

The findings just reported converge with studies using auditory stimuli. Studies by Lipton and Spelke (2003, 2005) found that by about 6 months, infants were able to discriminate 8 from 16 sounds but not 8 from 12 sounds, ability achieved only by 9 months of aged. The Authors claimed that, in contrast to two-dimensional visual displays, one-dimensional auditory sequences allow for the control of all continuous temporal variables simultaneously. In these studies, a modified version of the head-turn preference procedure (Kemler, Nelson et al., 1995) was employed in order to investigate 6- and 9-month-old infants' discrimination of sound sequences that differ by a ratio 1:2 (i.e., 8 sounds vs. 16 sounds) or 2:3 (i.e., 8 sounds vs. 12 sounds). Sounds of equal amplitude were presented throughout the experiment, with the rate and durations of individual sounds equated across the two numerosities during familiarization, and with total sequence durations and amount of acoustic energy equated across the two numerosities during the test. Successful discrimination of these sequences therefore could not depend on any of these continuous variables and more likely would depend on number (Lipton & Spelke, 2003).

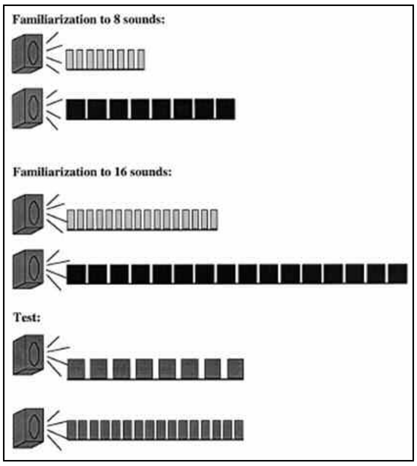

Figure 14: Schematic representation of one of the auditory sequences used in Lipton and Spelke (2003) study.

Both 6- and 9-month-old infants were able to discriminate the sound sequences those differ by the larger ratio (i.e., 1:2), but only by 9 months they succeeded with the smaller ratio (i.e., 2:3). These results fit the data obtained with visual display, and confirm that from 6 months of age infants discriminate a wild range of values that differ by a 1:2 ratio in both auditory and visual domain and that numerical discrimination becomes more sensitive with age.

3 Ordinal numerical knowledge in infancy

The data above reviewed suggest that infants make cardinal numerical discriminations. That is, infants from 6 months of life seem to be able to perform a computation such as X is numerically different to Y or X is not numerically equivalent to X. Less is known about infants' sensitivity to ordinal relationships. To illustrate the difference between cardinal and ordinal numerical knowledge, imagine to be able to differentiate two objects from three objects but not knowing which set is numerically grater. One possibility is that infants first comprehend only the cardinal properties of number and then later come to appreciate ordinal relationships between numbers through observing numerical transformations in their environment or through reinforcement (see Cooper, 1984; Dehaene & Changeux, 1993; Kitcher, 1984; Strauss & Curtis, 1984). An alternative view maintains that infants represent numerical ordinality from the start (e.g., Wynn, 1995). The question boils down to whether for a young infant "twoness" is to "threeness" much like a blender is to a chair, or alternatively whether even for the very young infant "twoness" and "threeness" are perceived as different values along one numerical continuum.

Only a handful of studies have directly addressed the development of ordinal numerical knowledge in young children. Children as young as two years of age represent the ordinal relations between numerical values as large as 5 or 6 even when surface area is controlled (Brannon & Van de Walle, 2001; see also; Bullock & Gelman, 1977; Huntley-Fenner & Cannon, 2000; Sophian & Adams, 1987; Strauss & Curtis, 1984). However, few studies have specifically tested for ordinal numerical knowledge in the first months of life (Brannon, 2002; Cooper, 1984; Wynn, 1992; Feigenson, Carey & Hauser, 2002).

Cooper (1984) habituated infants to pairs of stimuli that were presented successively and that maintained a constant ordinal relationship between the number of elements in the first and second stimulus while varying the absolute values (values ranged from 1-4). Thus on habituation trials infants were always shown a small number followed by a large number or the reverse. Infants were then tested with pairs of numerical stimuli where the ordinal relationship between the two stimuli was the same as in habituation, was reversed, or was eliminated by equating the numerical value of the first and second stimulus. Ten to 12-month old infants looked longer when tested with the novel pairs that contained two equal numerical values but failed to discriminate the reversal in ordinal direction. In contrast, 14-16 month-old-infants dishabituated to both a change in ordinal direction and the elimination of ordinal relations. These results suggest an intriguing developmental trend in ordinal numerical knowledge. Infants under 12 months of age only differentiated equal and unequal numerical relations and failed to distinguish greater than from less than relations whereas by 14 months of age infants displayed ordinal numerical knowledge.

One relevant type of data comes from research showing that infants keep track of the number of objects behind an occluder (e.g., Koechlin, et al., 1998; McCrink & Wynn, 2004; Simon, Hespos, & Rochat, 1995; Wynn, 1992, 1995, 1998). In these studies was demonstrated that 5-month-old infants are able to operate simple arithmetical computation (i.e., addition and subtraction) and can represent ordinal numerical relations. As reviewed before, for example Wynn (1992) demonstrated that 5 month-olds are able to perform numerical computations with small numerosities (e.g., 1 +1 or 2-1). More recently McCrink and Wynn (2004), using a procedure similar to Wynn (1992), extended the previous results to large numerosities. In this study, 9-month-old infants were given correct and incorrect outcomes to a mathematical operation on large numerosities (5 + 5 or 10 - 5). Infants who saw the addition operation looked longer to an outcome of 5 than to an outcome of 10, and infants who saw the subtraction operation looked longer to an outcome of 10 than to an outcome of 5. All these data suggest that infants are capable of addition and subtraction and, consequently, that they can represent ordinal numerical relations (but see Cohen & Marks, 2002, and Wakeley, Rivera & Langer, 2000)

Using a different paradigm, Feigenson, Carey and Hauser (2002) investigated more directly the ordinal numerical knowledge in infancy. In this study, 10- and 12-month-old infants spontaneously choose the numerically larger of two sets of food items when amount of food was confounded with number but failed to do so when amount of food was equivalent. A new choice task, named the *crackers choice task*, was used to explore infants' spontaneous representations of more and less.

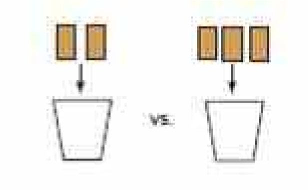

Figure 15: Cracker choice task [source: Feigenson, Dehaene, & Spelke, 2004]

Ten- and 12-month-old infants saw crackers placed sequentially into two containers, and then they were allowed to crawl and obtain the crackers from the container they chose. In addition, even when amount of food could have been used as a cue, infants succeeded at 1 versus 2 and 2 versus 3 and failed at 2 versus 4, 3 versus 4 and 3 versus 6 suggesting that the numerical ratio was not what controlled performance but instead that infants were limited by the numerical size of the values being compared. It is important to note that these numerical sets were constructed sequentially and the infants were required to remember the number of food items they observed being placed in a container. Infants' performance was strongly affected by the total number of elements, performing successful choice only with small number of crackers. From the data, Feigenson et al, claimed that infants use a non-numerical mechanism related to a object-file system, based on continuous features of the object (e.g., area) to represent each food item and that information about surface area is preserved and used in the comparison process.

Another recent study (Brannon, 2002) has provided evidence that the capacity for non-numerical ordinal judgments may develop before the capacity for ordinal numerical judgments. Eleven- and 9-month-old infants were habituated to three-item sequences of numerical or continuous magnitudes presented in ascending or descending order. Each trial consisted of a repeating five-frame cycle that began with a black screen followed by a brief white screen and then three consecutively presented numerical displays (Figure 9). The black and white screens were used to mark the beginning of each presentation of the sequence. Following habituation, infants were tested with new numerical or continuous values where the ordinal relations were maintained or were reversed from the habituation. Therefore, in this study infants were required to recognize the direction of the ordinal sequence.

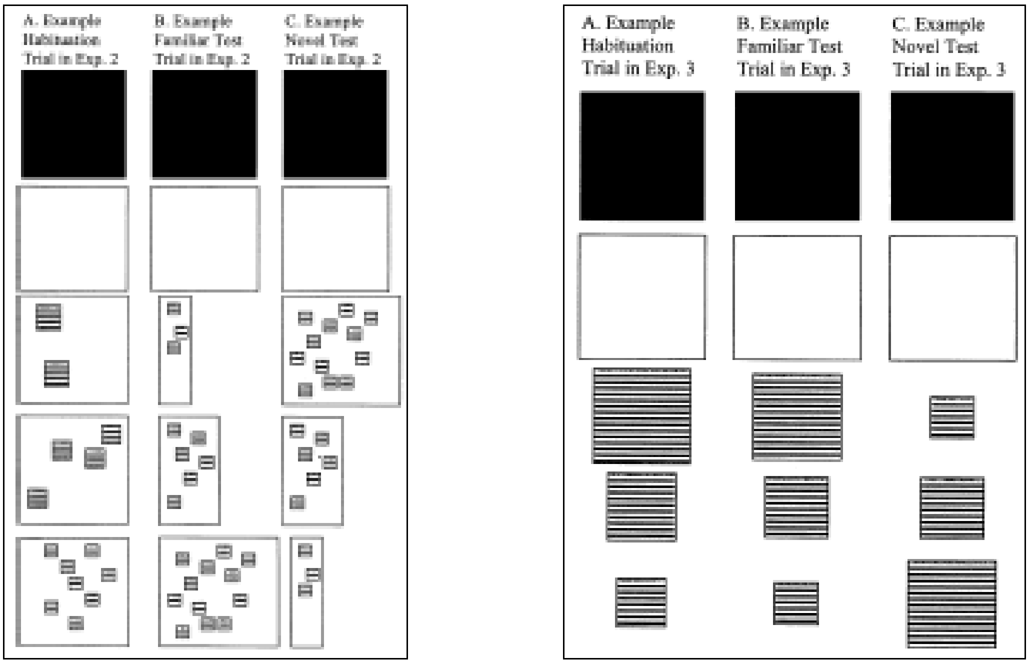

Figure 16: Sample of frames used in Habituation, familiar test and novel test trial in Brannon (2002) study, left panel: numerical ordinal sequence: right panel: continuous ordinal sequence.

Brannon hypothesized that if infants looked longer at the ordinal reversed direction compared to the ordinal maintained direction, then they are able to represent ordinal relations. Eleven-month-olds succeeded in both continuous and numerical tasks, while 9-month-olds failed at performing with numerical magnitudes. From the data it was highlighted a developmental trend suggesting that at 9 months of life infants are already able to detect the ordinal relationships between continuous magnitude and only from 11 months of life they show the sensitivity to ordinal relationships between numerical magnitudes. These data might be interpreted as a demonstration of the existence of two different magnitude representational processes: one lately specific for detecting ordinality between discrete magnitudes (i.e., numbers) and an early one for detecting ordinality between continuous magnitudes. Alternatively it could be proposed that the specific characteristics of the procedure used in this study implied too high cognitive requirements for 9-month-old infants.

4. Small vs. large numerosities discrimination: A comparison

Some studies have investigated numerosity discrimination in infants, comparing their performance on both small and large numbers under condition on which continuous variables were controlled (e.g., Feigenson, Carey & Hauser, 2002; Xu, Spelke & Goddard, 2005; Wood & Spelke, 2005). For example, Wood and Spelke (2005) have investigated the 6-month-olds' abilities to discriminate small and large numbers of events, holding constant the ratio between them. This study used a variant of the method of Wynn (1996) to test whether 6- and 9-month-old infants discriminate sequences of 4 vs. 8, 2 vs. 4 and 4 vs. 6 jumps. During habituation phase, babies saw a puppet that jumped a constant number of time (e.g., 4 jumps), but every time extent and duration of the sequence of jumps varied. Therefore, infants were habituated to different jump sequences in which the only invariant variable was the number of jumps. During test phase, two new sequences were presented to the babies, one with the familiar number of jumps (e.g., 4) and the other with a new number of jumps (e.g., 8). With this procedure, the Authors held controlled continuous variables as tempo, rhythm or duration more strictly than Wynn (1996) study. Results show that at 6 months of age infants succeed at discriminating only large number of events with a ratio of 1:2 (i.e., 4 vs. 8) and at 9 months large number with a ratio of 2:3 (e.g., 4 vs. 6). This data are consistent with earlier studies that demonstrated that numerical discrimination improves in precision in the first months of life (e.g., Lipton & Spelke, 2003, 2004, Xu & Spelke, 2000). Moreover, it resulted that at 6 months babies are not able to discriminate small numbers of events (i.e., 2 vs. 4) when continuous variables are controlled.

Results such as these have led to the hypothesis that 6-month-olds rely on two different representational systems: one implied in the processing of small numerosities on the basis of continuous variables (i.e., object-file system) and represents up to 3 elements, and one implied in the processing of large numerosities on the basis of number and is ratio dependent (i.e., analog magnitude system) (e.g., Xu, 2003; Carey, 1998; Feigenson, Spelke, and Dehaene, 2005; Simon, 1997; Uller at al., 1999).

5 Conclusions

The studies on infants' numerical abilities suggest that very early in the development the human cognitive system can represents both cardinal and ordinal numerical information, performing in numerical tasks. Infants' enumeration of small numerosities is affected by the total number of elements (i.e., up till 4 items) and by continuous variables, as total filled area or contour length (e.g., Clearfield & Mix, 2001; Feigenson & Carey, 2005; Starkey, Spelke & Gelamn, 1983). Enumeration of large numerosities is ratio-dependent, thus is that infants can discriminate between large numbers of items solely with a large ratio between them (Lipton & Spelke, 2003; Xu & Spelke, 2000; Xu & Arriga, 2007). Moreover, the representations of large numerosities increase in its precision during the first year of life (Lipton & Spelke, 2003; Xu & Spelke, 2000; Xu & Arriga, 2007). The general picture that results from these data seems to partly fit with the existence in adults of two distinct numerical systems: An analog magnitude system for approximate large numerosities and a tracking system for precise small numerosities (e.g., Dehaene, *et al.,* 1998; Gallistel & Gelman, 1992).

Moreover, some studies have directly addressed the development of ordinal numerical knowledge in the first months of life (e.g., Brannon, 2002; Cooper, 1984; Feigenson, Carey, & Hauser, 2002; McCrink & Wynn, 2004; Wynn, 1992, 1998). The findings from these studies suggest that at least from 9 months of age infants are able to detect and elaborate spatial ordinal information (i.e., area), and only from 11 months they show the sensitivity to ordinal relationships between numerical magnitudes (Brannon, 2002).

Although the data reviewed suggest that infants in some way represent numerosity, the nature of these numerical representations remain largely unspecified and different hypothesis have been proposed to address how these language-independent abilities arise and develop in the first months of life.

In the next chapter these different hypothesis will be discussed.

Chapter 3

Models of non-verbal number representation in infancy

The data reviewed in the second chapter seem suggest that young infants discriminate both small (e.g., Starkey, Spelke & Gelamn, 1983; Wynn, 1992) and large (e.g., Xu & Spelke, 2000; Lipton & Spelke, 2003) numerosities of elements. Moreover, they discriminate small numbers of items, regardless if they are visual objects (e.g., Antell & Keating, 1983), events (e.g., Wynn, 1992) or auditory-visual stimuli (e.g., Starkey, Spelke & Gelman, 1983). Young infants succeed not only in representing cardinal values of set of elements, but they seem to be able also to understand ordinal relationships between magnitudes (Brannon, 2002). Although, these results suggest that infants are able to operate at a striking abstract level, the source and the development of these numerical representations remain unclear. As it was proposed for adult's representation of numerosity (see Chapter 1), even for infants two dominant models or hypothesis to explore how infants can represent numbers were suggested: Analog magnitude models (e.g., Gallistel & Gelman, 1991; Dehaene & Changeux, 1993), and object-file models (e.g., Carey, 1998; Hauser & Carey, 1998; Leslie, Xu, Tremoulet, & Scholl, 1998; Simon, 1997; Uller, Carey, Huntley-Fenner, & Klatt, 1999). The major difference between the object-file models and the analog magnitude models is that the object-file models predict that discrimination is limited by absolute set size, whereas the analog magnitude models predict that discrimination is modulated by the numerical ratio of the values compared. In this chapter, both of these models will be described.

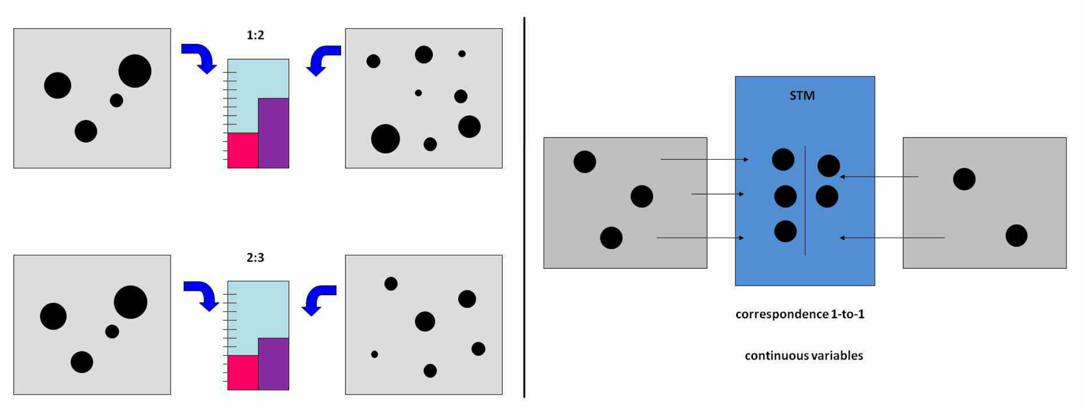

Figure 17: diagram of numerosities processing hypothesized by Object-file and Analog magnitude systems

1 Object-file models

As reviewed in Chapter 2, some data from habituation and violation of expectancy looking time paradigms have demonstrated that infants distinguish small sets on the basis of number of individual in them (e.g., Antell & Keating, 1983; Wynn, 1992; Feigenson & Carey, 2005). Many researchers (e.g., Scholl & Leslie, 1999; Simon, 1997; Uller, et al., 1999) have suggested that a representational system, very different from analog magnitude one, might support infants' number sensitivity in these experiments. On this view, numerical abilities showed in the first months and years of life are led by some general non-numerical abilities and they rise from a general and automatic attentional system of object tracking, through which very early the cognitive system can individuate single objects in the visual field, on the basis of their spatio-temporal properties (Uller et al. 1999).

Object-file models come from the adults' literature on object-based attention (e.g., Trick and Pylyshyn's FINST Theory, 1994; for a review see Chapter 1). In object-tracking system, number is only implicitly encoded: Symbols are not present for number at all, because the representations include a symbol for each individual in an attended set. A reference token is assigned to each distinct feature cluster in a scene. These reference tokens are limited in number (up to four in general) and are assigned in parallel. Tokens are used to code the object's location as long as it remains visible.

Object-file models, assume that infants and young children use these tokens to respond to quantitative tasks. For example, the ability to discriminate one from two from three entities does not entail that infants understand anything about the numerical relations between one and two and three, such as that two is less than three, or that three is exactly one more than two. Infant success in number tasks can be explained assuming that they each object of an array is encoded in terms of a separate object-file (e.g., Kahneman & Treisman, 1984). Thus, a set containing one apple might be represented as "#" and two apples might be represented as "# #", and so forth. When infants are required to compare two visual sets (e.g., 2 vs. 3), the Object-file models assume that a representation of *n* object files (e.g., # #) is constructed and stored in short-term memory, and here is compared with representation of the other n object files (# # #) by a process that detects one-to-one correspondence between object-files in the two representations.

Therefore, Object-file models require specific memory demands, since memory loads for lists of object files vary dramatically with list length. The data from addition/subtraction studies support this properties of Object-file models, because they show a dramatic effects of list length. Compare 1+1=2 or 1 with 2-1=1 or 2. The list length of the test event is larger in the addition version (i.e., 2) of the task than in the subtraction version of the task (i.e., 1). That is, in the addition version the infant must hold a longer list in memory, and must evaluate one-to-one correspondences between larger sets during the outcome phase of the study. The Object-file model predicts, therefore, that addition will be more difficult than subtraction, and indeed infants succeed on subtraction tasks more robustly than on addition tasks (Wynn, 1992). An even more dramatic effect of list length is seen in the apparent upper limit on infant number representations. Object-file accounts predict such a limit, since there is a limit on parallel individuation, the number of distinct objects that can be simultaneously tracked in a visual model of an array (Trick & Pylyshyn, 1994). Thus, Object-file models predict that infants should only be able to represent small sets of objects. It then follows that infants should succeed at discriminating 2 versus 3 but fail at discriminating 4 versus 6 (e.g., Starkey and Cooper, 1980) since there are only 3 or 4 object files in the visual system that can be used at any one time.

Simon (1997, 1999) suggests one of the most straightforward examples of Object-models. Simon (1999) proposes an account whereby the observed reactions of infants in numerical tasks can be generated from a set of domain-general competencies. He suggests that numerically relevant competencies demonstrated by infants lie predominately in their object representation and individuation abilities, which also appear to depend on the brain's visuo-spatial processing regions. Specifically, Simon's hypothesis is that the foundations of numerical processing emerge primarily from some general characteristics of the human perception and attention system, that is, in brain regions primarily adapted for visuo-spatial processing. The Author has defined three visuo-spatial abilities that might account for infants' performance in numerical tasks:

1) to individuate and to represent objects as discrete entities,

2) to form categorical representations of spatial relations,

3) to detect ordered sequences.

Some recent studies support Simon's model showing that even newborns are able to perceive and represent the objects present in an array and their spatial relationship. For example, 3-day-olds were able to recognize the identity of partly occluded objects (Valenza, et al., 2006) or to perceive kinetic illusory contours (Valenza & Bulf, 2007). Both of these abilities imply to perceive correctly the relationship among the elements present in the display. For example in order to perceive an illusory figure such as a Kanizsa triangle, infants must perceive the illusory figure must as forwards the inducers and closer to the observe, whereas the inducer elements must be perceived as completed circles located behind the illusory figure.

In line with these evidences, it is strongly arguable that, newborns might posses some visuo-spatial abilities endowed by the Object-file system.

This possibility will be tested in the next chapter.

2 Analog magnitude models

Object-file models cannot explain how infants discriminate 8 vs. 16 elements (Xu & Spelke, 2000), nor they can explain infants' ability to discriminate the numerosity of events or sounds, which should not open object files (e.g., Bijeljac-Babic, et al., 1993; Wynn, 1996).

To explain these abilities some Authors have assumed the existence of an inborn and biologically determined predisposition to elaborate the numerical information (e.g., Wynn, 1992, 1995; Spelke & Dehaene, 1999). These models posit that numerosities are represented as a single continuous magnitude that is proportional to the number value that it represents (Deahene, 1992; Gallistel & Gelman, 1992; Wynn, 1998). Two main numerical models have been proposed, both assuming an analog representation of quantity: The accumulator model (e.g., Meck & Church, 1984; Gelman & Gallistel, 1992; Xu & Spelke, 2000), and the neural model (Dehaene and Changeux, 1993).

2.1 <u>Accumulator model</u>

The accumulator model was initially proposed by Meck and Church (1983) to account for animals' numerical competencies, and successively Gallistel and Gelman (1992) adapted it to pre-verabl human infants' numerical performances. Specifically, this model posits a general-purpose mechanism that allows quantification of both duration and number (e.g., Meck & Church, 1984; Meck & Church, 1983). This model rose from data showing that rats were able to discriminate between two stimulus sets based both on the number of elements and on the duration of the sequence of elements (Meck & Church, 1983; Gallistel, 1990). In a training regime in which stimulus duration and stimulus numerosity co-varied, the rats learned the relation between both variables and the correct response. When sequence duration could not be used to predict the correct response, they chose on the basis of the number of cycles in the sequence, and *vice versa*. Moreover, the results showed that the rat's representation of the numerosity of the cycles in the sequence and its representation of the duration of the sequence are indistinguishable from a psychophysical standpoint. Meck and Church (1983) explain this result assuming that numerosity is represented by the same mental magnitudes that represent temporal durations. Their Accumulator

Model further assumes that the mental magnitudes representing numerosity have the same scalar variance property as the mental magnitudes representing duration. The standard deviation of the population of magnitudes that represents a given numerosity (or a given duration) increases in proportion to the mean of the population.

Meck and Church (1983) proposed that the Accumulator Model supposes a preverbal counting mechanism that works as follows: Nervous system is endowed with an accumulator mechanism that produces pulses at a constant rate. These pulses can be passed into an accumulator by the closing of a switch. For each entity that is to be counted, the switch closes for a fixed brief interval, passing the pulses into the accumulator during that interval thus the accumulator fills up in equal increments, one increment for each entity counted (Figure 2). The final fullness level of the accumulator represents the number of items counted. The entire mechanism contains several accumulators and switches to allow the counting of different sets of entities simultaneously.

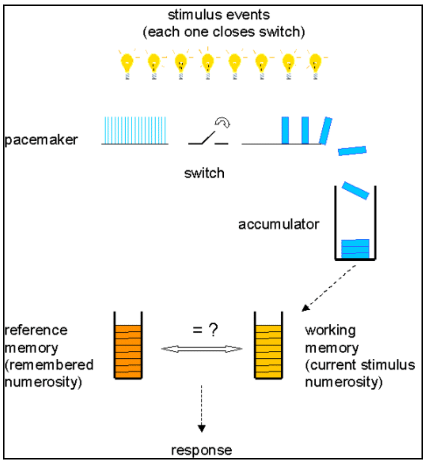

Figure 18: Functioning of accumulator mechanism proposed by Meck and Church (1983). [Source: Emmerton, 2001].

The switch can operate in one of three different modes depending on the nature of the stimulus. When the mechanism is used to generate magnitudes that represent the duration of an interval (i.e., timing mode), the switch can close at the beginning of the interval of a sequence of events and opens at the end of the sequence, so that the magnitude in the accumulator is proportionate to the cumulative duration of the interval (Run mode). Alternatively the Accumulator Model can close at the end of every event yielding the timing of the cumulative duration of individual events (Stop mode). This timing mechanism becomes a counting mechanism (Event mode) when the gate closes for a short fixed interval once for each stimulus in the sequence being counted, so that the magnitude in the accumulator at the end of the sequence is proportionate to the number of elements in the sequence. (Meck & Church, 1983).

The total accumulated energy forms an analog representation of magnitude (i.e., time or number). This representation is stored in the short term memory system, store in which it is compared with the previous accumulated magnitude through a 1-to-1 comparison process. As the accumulator is a physical mechanism and random variability is inherent to any physical process, the storing process of the magnitudes in the memory is not precise, ensuing that these magnitudes in memory are noisy (Figure 2) (Gelman & Gallistel, 2000). Consequently, the magnitudes' representation exhibits a scalar variability, which is the precision of the representation is inversely proportional to the numerosity considered, obeying Weber's law. Specifically, it is posited that the mean value and the variability of the mental magnitude distribution for numerosity are proportional to the numerosity (Cordes, Gelman, Gallistel & Whalen, 2001). In other words, larger is the numerosity more will be the mental distribution variability and so less the discriminability.

This variability can account for numerical ratio effect and the resultant numerical distance and size effects demonstrated in human and animal studies (for a review see Chapter 1). Moreover, the assumption that the preverbal representatives of numerosity are magnitudes with a scalar variability offers one explanation of the results from numerical discrimination experiments in human infants. As reviewed in Chapter 2, infants seem to be able to represent numerosity in some way, thus is that it has been found that infants do discriminate large numerosities, provided that their ratio is large (e.g. 8 versus 16) (e.g., Xu & Spelke, 2000) This finding is consistent with the hypothesis that the failures of numerical discrimination found in infants are rooted in the noisiness of their non-verbal representation of numerosity rather than in an ontogenetic discontinuity in the mode of numerical representation (Gallistel & Gelamn, 2000).

2.2 Dehaene and Changeux model: D&C neural network

A second magnitude model is the Dehaene and Changeux neural network model (1993). From the findings that animal and human infants are sensitive to numerical regularities in their environments, can represent these regularities internally, and can perform elementary and approximate computations with numerical quantities (e.g., Gallistel, 1990; Starkey & Cooper, 1980), the Authors suggest the existence of specialized neural systems for processing numbers on a non-linguisitcs basis (Dehaene & Changeux, 1993). They proposed a simple model of the implementation of elementary numerical abilities in a formal neuronal network. Starting from behavioral and anatomical data, the Authors have tried to delineate elementary principles of neural architecture that give rise a defined function. They have implemented these principles into a minimal formal model that provides a highly simplified view of the relevant biological mechanism (Changeux & Dehaene, 1988). This model posits that there are numerosity detectors that can represent the abstract number of the objects independently of the size and configuration of the stimuli. Moreover, the Authors have posited that the numerosity detection system corresponds to the initial state of human and animal numerical cognition. Specifically, they have described two major stages in the acquisition of elementary numerical abilities: An initial stage in which only numerosity detection abilities are present, and a second stage, supposedly appearing at the end of the first year of life, in which babies become able to compare two numerosities and to understand ordinality.

The first fundamental component of the D&C model is the *numerical detection system*, comprising there three layers; an input "*retina*" on which objects of various sizes and locations can be presented, an intermediate topographical *map of object locations* in which each object, regardless of its size, is represented by a fixed pool of neurons, and a map of *numerosity detectors* that sums all outputs from the location map. In this way, the numerosity detectors provide a quantity highly correlated with numerosity and sufficient to approximate it. In addition, numerosity detectors also receive and combine inputs from an *echoic auditory memory*. As a result, the numerosity detector for a specified numerosity (e.g., 2) will react identically to 2 visual objects, to 2 auditory objects, or to the simultaneous occurrence of one object in booth modalities. Therefore, together these three layers achieve a representation of number irrespective of object size and of modalities. The resulting representations are functionally equivalent to that of the accumulator model because they are magnitudes that are proportional to the numbers they represent.

To account for the subsequent stage of human development in which same-different and larger-smaller comparison rises, the model is endowed with a *short-term memory module* for past numerosity and a *point-to-point matching module* for comparing the past and present numerosities. The memory module permits the temporary maintenance of an active representation of the previous numerosity while a new one is being processed. A *point-to-point matching* module monitors the points' similarity between the past and present representations.

Since human infants do not have to be trained to acquire concepts of "more" and "less", but instead this ability rises spontaneously during the development, the Changeux and Dehaene (1988) have provided the D&C model of a reward internally generated by an internal autoevaluation loop. The network endowed with self-organization capacity "plays" with a set of objects by randomly choosing one of two possible actions: Adding one object or deleting one object. The yielded modification of numerosity is noted by the numerosities detection system. On the basis of the memorized and present numerosities, the system attempts to reconstruct the selected action (e.g., adding or deleting). An internal action-matching module evaluates the similarity of the reconstructed and the present actions, and sends a positive or negative internal reward signal accordingly. In due course the system discovers that an increase in numerosity implies addition, and that a decrease implies subtraction.

Although, the D&C model is restricted only to the earliest stages of numerical development, it can demonstrate the feasibility of extracting approximate numerosity in parallel from a visual display, without serial counting.

The D&C model illustrates how one may account for animals' and human infants' numerical abilities without assuming that they can account (Gallistel & Gelamn, 1992).

2.3 Accumulator model and D&C neural network: A comparison

The main difference between the accumulator and D&C models is that the accumulator model involves an iterative process that is functionally equivalent to counting (Meck and Church, 1983; Gallistel and Gelman, 1992) whereas the D&C model is not iterative. Thus, the accumulator model predicts that infants would serially enumerate whereas the D&C model predicts that infants would perceive number in parallel (i.e., all at once). A second unique aspect of the D&C model is that it posits that the initial state consists solely of numerosity detectors and that the system learns the relationship between quantities and motor outputs (e.g., Arabic numerals etc.) from external reward input or from an autoevaluation loop. The D&C model predicts that the ability to make ordinal numerical judgments arises after the ability to make cardinal discriminations. Furthermore, a specific prediction is made by the D&C model that ordinal judgments come on line with the maturation of the frontal lobes at about 10 months of age.

2.4 A theory of magnitude (ATOM)

Recently, it has been proposed a new theory (A Theory Of Magnitude; ATOM) that expands the analog magnitude representations' application to space information (Walsh, 2003).

From behavioral (e.g., Dehaene, Dehaene-lambertz & Cohen, 1998), neuropsychological (e.g., Mohl & Pfurtscheller, 1991) and brain imaging (e.g., Harrington & Haaland, 1999) evidence, Vincent Walsh posits a common processing mechanism for the representations of all quantities: time, space and quantity (2003).

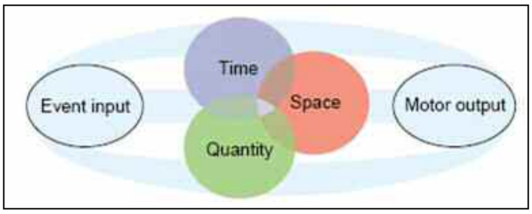

Figure 19: Schema for processing time, space and quantity. The three magnitudes could be analyzed in a generalizes magnitude system as suggest by ATOM [source: Walsh (2003)].

This theory is distinguished by four aspects. First of all this representational mechanism applies to those dimensions that can be experienced as “more than” and “less than”, involving ordinal processing of magnitudes. Second, this representational mechanism obeys Weber’s Law, following the analog magnitude representations’ nature (i.e., ratio effects). Third, it is proposed that this single magnitude system is operating from birth. In fine, the apparent specializations for time, space and quantity develop from this generalized magnitude system. It is important to note that these latter claims are not focused on the idea that a single mechanism must be used to form different types of magnitude representations but instead focus on the idea that the resulting representations have a common format and perhaps also a common neural substrate (Cordes & Gelman, 2005; Gallistel & Gelman, 2000; Walsh, 2003).

Evidence supporting Walsh’s theory can be found in some recent studies in which it has been demonstrated that 6-month-olds’ discriminate not only discrete quantity (for a review see Chapter 2) but also continuous quantities, as space (e.g., Brannon, Lutz & Cordes, 2006; Clearfiled & Mix, 2001; Feigenson, Carey & Spelke,

2002) and time (Brannon, Suanda & Libertus, in press ; Clearfield, 2004; vanMarle & Wynn, 2006).

About space discrimination, Brannon at al. (2006) habituated 6-month-old infants to stimuli with a single small or large Elmo face and then tested with a single and a small Elmo face. The ratio of the area of the small and large faces varied by a 1:4, 1:3, 1:2 or 2:3 ratio, and each infant was tested with only one ratio change.

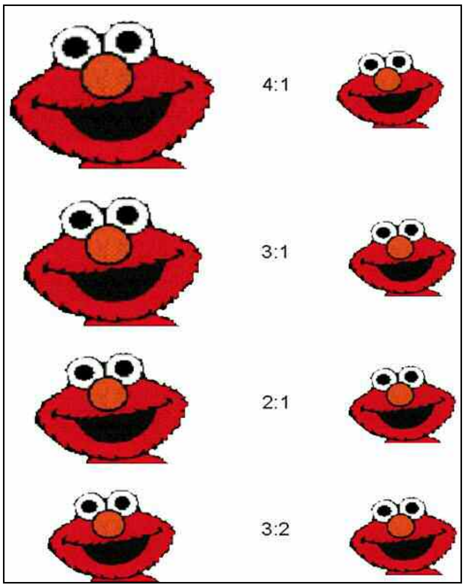

Figure 20: Schematic representation of the ratios of the stimuli used in Brannon, et al.(2006) [source: Brannon et al. (2006)].

The main finding was that at 6 months of age infants are unable to detect a 2:3 ratio change in the size of a single element and required a 1:2 ratio change to show a novelty preference. A second important finding was that the magnitude of the looking time difference between the familiar and the novel area test was modulated by the degree to which the areas differed.

In the case of time, vanMarle and Wynn (2006), using a visual habituation procedure, have studied temporal discrimination in 6-month-old infants. In their study infants were habituated to a puppet of “Sylvester the Cat” that danced and emitted a tone for a given duration and where then tested with the same puppet dancing and sounding for the habituated duration or a novel duration. They found that 6-month-olds successfully discriminate events based on their duration and discriminate durations with a 1:2 ratio but not those with a 2:3 ratio. Moreover, infants’ temporal discrimination follows a Weber’s law function in that it was proportionate, not absolute, difference between values that determined discriminability. Moreover, Brannon, Suanda and Libertus (in press) have recently extended these findings investigating the increasing precision in temporal discriminations between 6 and 10 months of age. In their study, at 6 months infants require a 1:2 ratio in duration for successful discrimination, however by 10 months of age infants are able of discriminating intervals that differ by a 2:3 ratio.

Figure 21: Still images from the videos used in Brannon, Suanda & Libertus (in press) study on temporal discrimination.

From these data together with the ones reviewed in Chapter 2, it seems that the same ratio change is needed at 6 months of age for number, time and area discriminations. It appears that temporal and area discrimination follows a similar developmental trajectory to that of number. The common trajectory may reflect a common currency for those magnitudes, as suggested by ATOM model.

To sum up, analog magnitude models were recently theoretically criticized by ATOM, which posits that numerical knowledge arise from ordinal knowledge in a general magnitude representational system (Walsh, 2003). Moreover, this hypothesis has been confirmed by numerous evidence which has confirmed that even 6-month-olds are able to represent discrete quantity as well as continuous quantities, like space and time, obeying Weber's Law (e.g., Brannon, Lutz, & Cordes, 2006; Clearfield, 2004; Xu, Spelke & Goddard, 2005). These converging lines of evidence strengthen the ATOM model's proposal of a representational system that, from birth, operates on different kinds of magnitudes (i.e., space, time and quantity), and based on ordinal processing of these magnitudes.

In accordance with the previous findings, in the next chapters it will be hypothesized that ordinal processing might be present earlier than 6 months of life and that the priority of continuous ordinal elaboration, might be found already in the first months of life.

3 Core knowledge thesis

Recently, the analog magnitude and the Object-file models have been combined in a unique theory by the Core knowledge thesis (e.g.,Spelke, 2003; Spelke & Kinzler, 2007). The Core knowledge thesis tried to answer to the general question how humans develop and deploy complex, species-specific, and culture-specific cognitive skills. This theoretical approach rests on six assumptions (Spelke, 2000; Hauser & Spelke, 2004; Kinzler & Spelke, 2007):

1. Knowledge arises early;
2. Initial knowledge is domain-specific (each system functions to represent particular kinds of entities);

3. Initial knowledge implies a set of signature limits on the elements within a knowledge domain;
4. Initial knowledge is innate;
5. Initial knowledge is the core of adults' knowledge;
6. Initial knowledge is task specific (each system uses only a subset of the information delivered by an input system and sends information only to a subset of the output system).

It has been posited that humans are endowed with a small number of innate separable systems of core knowledge, which form the building blocks for uniquely human skills. New, flexible, skills and belief systems build on these core foundations. Each system centers on a set of principles that serves to individuate the entities in its domain and to support inferences about the entities' behavior. Each system, moreover, is characterized by a set of signature limits that allow investigators to identify the system across tasks, ages, species, and human cultures (Kinzler & Spelke, 2007). Studies on human infants and non-human animals provide evidence for five core knowledge systems (Spelke, 2004; Kinzler & Spelke, 2007): core system of object representation, agents and their actions, number, space (i.e., geometry of the environment), and social partners (Kinzler & Spelke, 2007).

The Core knowledge thesis posits that the earlier numerical abilities imply two different systems of knowledge: the number system and the object representation system. These two systems correspond respectively to the models of a system of analog magnitude representations of number and a system of parallel individuation of small sets of elements. Indeed, many studies indicate that infants possess a system for quantification, which yields a noisy representation of approximate number. This system (i.e. the number system) captures the inter-relations between different numerosities, and it is robust across modalities and across variations in continuous properties. The number system is implied in the representations of cardinal values of large sets of individual along a mental number line.

Infants and adults have a second system for precisely keeping track of small numbers of individual objects and for representing information about their continuous quantitative properties that differs dramatically from that observed with large numerosities. The core system of object representation is an inborn system of objects' representation and it centers on the spatio-temporal principles of cohesion, continuity and contact. In this system number is implicitly represented by a correspondence 1-to-1 in visual short-term memory system. Infants are able to represent only a small number of objects at time about 3.

4 Conclusions

Several studies have demonstrated that from 6 months of life infants are able to discriminate both small numerosities, on the basis of continuous variables, and large numerosities, on the basis of the ratio between the numerosities. Risen from these data two different models are suggested: object-file models and analog magnitude models. Nevertheless the severe differences between these models, both these classes of hypothesis posit the existence of innate numerical abilities. However to my knowledge, no one study has been carried out for investigating the abilities showed before 6 months of age (but see Antell & Keating, 1983).

The researches that will be described in the next chapters start from this lack and try to investigate whether some abilities implied by both of these theoretical models are present in the first days and months of life. More specifically, in the next chapters, I will describe three different studies focused on investigating the presence at birth of the visuo-spatial abilities required by Object-file system (Chapter 4 and 5) and the nature and the developmental trend of ordinal processing of continuous magnitudes in the first 3 months of life (Chapter 6).

Chapter 4

Visuo-spatial abilities at birth: Newborns' categorical representations of spatial relationships.

As it is extensively described in the previous chapter, Object-file models posit that numerical abilities lay predominately in object representation which are dependent from visuo-spatial processing (e.g., Uller, et al., 1999). Three visuo-spatial abilities are hypnotized to account infants' performance in numerical tasks (Simon, 1997): 1) to individuate and to represent objects as discrete entities, 2) to form categorical representations of spatial relations, 3) to detect ordered sequences. In this chapter the presence of newborn's ability to categorize spatial information will be tested.

1 Perceptual categorization in infancy

Perceptual categorization refers to "the process by which organism recognize discriminably different objects as members of the same category based on some internalized representation of the category" (Edelman, 1987). A large amount of evidence suggests that infants as young as 3 to 4 months of age group distinct but related objects into meaningful classes, responding equivalently to novel instances of a perceptual category (e.g., Bomba & Siqueland, 1983; Quinn, & Eimas, 1996a, 1996b; Quinn, Slater, Brown, & Hayes, 2001). In a seminal study Bomba and Siqueland (1983) demonstrated that, following exposure to six exemplars within each of three geometrical form categories (i.e., triangles, diamonds, and squares), 3-and-4-month-old infants manifested a novelty preference for an exemplar from a novel category rather than for a novel exemplar from the familiar category. Subsequent studies confirmed and extended this finding, demonstrating that young infants are able to perceptually categorize a large range of complex visual stimuli (e.g., animals, furniture) on the basis of their resemblance to a common perceptual property (e.g., Behl-Cadha & Eimas, 1995; Behl-Cadha, 1996; Madole & Oakes, 1999; Mareschal & Quinn, 2001; Quinn & Bhatt, 2006; Quinn, 1994, 2002; Quinn, Eimas, & Rosenkranz, 1993; Quinn, Schyns & Goldstone, 2006; Quinn, Westerlund & Nelson, 2006; Younger & Fearing, 1999; for reviews, see Quinn, 2003).

1.1 Spatial perceptual categorization in infancy

Perceptual categorization is not just for objects but refers also to the ability to organize the physical space into categories defined by spatial relationships that is by objects positional arrangement (Bornstein, 1984; Edelman, 1987; Quinn & Eimas, 1996a). Literature converges to suggest that even young infants experience objects in an organized spatial arrangement rather than as spatially disconnected entities located in unrelated positions (e.g., Quinn, 1994, 2003, 2004). However, categorical representation of spatial relationships seems to emerge at different points during development for different spatial relationships. Specifically, at 6 months of age, infants show the ability to encode the location of a target in relation to multiple landmarks that define a local spatial framework (i.e., a dot between two referent bars), whereas 3-to-4-month-old infants are able to encode the location of a target relative to only a single landmark (i.e., a dot above/below or left/right a referent bar) (Quinn, Cummins, Kase, Martin & Weissman, 1996; Quinn, 1994, 2004; Quinn, Adams, Kennedy, Shettler & Wasnik, 2003).

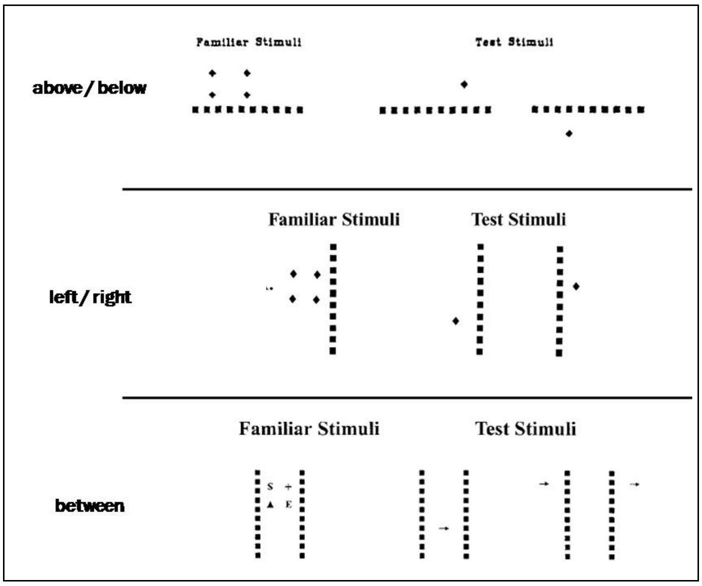

Figure 22: Stimuli used in Quinn and colleagues studies on categorical representations in infancy [source from the top to the bottom: Quinn, Cummins, Kase, Martin & Weissman, 1996; Quinn 2004; ;Quinn, Adams, Kennedy, Shettler & Wasnik, 2003]

Moreover, in infants younger than 6 months the categorical representations of spatial relationships are limited to the objects depicting the relations, and only later the equivalence of the spatial relationships is maintained regardless of the objects used. Therefore, even if categorical representation for small-scale spatial relationships (e.g., above, below) appears very early in development, it does not take on an abstract form until 6 months of life (Quinn et al., 1996; Quinn et al., 2003; Quinn, 1994, 2004).

1.2 *Spatial categorization at birth*

The present study was aimed at investigating the origins of the ability to represent objects' position in an array, testing whether even newborns are able to discriminate and categorize a spatial relationship that is defined by the positional relationships of two objects. The hypothesis that an earlier form of spatial categorization is present from birth is supported by evidence revealing newborns' ability to group object–based stimuli into perceptual categories. From birth infants detect and recognize perceptual invariance between distinguishable appearances of the same stimulus (e.g., Caron, Caron, & Carlson, 1979; Granrud, 1987; Slater & Morison, 1985; Slater, Mattock & Brown, 1990; Slater, Mattock, Brown, & Bremner, 1991). For example, Granrud study's (1987) findings indicate that newborn infants recognize an object as being the same size despite changes in its distance, which in turn causes changes in its retinal size and phenomenal appearance (i.e., size constancy). Some authors consider this phenomenon, termed *perceptual constancy*, as the earliest form of categorical competence, because newborns reduce different instances of a stimulus to a single category and treat them as equivalent (Bornstein, 1984; Cohen, 1991). More recently, however, it has been shown that categorical abilities at birth are not confined to perceptual constancy, because even 3-day-old infants are able to group visual stimuli into categories, on condition that such categories are relatively different and therefore perceptually dissimilar (e.g., closed vs. open geometric forms; Turati, Simion & Zanon, 2003).

Evidence exploring categorical competences of infants before 2 months of age in the domain of spatial relationships is very scarce. To the best of my knowledge only one study attempted to test whether the ability to extract invariant relational information is present at birth (Antell & Caron, 1985).

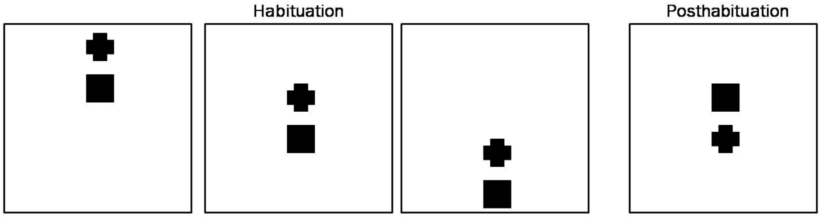

Figure 23: Stimuli used in the Antell & Caron (1985) study.

However, this study differs from previously cited evidence, given that a crucial methodological requirement was not adopted. Indeed, in order to establish whether infants are able to detect a spatial relationship between two objects, it is decisive to determine whether infants perceive the experimental stimuli as composed of two distinct elements or as a single holistic pattern. To this purpose, studies conducted on 3-to-4-month-old infants' categorization of spatial relationships usually used a bar that served as spatial reference (Quinn et al., 1996, 2003; Quinn, 1994, 2004). The benefit in using a central bar as spatial referent is confirmed by the data collected by Quinn (1994), which demonstrated that 3-month-old infants did not display a preference for the stimulus defined by a novel-category spatial relationship when the reference bar was omitted. One additional limitation of the Antell and Caron (1985) study is that the spatial relationships under investigation involved only two objects, which hold constant the all features (e.g., distance between the shapes) and varied only the absolute location of the entire array. As a consequence, the within-category variability is extremely low and does not allow concluding that newborns form an abstract representation of the spatial relationship, limiting the conclusions only to the newborns' ability to discriminate a novel arrangement of the elements.

2 Study 1

The purpose of the present study was to verify whether an earlier form of the capacity of representing the left/right spatial relationship, well demonstrated in 3-month-old infants (Quinn, 2004), is already present at birth. Newborns were presented with a square located at the left or the right of a vertical landmark (i.e., a bar). The landmark (i.e., the bar) differed from the target object (i.e., the square) not only for the dimension and the shape, but also because the square was dynamic whereas the landmark static. The use of a dynamic target stimulus might trigger attention toward the element that changes position enhancing newborns' ability to detect a spatial relationship. Indeed motion is an important source of information that promotes many perceptual abilities in the first postnatal life (Kellman & Arteberry, 1998) such as perception of illusory contours (e.g., Otsuka & Yamaguchi, 2003; Valenza & Bulf, 2007) or perception of object unity (e.g., Johnson & Aslin, 1995; Valenza, Leo, Gava, & Simion., 2006).

Five different experiments were carried out using the visual habituation or familiarization technique. Newborns' ability to discriminate the square's positions with respect to the referring bar (Experiment 1, 2, and 5) and to recognize a perceptual invariance between left/right spatial relationships in conditions of low (Experiment 3) and high-perceptual variability (Experiment 4) of the square's positions were tested.

Experiment 1

The goal of Experiment 1 was to investigate whether newborns are able to discriminate two configurations on the basis of the spatial positions of an object-target (i.e., a blinking square) with respect to a referring bar. More specifically, newborns' ability to discriminate the switching of a blinking square from one side to the other side of a central vertical bar was tested. Infants were habituated to a configuration in which a blinking square appeared to the upper (or lower) left (or right) side of the vertical bar. In the test phase, two stimuli were simultaneously presented, one in which the square was in the familiar position (e.g., up-left) and one in which the square was in the novel position with respect to the central bar (e.g., up-right). Newborns' ability to discriminate the new position of the square with respect to the bar would produce a novelty preference for the configuration in which the square occupies a novel position.

Method

Participants

Twenty-seven healthy, full-term newborn infants (mean age = 36.1 hr, *SD* = 16.4) were recruited at the maternity ward of the Paediatric Clinic of the University of Padova. All infants met the screening criteria of normal delivery, a mean birth weight of 3432 g (*SD* = 396), and a 5 min Apgar score above 7. Eight infants were not included in the final sample because of failure to maintain the desired state (3) or a strong position bias during the preference test phase, looking 80% of the time in one direction (4), or due to technical problems (1). Thus, the final sample consisted of 19 infants (8 females, 11 males), randomly assigned to four different habituation conditions: Up-right condition, down-right condition, up-left condition and down-left condition.

Infants were tested only if awake and in an alert state, after the parents gave their informed consent.

Stimuli

The stimuli were created using the software Paint Shop Pro 7.02. Each stimulus (see Figure 3) was composed by a central vertical white bar (1.4 cm wide x 9.2 cm high; about 3° x 18°) and a blinking white square (2.6 cm; about 5°), depicted on a black rectangular frame (11.3 cm high x 14 cm wide; about 22° x 27°). The white square turned on/off at a very fast rate (500 ms). The blinking square was positioned 1.5 cm (about 3°) on the left (or right) of the bar. The bar and the square were aligned on the upper (or lower) sides. In the habituation phase, the stimulus was arranged onto a grey frame (30 cm high x 16.7 cm wide; about 57° x 32°) in the central position. During the test phase, both the familiar and the novel stimulus, that was identical to the familiar one except for the position (left -right) of the square, were presented onto the grey frame with a distance between them of 8 cm (about 7°) (see Figure 3).

Between the habituation and the test phases, two red discs, one greater than the other (i.e., greater one's radius: 2 cm, about 4°; smaller one's radius: 1 cm, about 2°), were alternatively presented as central fixation point at a rate of 500 ms.

Apparatus

The infant sat on a student's lap, in front of a black panel, at a distance of about 30 cm. The student was naïve to the hypothesis being tested.

Infant's eyes were aligned with the central fixation point composed of the red blinking discs, located in the centre of a computer screen. The discs were used to attract the infant's gaze at the start of the test phases, subtended about 2° of a visual angle and, when turned on, blinked at a rate of 500 ms on and 500 ms off. To prevent interference from irrelevant distracters, two white panels placed on both sides of the infant limited peripheral vision.

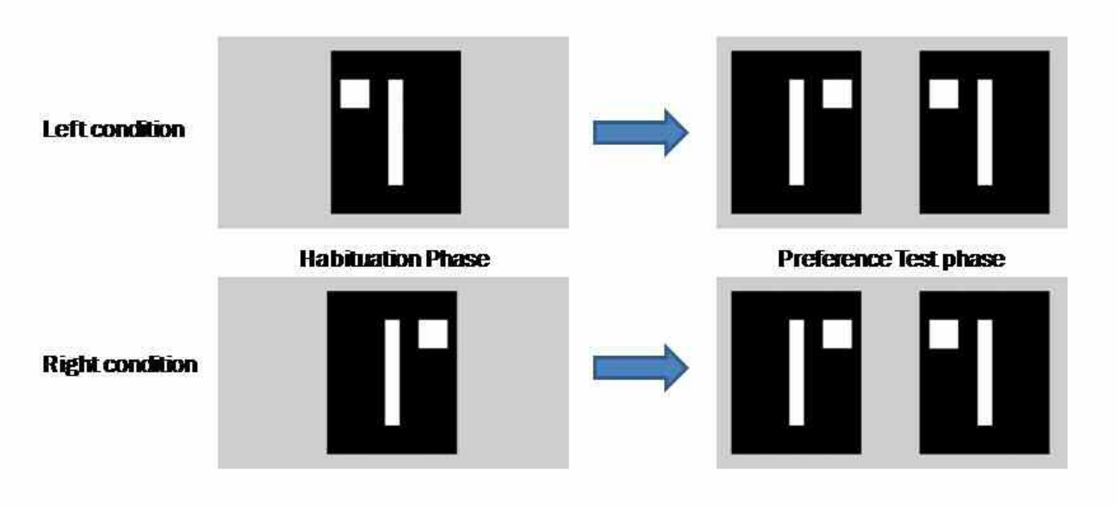

Figure 24: Sample of the stimuli used in Experiment1.

Procedure

Newborns were randomly assigned to one of two groups: Infants habituated to a configuration in which the blinking square appeared on the left side of the bar belonged to the *Left condition*; infants habituated to a configuration in which the blinking squared appeared on the right side of the bar belonged to the *Right condition*. In both conditions (i.e., Left or Right) half newborns saw the square in the upper part of the configuration, and the other half saw the square in the lower part of the configuration. The upper (or lower) position of the square was maintained constant through the habituation and the test phases, that is newborns were presented either with stimuli in which the blinking square appeared in the upper part of the configuration, or with stimuli in which the blinking square appeared in the lower part of the configuration (see Figure 3).

As soon as the infants were apparently at ease and their gaze was properly aligned with the central fixation point, the habituation phase was begun, by pressing a key on the keyboard. This automatically turned off the central fixation point and activated the habituation stimulus. During the habituation phase, a single stimulus was projected centrally on the screen.

The duration of each fixation was coded on-line by an experimenter, who could not see the display and was blind with respect to the specific left/right position of the familiar and novel stimuli in test trial. A look-way criterion of 2 s was used to determine the end of each fixation. In order to be sure that this criterion was strictly respected, the software was planned so that it automatically compacted two consecutive fixations that were not separated by a time interval of at least 2 s.

The stimulus remained on the screen until the habituation criterion was reached. The infant was judged to have been habituated when, from the fourth fixation on, the sum of any three consecutive fixations was 50% or less than the total of the first three (Horowitz, Paden, Bhana, & Self, 1972). Only when the habituation criterion was reached, the stimulus was automatically turned off and the central fixation point was turned on.

As soon as the infant's gaze was realigned to the central fixation point, a preference test phase started. Each infant was given two paired presentations of the test stimuli. During each presentation, infants were simultaneously presented with the familiar stimulus (e.g., up-left side of the bar) and a new stimulus in which the square appeared in a new spatial position (i.e., up-right side of the bar). The two paired stimuli were always shown in both left and right positions, the position being reversed from presentation 1 to presentation 2. The central fixation point flickered between the first and the second test trials, but did not flicker when the test stimuli were on.

The experimenter recorded the duration of each fixation on the stimuli by pressing two different push buttons depending on whether infants looked at the right or left position. Each presentation lasted when a total of 20s of looking to the novel and/or familiar stimuli had been accumulated.

Moreover, videotapes of eye movements throughout the trial were subsequently analyzed frame by frame by a second coder unaware of the stimuli presented. Inter-coder agreement was 1.00 (Cohen Kappa) for the number of orienting responses toward the stimuli and 0.89 (Pearson correlation) for total fixation time.

Results

All the infants reached the habituation criterion. The average number of trials and the average total fixation time to reach the habituation criterion was respectively 10.32 (*SD* = 3.6) and 109.72 s (*SD* = 50.6). Preliminary statistical analyses showed no significant effect or interactions involving the 4 distinct conditions (i.e., Left-upper vs Right-upper vs. Left-lower vs. Right-lower conditions, F (3,15) = 2.247; $p > .05$ and F (3,15) = 1.796; $p > .05$ for number of trials and for total fixation time respectively). As a consequence, data were collapsed across these factors.

Newborns oriented equally often towards the two test stimuli (*M*= 5.32 number of orienting toward the familiar and the novel stimuli), t (18) = 2.03, $p < .10$. However, they looked longer at the novel stimuli (*M* = 27.35s, *SD* = 6.9) than the familiar stimuli (*M* = 18.53, *SD* = 6.7), t (18) = 2.95; $p < .009$.

In order to test whether newborns were able to recognize the position of the square to which they were habituated, a novelty preference score (percentage) was computed. Each infant's looking time at the new stimulus during the two presentation sessions was divided by the total looking time at both stimuli, and subsequently converted into a percentage score. Hence, only scores significantly above 50% indicated a preference for the novel position of the square.

To determine whether the novelty preference score was significantly different from the chance level of 50%, a one-sample t-test was applied. Preference scores for the stimulus with the novel position of the square were significantly above chance (*M* = 59.74 %, *SD* = 14.18), *t*(18) = 2.993, *p*< .009. Therefore, newborns showed a preference for the novel position of the blinking square, revealing that from birth infants show the ability to discriminate the switching of a blinking square from left to the right side (or vice versa) of a vertical bar.

Experiment 2

Data collected in Experiment 1 have demonstrated that, at birth, infants are able to discriminate the position of a square that switches from one side to the other side of a central vertical bar was tested. Experiment 2 was aimed to verify whether newborns are able to recognize as different the position upper and lower of the blinking square in the array, when it was presented on the same side of the referring bar. It was hypothesized that newborns would manifest a visual preference for the stimulus that presents a new position of the blinking square.

Method

Participants

Sixteen healthy, full-term newborn infants (mean age = 30.75 hr, *SD* = 18.2) were recruited at the maternity ward of the Paediatric Clinic of the University of Padova.

All infants met the screening criteria of normal delivery, a mean birth weight of 3550 g (*SD* = 474.36), and a 5 min Apgar score above 7. Two infants were excluded from the final sample: One did not complete testing due to fussiness and one presented a position preference. Therefore, the final sample consisted of 14 infants (8 females, 8 males), randomly assigned to 4 different habituation conditions: Up-right, down-right, up-left, and down-left conditions. Infants were tested only if awake and in an alert state, after the parents gave their informed consent.

Stimuli

The same set of stimuli used in Experiment 1 was employed in this experiment (see Figure 4).

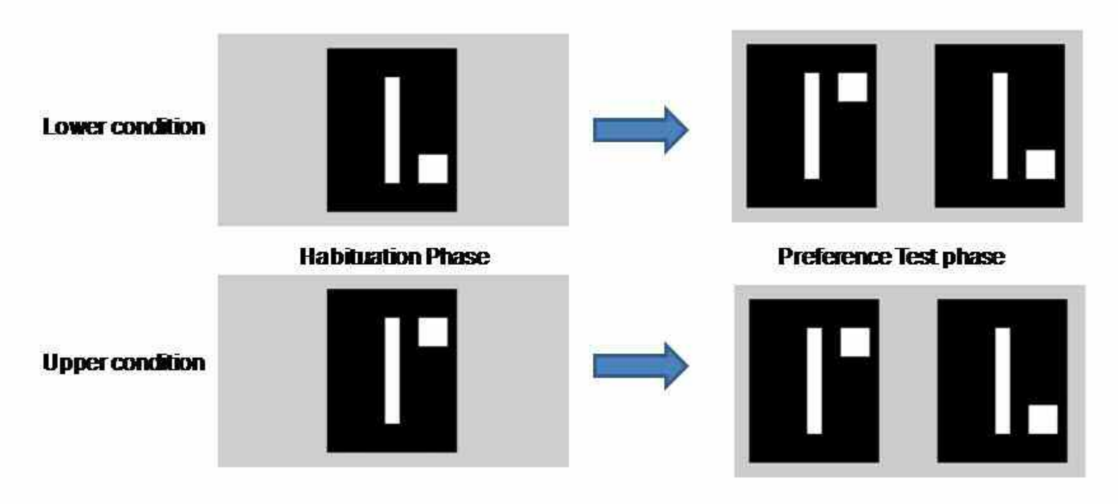

Figure 25: Sample of the stimuli used in Experiment 2.

Apparatus, and procedure

The apparatus and procedure were identical to those employed in Experiment 1. The only difference between Experiments 1 and 2 regards the stimuli in the test phase. In the present experiment, half infants were habituated to a configuration in which the blinking square appeared on the upper part of the array (i.e., *Upper condition*); half infants habituated to a configuration in which the blinking squared appeared on the lower part of the array (i.e., *Lower condition*). In both conditions (i.e., Upper or Lower) half newborns saw the square on the left side of the referring bar, and the other half saw the square on the right side of the referring bar. The left (or right) position of the square was maintained constant through the habituation and the test phases, that is newborns were presented either with stimuli in which the blinking square appeared in the left part of the configuration, or with stimuli in which the blinking square appeared in the right part of the configuration (see Figure 4).

As in the previous experiment, videotapes of eye movements throughout the trial were subsequently analyzed frame by frame by a second coder unaware of the stimuli presented. Inter-coder agreement was 0.99 (Cohen Kappa) for the number of orienting responses toward the stimuli and 0.94 (Pearson correlation) for total fixation time.

Results

The average total fixation time to reach the habituation criterion was 93.99 s (*SD* = 32.31). The average number of fixations was 7.43 (*SD* = 2.65). As in experiment 1, preliminary statistical analyses showed no significant effect or interactions involving the 4 distinct conditions presented (i.e., Left-upper vs Right-upper vs. Left-lower vs. Right-lower conditions), *F* (3,10) = .705; *p* >.05 and *F* (3,10) = .756; *p* > .05, for number of fixations and for total fixation time respectively. Therefore, data were collapsed across these factors.

The mean number of orienting was 6.33 (*SD* = 1.2) toward the new stimulus and 5.33 (*SD* = 1.53) toward the familiar stimulus, *t* (13) = 1.197, *p* > .05. Newborn infants looked at the new and at the familiar displays for 32.34 s (*SD* = 10.4) and 17.4 s (*SD* = 4.82) respectively, *t*(13) = 3.274, *p* < .007.

In order to test whether newborns were able to recognize the familiar position of the square to which they were habituated, a novelty preference score (percentage) was computed. Each infant's looking time at the new stimulus during the two presentation phases was divided by the total looking time at both stimuli, and subsequently converted into a percentage score. Hence, only scores significantly above 50% indicated a preference for the new position of the square. To determine whether the preference score for the new position was significantly different from the chance level of 50%, a one-sample t-test was applied. Preference scores for the new stimulus were significantly above chance (*M* = 61%, *SD* = 12.11), *t*(13) = 3.40, *p* < .006.

Infants looked longer at the stimuli that presented the square in a new position, confirming that newborns are able to discriminate between the different locations of the square in the array (i.e. up versus down), despite the fact that the square appeared on the same side of the vertical bar (e.g. left).

Experiments 1 and 2 demonstrated that, at birth, newborn infants discriminate the spatial configurations on the basis of the positions of the square with respect to the vertical bar (Experiment 1) and with respect to the absolute location of the square on the same side of the bar (Experiment 2). This finding indicates that newborns are able to attend to and differentiate perceptual changes related to the spatial position of an object-target with respect to a landmark in a visual array. Experiment 3 will address the question of whether newborns are able to treat as similar the spatial position upper/lower, well discriminated in Experiment 2, when they are required to discriminate two configurations only on the basis of left/right spatial relationship. In other words, the next experiment is focused on investigating newborns' ability to extract and recognize an invariant property related to the spatial relationships between an object-target and a landmark, regardless of the specific upper/lower spatial position of the object-target.

Experiment 3

A modified version of the recognition-memory procedure was used (Quinn & Eimas, 1996), in which both square's positions presented in the preference test phase were novel. For one of them, the square's position was highly different from those of the familiarized configuration, whereas for the other it was highly similar. It was predicted that if newborns were able to extract and recognize a basic perceptual invariance related to the spatial relationships between the square and the referring bar, during the test phase, they would prefer a novel square's position (e.g.,upper) with highly different spatial relationships (e.g.,left) over a novel square's position (e.g., upper) with spatial relationships (e.g., right) highly similar to those of the habituated stimulus configuration (e.g., lower-right). Alternatively, if newborns were not able to extract and recognize a basic perceptual invariance, they would perceive the two test stimuli as equally novel. Therefore, they would not show any novelty preference in the test phase.

Method

Participants

Participants were twenty-three healthy and full-term newborns (mean age = 46.7 hr, *SD* = 25.03). The infants were recruited at the maternity ward of the Paediatric Clinic of the University of Padova and met the screening criteria of normal delivery, a birth weight between 2740 and 3950 g, and a 5 min Apgar score above 7. Seven newborns were excluded from the final sample: One infant was excluded because he did not complete testing due to fussiness, 2 babies showed a position bias during the preference test phase and 4 were excluded from the final sample for technical problems. Thus, the final sample included 16 newborns (8 females, 8 males). Infants were tested only if awake and in an alert state, after their parents gave their informed consent.

Stimuli, apparatus, and procedure

Stimuli, apparatus and procedure were identical to those employed in Experiment 1. The only difference between Experiments 1 and 3 concerns the stimuli shown in the test phase. In the present experiment, two new stimuli were shown in the test phase: One stimulus was new for the upper/lower position of the square with respect to the bar but displayed the left/right familiar spatial relationship, and one stimulus was new for both these attributes (see Figure 5). For instance, infants were familiarized to a configuration in which the square presents the left spatial relationship with the bar and was located on the upper part of the array. In test phase, one of the stimuli presented the square with the familiar spatial relationship to the bar (i.e., left) but in a novel location (i.e., lower); the other stimulus presented the square both with a novel spatial relationship (i.e., right) and in a novel location (i.e., lower).

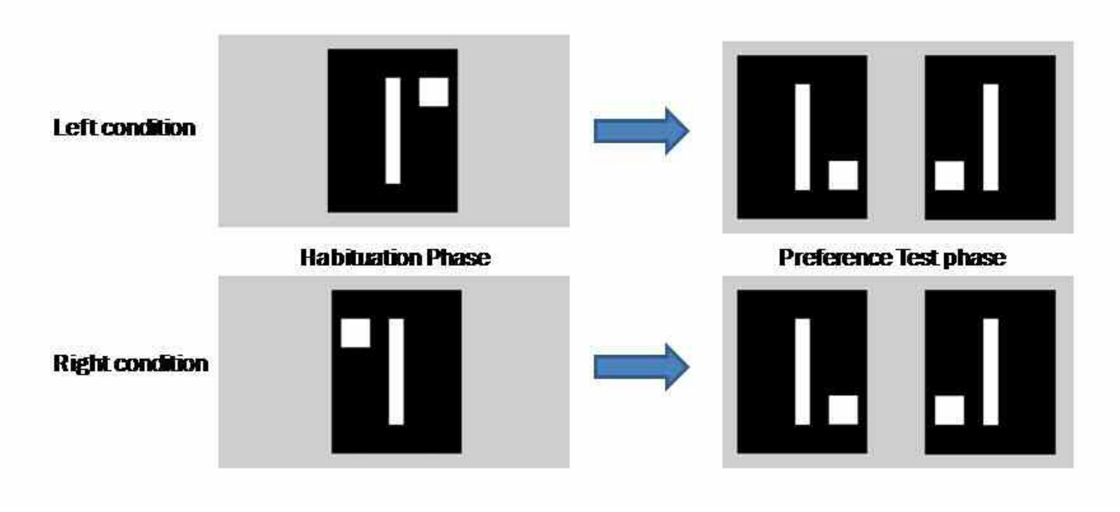

Figure 26: Sample of the stimuli used in Experiment 3.

As in the previous experiments, videotapes of eye movements throughout the trial were subsequently analyzed frame by frame by a second coder unaware of the stimuli presented. Inter-coder agreement was 0.99 (Cohen Kappa) for the number of orienting responses toward the stimuli and 0.94 (Pearson correlation) for total fixation time.

Results

The average total fixation time to reach the habituation criterion was 107.44 s (*SD* = 40.64). The average number of fixations was 7.69 (*SD* = 1.85). As in the previous experiments preliminary statistical analyses showed no significant effect or interactions involving the 4 distinct conditions (i.e., Left-upper vs Right-upper vs. Left-lower vs. Right-lower conditions), *F* (3,12) = .387; *p* > .05 (number of fixations), and *F* (3,12) = .766 ;*p* > .05 (total fixation time).

The average number of orienting and the average total looking time to the stimuli were calculated. Newborns oriented more frequently toward the highly different stimulus than toward the highly similar stimulus. The average number of orienting was 6.31 (*SD* = 1.92) for the highly different stimulus and 5.25 (*SD* = 1.95) for the highly similar one, *t* (15) = 2.22, *p* < .043. Moreover, newborns looked longer at the more different stimulus (*M* = 28.02 s, *SD* = 7.29) than at the similar one (*M*= 18.9 s, *SD* = 6.01), *t* (15) = 3.02, *p* < .01.

To determine whether newborns were able to extract and recognize an invariant property related to the square's positions in the array, a preference score for the highly different stimulus (percentage) was computed and a one-sample t-test was applied. Preference scores for the highly different stimulus were significantly above chance (*M* = 59.50%, *SD* = 12.7), *t*(15) = 2.99, *p* < .01.

Discussion

Overall, collected data demonstrated that newborns presented with a stimulus depicting the square to one side of the bar generalized their habituation to the square in a novel position on the same side of the bar and showed a preference for a stimulus depicting the square on the opposite side of the bar. This means that the spatial configuration with similar position of the square with respect to the bar (i.e., left-right spatial relationship) was treated as more alike the familiar spatial configuration than a novel spatial configuration with dissimilar left/right spatial relationship. Newborns ignored some of the perceived differences and respond to spatial configurations in term of similarity. Consequently, evidence has provided that, even in well-contrasted configurations, newborns detect and recognize an invariant perceptual property related to the left/right spatial relationship between the object-target and the landmark.

Nevertheless, in the present experiment, newborns' ability to detect a perceptual invariance was investigated by habituating newborns to one single exemplar of spatial relationship. That is to say, newborns had to detect a perceptual similarity between two stimuli: The habituated spatial configuration and the spatial configuration with highly similar spatial relationship shown during the test phase. Therefore, the within-category variability was extremely low because of the small number of exemplars that represented the perceptual category (i.e., 2). This factor might have represented a facilitating condition that might have enhanced newborns' performance. Experiment 4 was designed to test newborns' ability to perceive perceptual commonalities among spatial configurations in a condition of higher perceptual variability of the square's position, that is as usually older infants are tested (see Quinn et al).

Experiment 4

The aim of Experiment 4 was to investigate whether newborns are able to manifest the capacity to recognize a perceptual similarity when greater number of spatial configurations with different positions of the square were displayed. To address this question, infants were familiarized with three different exemplars of spatial configurations belonging to the same perceptual category (e.g., left spatial relationship) and then tested with a new exemplar from the familiar-category paired with a novel-category exemplar (e.g., right spatial relationship). It was predicted that, as a result of familiarization, newborns would recognize a basic perceptual similarity among the spatial relationships of the familiar category and prefer the novel-category exemplar rather than the familiar-category exemplar.

Method

Participants

Nineteen healthy, full-term newborn infants (mean age = 53 hr, *SD* =17.2) were recruited at the maternity ward of the Paediatric Clinic of the University of Padova. All infants met the screening criteria of normal delivery, a mean birth weight of 3332 g (range 2740 g – 3950 g), and a 5 min Apgar score above 7. Three infants were excluded from the final sample: One did not complete testing due to fussiness and one presented a position preference. Therefore, the final sample consisted of 16 infants (9 females, 7 males), randomly assigned to 2 different habituation conditions: Right and Left conditions. Infants were tested only if awake and in an alert state, after the parents gave their informed consent.

Stimuli

Eight stimuli, composed by a black background (11.3 cm high x 14 cm wide; about 22° x 27°) in which were depicted a central vertical white bar (1.4 cm wide x 9.2 cm high; about 3° x 18°) and a blinking (500 ms) white square (2.6 cm; about 5°), were employed (see Figure 6). Four of them, referred to as belonging to the left category, depicted a single square in a different position to the left of a vertical bar (i.e., near- upper, far-upper, near-lower and far-lower). Similarly the four referred to as belonging to the right category, depicted a single square in a different position to the right of a vertical bar (i.e., near- upper, far-upper, near-lower and far-lower). The stimuli were therefore designed in such a way that only their position to respect to the central vertical bar varied.

When the square appeared in the near-upper (or in the near-lower) position it was allocated at a distance of 1.5 cm (about 3°) from the bar, whereas when the square appeared in the far-upper (or in the far-lower) position it was allocated at a distance of 3 cm (about 6°) from the bar.

Between the familiarization and the test phases, a configuration composed by two red discs, one greater than the other (i.e., greater one's radius: 2 cm, about 4°; smaller one's radius: 1 cm, about 2°), was presented alternating on the centre of the black array with a rate of 500 ms.

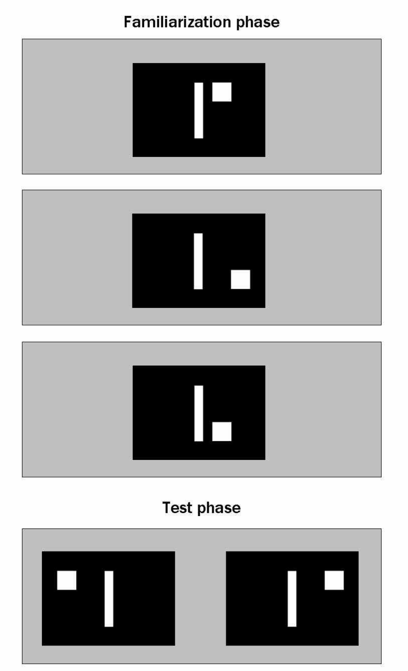

Figure 27: Sample of the stimuli used in Experiment 4.

Apparatus

The apparatus was identical to that employed in the previous experiments.

Procedure

Familiarization procedure was used. When the infant was apparently at ease and his/her gaze was properly aligned with the central red discs the procedure started. During the familiarization phase, infants were administered three familiarization trials, in which three different left (*Left condition*) or right (*Right condition*) exemplars were displayed. Each single exemplar was projected centrally on the screen. An experimenter recorded the duration of each fixation on the stimulus by pressing a push button that was connected to the computer. When a 20-sec total fixation time criterion was reached, the stimulus was automatically turned off and the central red discs were turned on. As soon as the infants were realigned to the central discs, the subsequent trial began. At the end of the familiarization trials, a preference test phase started. Each infant was given two paired presentation of test stimuli. During each presentation two novel stimuli were presented: A novel exemplar from the familiar category was paired with an exemplar from a novel category (see figure 6).

The two paired-stimuli were always shown in both the left and right positions, the positions being reversed from presentation 1 to presentation 2. The initial left-right order of presentation was counterbalanced across subjects. The experimenter recorded the duration of infant's fixations on each stimulus by pressing two different push buttons. A presentation lasted until each stimulus had been fixated at least once and a total of 20 sec. of looking had been accumulated.

The order and sequence of presentation of the four exemplars belonging to the familiar category (three for familiarization, one for preference testing) were counterbalanced between subjects using a balanced Latin square design.

Videotapes of eye movements throughout the trial were subsequently analyzed frame by frame by a second coder unaware of the stimuli presented. Inter-coder agreement was 1.00 (Cohen Kappa) for the number of orienting responses toward the stimuli and 0.89 (Pearson correlation) for total fixation time.

Results

Preliminary statistical analyses showed no significant effect or interactions involving the distinct familiarization conditions (i.e., Left condition vs. Right condition) presented, t (15) = 1.18, p > .05. As a consequence, data were collapsed across this factor.

The average number of fixations to orient toward the two stimuli was calculated. Infants looked more often to the novel-category stimulus (6.31 average number of orientations, *SD* 1.92) than to the familiar-category one (5.25 average number of orientations, *SD* 1.95), *t* (15) = 2.221; *p* < .043. Total looking time followed the same trend, in that the novel stimulus was fixated longer (*M* = 28.02s, *SD* = 7.28) than the familiar one (*M* = 18.9s, *SD* = 6.01), *t* (15) = 3.023; *p* < .01.

To test whether newborns perceived a perceptual similarity among the spatial configurations, a novelty preference score (percentage) was computed for each infants as in the previous experiments. That is, each infant's looking time at the novel-category exemplar during the two test presentations was divided by the total looking time to both test stimuli over the two presentations and converted into percentage score. Preference scores for the novel-category exemplar (59.5%) were significantly above chance *t* (15)= 2.994; *p*< .01. Two independent samples *t* tests were calculated to verify that there were no difference both for upper-lower condition, *t* (14) = -.289; *p* > .05, and for right-left condition, *t* (14) = .096<, *p* > .05.

Discussion

Overall, the findings indicate that 3-day-olds newborns are able to recognize common perceptual characteristics shared by spatial configurations that differ in the position of the square with respect to the bar, thus is the left/right spatial relationship between an object-target and a landmark. When familiarized with spatial configurations with the square in different positions with constant spatial relationship with the bar, in test phase newborns looked longer at the configuration markedly different from those they were familiarized to, that is, to the configuration with novel-category spatial relationships. Thus, the evidence obtained suggests that, at birth, infants are able to form a perceptually driven category representation for the left versus right relations of a blinking square and a vertical bar.

However, before this conclusion can be reached, an alternative interpretation of the obtained results must be discarded (Quinn & Eimas, 1996). In fact, it is possible that newborns did not differentiate between members of the same category (i.e. for the left conditions: Near- upper, far-upper, near-lower and far-lower). If it were the case, the novelty preference observed would be the consequence of newborn's inability to discriminate among the within-category exemplars, rather than the result of a categorization process. As a consequence, Experiment 1 and 2 do not serve as a proper control for Experiment 4, because they do not provide sufficient evidence that infants can discriminate between the different positions of the square presented during the habituation phase. Experiment 5 was designed to test this possible explanation.

Experiment 5

Reliable novel category preference scores can only be inferred as evidence for categorization if it is known that the individual exemplars for the familiar category are discriminably different for the participants (Quinn, 2002). This is an important condition that must be met when categorical abilities are explored. Experiment 5 was thus conducted to determine whether newborn infants could discriminate between exemplars selected within each of the two perceptual categories taken into account in Experiment 4 (i.e., left and right spatial relationships). Each infant was familiarized with an instance from one perceptual category and then tested with the familiar instance paired with a novel instance from the same category.

Method

Participants

The participants were twenty healthy, full-term newborn infants (mean age = 53 hr, *SD* =21.2) were recruited at the maternity ward of the Paediatric Clinic of the University of Padova. The screening criteria were the same as those used in the previous experiments. Three infants were not included in the final sample: One did not complete testing due to fussiness and two presented a position preference. Therefore, the final sample consisted of 17 infants (9 females, 8 males), randomly assigned to 4 different habituation conditions. About half of sample (8 infants) were habituated to the blinking square located at the right of the vertical bar, and the other half (9 infants) were habituated to the blinking square located at the left of the bar.

Infants were tested only if awake and in an alert state, after the parents gave their informed consent.

Stimuli and Apparatus

The stimuli and the apparatus were those used in Experiment 4.

Procedure

The procedure was the same utilized in Experiment 1. Each newborn was habituated to a blinking square positioned in one of the possible positions to respect to the bar (i.e., left/right, above/below, near/far) and therefore was tested for discrimination between two of the four exemplars used to represent the familiar categorization in a given familiarization and preference test condition of Experiment 4. The pair of exemplars was randomly chosen for each infant, as was which member of the pair would serve as the familiar stimulus. All the possible familiar-versus-novel instances pairing were tested, as a consequence, the pairing were different for each infant. For instances, all the newborns belonged to the same habituation condition (i.e. newborns habituated to the square located to the right-above-near to the bar) compared the familiar stimulus with a different novel stimulus: One of them was tested with the square located to the right-above-near the bar (i.e. familiar stimulus) paired with the square located to the right-above-far from the bar, one with the familiar stimulus paired with the square located to the right-below-far from the bar, and the third with the familiar stimulus paired with the square located to the right-below-near to the bar.

As in the previous experiment, videotapes of eye movements throughout the trial were subsequently analyzed frame by frame by a second coder unaware of the stimuli presented. Inter-coder agreement was 0.99 (Cohen Kappa) for the number of orienting responses toward the stimuli and 0.96 (Pearson correlation) for total fixation time.

Results

All the infants reached the criterion of habituation. The average total fixation time to reach the habituation criterion was 74.65 s (*SD* = 43.01). The average number of fixations was 7.94 (*SD* = 2.79). Preliminary statistical analyses showed no significant effect or interactions involving the distinct conditions (i.e., Left-upper vs Right-upper vs. Left-lower vs. Right-lower conditions), *F* (3,13) = .474, *p* >.0.05, and *F* (3,13) = .856; *p* > .05.

In the test phase, the mean number of orienting was 7.53 (*SD* = 2.4) toward the new stimulus and 6.2 (*SD* = 2.5) toward the familiar stimulus, *t* (16) = 2.047, *p* > .05. Newborns looked longer at the novel stimulus (*M* = 28.08, *SD* = 9.2) than at the familiar one (*M* = 16.96, *SD* = 7.34), *t* (16) = 2.822; *p* < .013.

To determine whether newborns were able to discriminate among members of the same spatial category, fixation times during the test phase were transformed into percentages as in previous experiments. A novelty preference score was computed for each infant and a *t*-tests were performed comparing the preference scores to chance. A reliable mean novelty preference score, significantly greater than chance level, was obtained when the newborns' performance was collapsed across the 4 habituation conditions (*M* = 61.24%, SD = .17), *t* (16) = 2.616, *p* <. 02.

Discussion

The reliable preference for the novel stimulus reveals that newborns both recognize the familiar exemplar and differentiated it from a novel exemplar selected from the same spatial category. This finding indicates that newborns were able to discriminate between within-category exemplars. Importantly, newborns manifested a novelty preference irrespective of the group to which they belonged. Altogether these results indicate that newborns were able to discriminate the exemplars from within left and right category, and that the novel category preference scores observed in Experiment 4 were unlikely to have risen from within-category discrimination failure.

Conclusions

In the domain of objects, investigation of perceptual categorization of newborns have established that a few days after birth infants are able to detect and recognize perceptual constancies (e.g., Granrud, 1987; Slater & Morison, 1985; Slater, et al., 1990) and to group stimuli into categories if these are sufficiently discriminable (Turati et al., 2003). The current study extends these findings to the domain of spatial relationships, suggesting that newborns can also discriminate and categorize spatial information that is defined by the positional relations of objects in the environment.

In Experiment 1 infants discriminate between a stimulus depicting the square to one side (i.e. left side) of the bar versus a stimulus depicting the square to the other side of the bar (i.e. right side). Experiment 2 indicates that neonates can discriminate between spatial configurations on the basis of the upper/lower positions of the square. Experiment 3 demonstrated that newborns treated two spatial configurations with similar spatial relationships as more alike than two spatial configurations with non-similar spatial relationships, showing that they are able to extract, process, and recognize a perceptually invariant property shared by the stimuli. Considered together the results of Experiments 1, 2 and 3 demonstrate that from birth infants show the ability to discriminate spatial configurations on the basis of their spatial relationships.

More intriguingly, Experiment 4 showed that, in conditions of higher within-variability, newborns are able to form a perceptual category of left/right spatial relationship and to respond to novel object arrangement on the basis of these representations. Since this result is not the consequence of newborn's inability to discriminate between instances of the same spatial category (Experiment 5), it is possible to conclude that from birth infants are able either to discriminate or to categorize spatial information.

An important strength of the present study is that a limit that affected Antell and Caron's study (1985) on newborns' categorical competencies was overcome. Here, we used a landmark (i.e., the bar) that differed from the target object (i.e., the square) not only for dimension and shape but also because the square was dynamic and the landmark was static. The use of a dynamic target stimulus intended to trigger newborns' attention toward the element that changed position (Fantz & Nevis, 1967), facilitating newborns to perceive the square and the bar as two spatially distinct entities rather than as a holistic configuration. Moreover, using higher within-category variability allows extending conclusions to the newborn infants' ability to form an abstract representation of the left/right spatial relationship. Based on this evidence future studies might be addressed to investigate whether the results reported in the current study might be extended to conditions where the target and the bar are both static, or whether the perception of spatial relationship is anchored in initial abilities to detect motion.

Evidence from this study is consistent with the idea that cognitive system appears predisposed from the onset to treat spatial relationship between object in a categorical manner, at least when the spatial relationship involves only two objects and they are easily discriminable from each other. In other words, evidence from the present study suggests that from the beginning the human perceptual system seems to be architecturally tuned to perceive objects in an organized spatial arrangement, on the basis of visuo-spatial processing.

These findings seem to be coherent with the Object-file models that maintain the existence from birth of a general and automatic attentional system of object tracking based on object representation and individuation abilities. Specifically, Study 1 demonstrated the presence even at birth of one of the visuo-spatial abilities implied in numerical performances with small numerosities in the first months of life, that is the ability to form categorical representations of spatial relationships (Simon, 1997).

In the next chapter the presence of a second ability implies in numerical performances will be tested. It concerns the ability to detect ordered sequences.

Chapter 5

Visuo-spatial abilities at birth: early foundations of ordered sequences detection

Study 1 demonstrated that from birth infants are able to form categorical representation of left/right spatial relations between an object-target and a landmark (Chapter 4). Findings from this study are consistent with the Object-file model supposed by Simon (1997). An additional competency expected by Object-file model is the ability to detect ordered sequence (Simon, 1997). In the present chapter the possibility that even newborns show this further ability will be tested.

1 Ordered sequences

Commonly, a sequence is defined as an ordered list of objects or events. For example, CRY is a sequence of letters that differs from YCR as the ordering matters. In sequence's definition is implicit the spatio-temporal feature. Indeed, in order to adapt and survive, all higher organisms must learn to operate within a temporally bounded environmental where sequential events occur (Lewkowicz, 2004). Sequential learning, which is the ability to encode and represent the order of discrete elements occurring in a sequence, is a fundamental process of perception and cognition (Conway & Christiansen, 2001). For example, the perception and interpretation of language, music, and behaviors of others all depend on our ability to perceive sequential ordering of a series of elements (e.g., Baldwin & Baird, 2001). It is possible to delineate three progressively more complex abilities in sequential learning: Learning fixed sequences, thus is to learn a sequence of elements that maintain an unchanging order (e.g., to remember a phone number), encoding statistical regularities of sequences, thus is to elaborate sequential patterns consist of combinations of frequently co-occurring elements (e.g., new language learners extract words from a continuous speech stream), and learning hierarchical structure, thus is to encode the frequency information for more than just the previous element of a sequence (Conway & Christiansen, 2001). The present chapter will be focused on the simplest type of sequential learning, thus is learning of an arbitrary, fixed sequence.

1.1 Perception of ordered fixed sequence in infancy

Studies that have examined infants' response to or production of serially organized sequences suggest that, infants possess serial order skills shown in a variety of tasks. For example, infants perceive word order (Mandel, Nelson, & Jusczyk, 1996), learn the transitional probabilities between adjacent members of a sequence of speech sounds (Aslin, Saffran & Newport, 1999), learn to move a series of mobiles and remember the order in which they moved them 24 hours later (Merriman, Rovee-Collier & Wilk, 1997), learn, remember and reproduce multi-act sequences in the correct order (Bauer, Wiebe, Waters & Bangston, 2001; Carver & Bauer,1999, 2001; Wenner & Bauer, 1999).

In a recent study Leslie & Chen (2007) have demonstrated that 11-month-old infants are able to recognize a sequence of four elements, formed by two pairs of different geometrical shapes, using violation of expectation paradigm[1]. Infants were familiarized either with an XXYY display, in which sequentially displayed pairs of objects are identical within but differ across pairs, or with an XYXY display, in which sequentially displayed pairs differ within but are identical across pairs

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[1] For a description of violation of expectation paradigm see Chapter 2.

(Figure 1). Familiarization trials began with the removal of the first pair from behind a screen and presenting it on stage. Each group of infants is then tested with one of two outcomes, XXYY or XYXY. If infants can individuate successive pairs of objects differing only in shape, then when the screen is removed unexpected sequence infants should look longer at outcomes than Expected sequence infants (Figure 1).

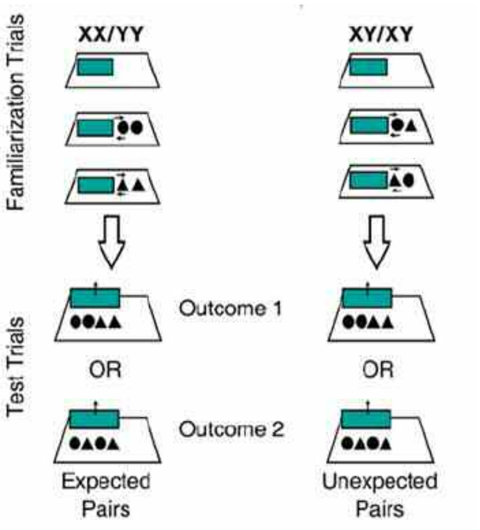

Figure 28: Procedure and sample of the stimuli used in Leslie & Chen (2007) study.

Infants looked longer at the unexpected sequence outcome, suggesting that infants around 11 months can use shape to individuate an ordered sequence.

More intriguingly, a study carried out by Lewkowicz (2004) suggests that, under particular conditions the ability to detect ordered list of objects may appear very early. Using a multimodal habituation paradigm, Lewkowicz (2004) demonstrated that 4-month-old infants are able to recognize the serial order of a sequence of three moving objects, specified multimodally. Specifically, the aim of this study was to investigate whether infants can perceive serial order, with a particular emphasis on whether they can detect the ordinal position of the members of a series of items. Four- and 8-month-old infants were habituated to an audiovisual display consisting of sequentially moving and sounding objects and then tested in separate test trials for their ability to detect changes in the auditory, visual and audiovisual attributes of serial order.

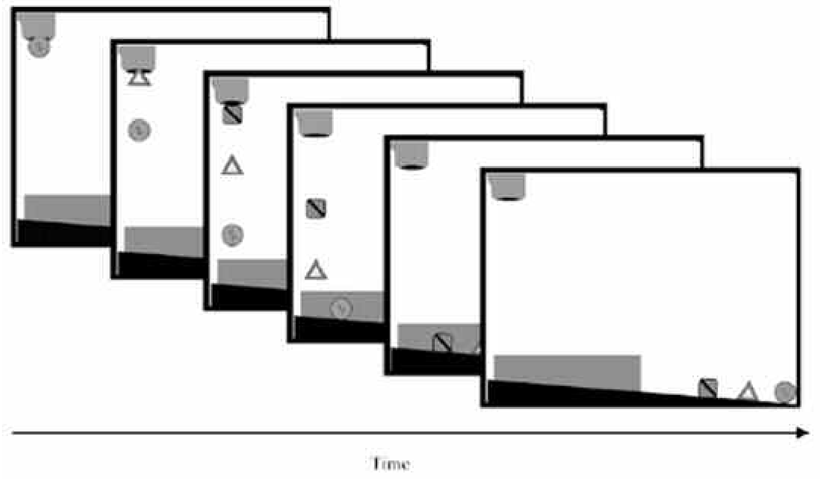

Figure 29: The three visual objects and the schematic representation of their movement over time in Lewkowicz (2004) experiment [source: Lewkowicz (2004)].

Four-month-old infants perceived spatiotemporal serial order when it was multimodally specified, whereas 8-month-olds perceived serial order regardless of whether it was multimodally or unimodally specified. These findings provide direct evidence that infants can perceive and learn the sequential ordering of a series of geometrical figures and then detect its reordering. The fact that infants as 4 months of age can perceive and learn spatiotemporally distributed lists is a testament to humans' greater sequential learning powers early in development (Lewkowicz, 2004).

Another condition that provokes an earlier source of sequential learning is the removing of temporal information from the sequence. Indeed, some findings have suggested that the perception and learning of serial lists that are temporally distributed is more difficult than if such lists consist of spatially distributed and simultaneously available items (e.g., Lewkowicz, 2004; Gower, 1992).

Altogether these studies show that perception of spatio-temporal serial order of sequence composed by different geometrical figures emerges early in infancy and that its perception is initially facilitated by multimodal specification or by deleting temporal information and presenting spatially distributed and simultaneously available elements (e.g., Lewkowicz, 2004).

2 Study 2

In the present study was investigated the foundations of detecting ordered sequences of objects in the first days of life. Specifically, the goal of Study 2 was to investigate whether newborns are able to detect visuo-spatial serial order sequences, arranged in according with left/right spatial-relation principles.

Since, as reported above, some studies have suggested that in general the perception and learning of lists consist of spatially distributed and simultaneously available elements is easier than temporally distributed sequences, in the present study it was hypostasized that the deletion of any temporal information could facilitate infants' ability to detect an order list of elements

Hereafter, for emphasizing that the sequence presented in this study employ spatial but not temporal features the experiments are designed as *spatial order sequences*.

To sum up, the purpose of the present study was to extend the early capacity of representing the left/right spatial relation between an object-target and a landmark, well demonstrated in 3-day-old infants (Study 1), to the capacity to detect a spatial order sequence of three objects, arranged in according with left/right spatial-relation principles. To this aim Experiments 6 and 7 were carried out using the familiarization technique.

Experiment 6

Experiment 6 was employed to investigate whether 3-day-olds newborns are able to detect a spatial sequence of three objects. To address this issue, newborns were randomly assigned to two different conditions. Subjects belonging to the experimental condition were familiarized with three objects of a spatial order sequence, whereas subjects belonging to the control condition were familiarized with the same three objects displayed in a random sequence. After familiarization phase newborns of both the conditions (experimental vs control condition) were tested with a new exemplar from the familiar sequence paired with an exemplar of a novel sequence. It was predicted that, as a result of familiarization, infants familiarized with an ordered sequence would recognize the new exemplar of the familiar sequence and prefer the exemplar of the novel-sequence, whereas infants familiarized with a random sequence should not manifest any preference for one of the spatial sequences presented in test phase.

Method

Participants

Forty healthy, full-term newborn infants (mean age = 41.9 hr, *SD* = 19.9) were recruited at the maternity ward of the Paediatric Clinic of the University of Padova. All infants met the screening criteria of normal delivery, a mean birth weight of

3315 g (range 2414g – 4040g), and a 5 min Apgar score above 7. Two infants did not complete testing due to fussiness and two were excluded to technical problems. Therefore, the final sample consisted of 36 infants (16 female, 20 male), randomly assigned to two different conditions: 20 infants to the experimental condition and 16 to the control conditions. Infants were tested only if awake and in an alert state, after the parents gave their informed consent.

Stimuli

The stimuli were created using the software Paint Shop Pro 7.02. They were composed by a black background (8 cm high x 9 cm width; about 15.28° x 17.19°), which was divided in an imaginary 3x3 grid. Three white geometrical shapes, presenting all the same area (*i.e.*, 4 cm^2), were depicted on the background: a circle, a triangle, and a square. Each figure was centered in the cells composing the grid. Consequently, each shape was far from the others by a range of 0.5 cm and x 1 cm.

During the familiarization phase each stimulus occupied a single cell of the imaginary grid (never occupying all the same row contemporaneously), appearing in the upper, central or bottom part of the black array. Under the experimental condition each stimulus changed its position across the familiarization trials, but hold constant the spatial relationship with the other shapes (e.g., upper triangle - bottom circle - central square; central triangle – upper circle – bottom square). (Figure 3).

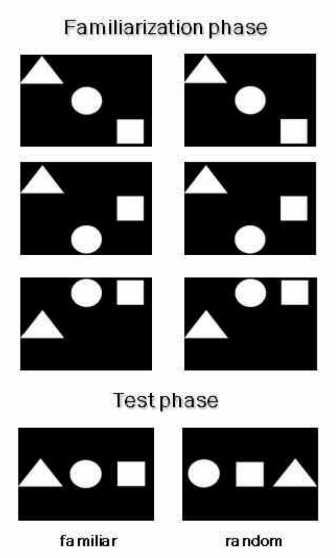

Figure 30: Sample of the stimuli used under the experimental condition of Experiment 6 (i.e., YCS condition).

On the contrary, under the control condition the geometrical shapes could randomly occupy any cell of the imaginary grid on the background, not holding constant left/right spatial relation between them (Figure 4).

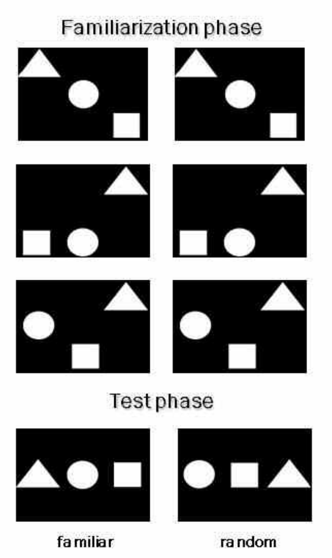

Figure 31: Sample of the stimuli used under the control condition of Experiment 6, (i.e., TCS condition).

During the test phase two novel stimuli were presented: A new exemplar of the familiar sequence paired with an exemplar of a novel sequence. All the shapes of the test stimuli concurrently occupied the central row (Figure 3 and 4). The exemplars of the novel-sequence were obtained by a permutation 3x2x1 without repetition of the familiar sequence, except the mirror familiar sequence and the familiar sequence itself.

Apparatus

The infant was placed on an experimenter's lap, in front of a black panel, at a distance of about 30 cm. The panel had two square holes where the black screens of two computer monitors appeared. Infant's eyes were aligned with a red flickering LED, located in the centre between the screens. The LED was used to attract the infant's gaze, subtended about 2° of a visual angle and, when turned on, blinked at a rate of 500 ms on and 500 ms off. Stimuli were projected at a distance of 4 cm from the central LED. To prevent interference from irrelevant distracters, two white panels placed on both sides of the infant limited peripheral vision.

Procedure

As soon as the infants were apparently at ease and their gaze was properly aligned with the central LED, the first familiarization trial was begun, by pressing a key on the keyboard. This automatically turned off the central LED and activated the stimulus. In each condition (experimental/control condition) half of the newborns were familiarized with three configurations depicting the sequence triangle - circle – square (i.e., *TCS sequence*), the other half with three configurations depicting the sequence square – triangle – circle (i.e., *STC sequence*). Stimuli were shown bilaterally, one on the left and one on the right of the central LED (see Figure 3 and 4).

The duration of each fixation was coded on-line by an experimenter, who could not see the display and was blind with respect to the specific position of the stimuli in each trial. A look-away criterion of 2s was used to determine the end of each fixation. In order to be sure that this criterion was strictly respected, the software was planned so that it automatically brought together two consecutive fixations that were not separated by a time interval of at least 2s. Each familiarization trail lasted until 20s of fixation were reached. After three trials of familiarization, the stimulus was automatically turned off and the central LED was turned on.

As soon as the infant's gaze was realigned to the central LED, a preference test phase started. Each infant was given two paired presentations of the test stimuli. Two different sequences were used: A novel exemplar of the familiar sequence paired with an exemplar of a novel sequence. The two paired stimuli were always shown in both left and right positions. All infants were submitted to two trials, in which the position of the stimuli was counterbalanced. The stimuli initial left-right position was counterbalanced across subjects. The central LED flickered between the first and the second presentation but did not flicker when the test stimuli were shown.

An observer, naïve to the hypothesis being tested and to the stimuli presented, recorded the duration of each fixation on the stimuli by pressing two different push buttons depending on whether infants looked at the right or left position. Each presentation lasted until 20 s of looking time were reached in each test phase. At this time, the experimenter turned off the stimuli, and the central LED started to blink again.

Results

Separate analyses were run for experimental and control conditions. For this reason they will be reported separately.

<u>Experimental condition</u>

Preliminary statistical analyses showed no significant effect or interactions involving the distinct familiarization condition (i.e., TCS condition vs. STC condition, *t* (19) = 1.18, *p*>.05), or the four different test random sequences, *F* (3, 16) = .853, *p*>.05. Therefore, data were collapsed across these factors.

Two t tests for dependent samples were performed, one for number of discrete looks and the other for total fixation time. Newborns oriented more often towards the exemplar of the novel sequence (*M* = 6.10 s, *DS* = 1.9) rather than to the exemplar of the familiar one (*M* = 4.90s, *DS*= 1.8), *t* (19) = 2.81, *p*>.012. Total fixation time followed the same trend, in that the exemplar of the novel sequence was fixated longer (M = 27.46s, *SD* = 7.88) than the exemplar of the familiar sequence (*M* = 18.14s, *SD* = 9.48), *t* (19) = 2.443, *p*<.026.

In order to test whether newborns, as a result of familiarization, recognize the new exemplar of the familiar sequence and prefer the exemplar of the novel-sequence a novelty preference score (percentage) was computed. Each infant's looking time at the exemplar of the novel sequence was divided by the total looking fixation time to both stimuli, and subsequently converted into a percentage score and a one-sample *t*-test was applied. Preference scores for the exemplar of the novel sequence were significantly above chance (*M* = 60.95%, *SD* = 17.8), *t* (19) = 2.750, p<.014.

Control condition

Also under this condition preliminary statistical analyses showed no significant effect or interactions involving the TCS sequence vs STC sequence presented during the familiarization phase (*t* (14) = 1.8, *p*>.05) or the four random sequence presented in test phase, *F* (3, 12) = 2.099, *p*>.05.. Consequently, data were collapsed across these factors.

Two paired-sample *t*-tests were performed to determine whether newborns' number of discrete looks and total fixation time differed for the two stimuli presented. The difference was not significant for either dependent variable. Newborns looked 5.88 times (*SD* = 1.99) at the novel exemplar of the familiar sequence and 6.19 times (*SD* = 1.79) at the new exemplar of the novel sequence, *t* (15) = -.49, *p*>.05. Similarly, they spent 20.44 s (*SD* = 7.85) and 22.9 s (*SD* = 7.99) looking at the familiar and novel sequences respectively, *t* (15) = -.628, *p*>.05.

As in the previous experiments, a preference score (percentage) was computed, in order to test whether infants looked longer to one of the sequences presented. The preference score for the novel sequence was not significantly different from chance (*M* = 48.13%, *SD* = 17.9), *t* (15) = -.418, *p*>.05.

Discussion

Collected data show that, when familiarized with spatial order sequences composed by three different geometrical figures and arranged in according to left/right spatial-relation principles (I.e., experimental condition), 3-day-old infants manifest a novelty preference for the exemplar of a novel sequence. On the contrary, when random sequences were presented in familiarization phase (i.e. control condition), newborns did not manifest any preference for one of the spatial sequences presented in test phase.

Two interpretations of these data can be advanced. Newborns detect each elements as discrete and recognize the left/right spatial relationship that connect each element to the other perceiving them as a single sequence. Alternatively, newborns do not perceive a sequence but detect only one shape (i.e, the circle) and recognize the it occupied always the same position (i.e., the centre). Before assuming that newborns are able to detect a spatial ordered sequence this alternative explanation must rule out. To this aim Experiment 7 was carried out.

Experiment 7

Infants were familiarized with three stimuli that changed their position across the familiarization trials, but hold constant the spatial relationship with the other two shapes. In other words, infants were familiarized to an ordered spatial sequence, exactly as happened during the familiarization phase of the experimental condition of Experiment 6. However, differently by the previous experiment, during the test phase two novel spatial sequences were presented. One of the test sequence was completely novel, the other one was the familiar sequence reversed, that is the familiar sequence presented on its opposite side so to obtain its mirror image. Importantly, the familiar sequence and its mirror image share the stimulus displayed in the central position. It was predict that if newborns are able to detect the spatial relations between the elements, they should not manifest any visual preference since both of the configurations presented new spatial relations within the sequences. On the contrary, if newborns detect only the central position of a single element, they should recognize the mirror sequence as familiar and show a novelty preference for the novel sequence.

Method

Participants

The participants were 20 healthy, full-term infants of mean age of 49.7 hr (*SD* 22.8) and a mean birth weight of 3181 g (range of 2500g – 4665g), recruited at the maternity ward of the Pediatric Clinic of the University of Padova. All infants met the screening criteria of normal delivery, and a 5 min Apgar score above 7. Three additional infants were tested, but they were excluded from the final sample because of position bias (n 1), fussiness (n 1), or experimenter error (n 1).

Stimuli, apparatus, and procedure

Stimuli, apparatus and procedure were the same used in the experimental condition of Experiment 6. The only difference regards the stimuli presented during the test phase. They were the mirror image of the familiar sequence paired with a sequence never seen before (see Figure 5).

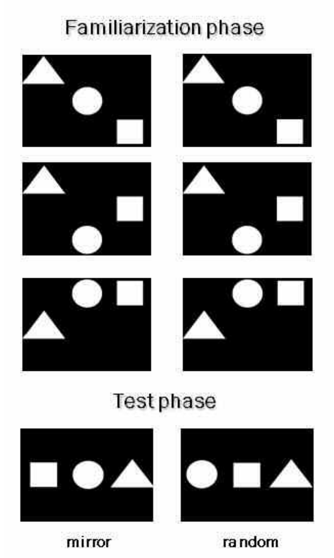

Figure 32: Sample of stimuli used in Experiment 8 (i.e., TCS condition).

Results

Preliminary statistical analyses showed no significant effect or interactions involving the distinct sequence (i.e., TCS vs. STC sequence, *t* (18) = 1.023, *p* > .05), or the four different random spatial sequence presented in test phase (*F* (3, 16) = .756, *p*>.05). As a consequence, data were collapsed across these factors.

As in the previous experiments, the average number of orientations toward the two stimuli was computed, but the difference was not significant. Newborns oriented 4.45 times at the novel spatial sequence (*SD* = 1.6) and 4.5 times to the mirror sequence (*SD* = 1.5), *t* (19)= -.127, *p*>.05. Total fixation time followed the same trend, in that newborns looked at the novel spatial sequence for 24.96 s (*SD* = 11.22) and at the mirror sequence for 25.4 s (SD = 11.78), *t* (19) = -.099, *p* >.05.

As in the previous experiments, a novelty preference score (percentage) for the novel sequence was computed, and it was not significantly different from chance level (*M* = 48.6%, *SD* = 19.26), *t*(19)= -.325, *p* >.05.

Discussion

Although non significant results should be interpreted with caution, these findings showed that when newborn infants were required to discriminate between the mirror image of the familiar sequence and a novel sequence, they perceived the two test stimuli as equally novel. This finding showed that even if the mirror sequence held constant the serial position of one element (i.e., the central figure), newborns are not able to recognize the mirror sequence as familiar. The obtained data suggest that, during familiarization phase, infants processed the spatial order sequences presented through different configurations based on the left/right spatial relations between the figures.

Conclusion

Some recent data have demonstrated that even by the first months of life, infants are able to detect and recognize sequences composed by three objects at least (e.g., Leslie & Chen, 2007; Lewkowkicz, 2004). The general purpose of the present study was to investigate the presence of some foundations of detecting ordered sequences of objects in the first days of life. Specifically, this study was aimed to explore newborns' abilities to recognize a spatial order sequence, arranged in according with left/right spatial-relation principles. Evidence from Experiment 6 demonstrated that, when familiarized with spatial order sequences arranged in according with left/right spatial-relation principles, 3-day-old infants prefer a novel spatial sequence. This novelty preference does not appear under condition that infants are familiarized with a random sequence. Moreover, when newborns are familiarized with spatial order sequences, and then they are tested with the mirror image of the familiar sequence paired with a novel sequence, again newborns do not manifest any preference.

Overall, these findings seem to suggest the presence of some fundamental abilities for detecting order sequences at birth, at least when no temporal information are available. Newborns are able to detect a spatial order sequence based on the spatial relations between three elements at least. It could be posited that these visuo-spatial abilities constituted the evolutionary trigger for the elaboration of spatio-temporal sequences, well- demonstrated in 4-month-old infants (Lewkowicz, 2004).

Results from Study 1 together with those obtained in Study 2 fit well with the proposal of the Object-file models, supporting the hypothesis that numerical abilities may came from some general visuo-spatial abilities such as to categorize visuo-spatial information and to detect ordered spatial sequence.

Furthermore, these data give some important indications on the capacity of visual short-term memory store in the first days of life. In fact, to be able to perform the task, newborns would be memorized the different geometrical figures and their serial positions within the spatial order sequence.

Consequently, results of Study 2 put forward some important implications, involved in another aspect of Object-file models: the comparison process 1-to-1 in short-term memory store. Once infants have individuated and represented objects as discrete entities, formed categorical representations of spatial relations between objects, and detected ordered sequences (Simon, 1999), the numerosity of the set is extracted from a 1-to-1 comparison in short-term memory store (Kahneman & Treisman, 1984) (see Chapter 3).

Chapter 6

Ordinal representations of continuous magnitude at birth and in the first months of life

As it is previously reported (see Chapter 3), the Analog magnitude models posit that cognitive system is endowed with an inborn and biologically determined predisposition to elaborate numerical information (e.g., Wynn, 1992; Spleke & Dehaene, 1999). These models hypothesize that numerosities are represented as a single continuous magnitude that is proportional to the number value it represents, obeying Weber's law and being subject to ratio effects (i.e., distance effect and size effect) (Deahene & Changeux, 1993; Gelman & Gallistel, 2000).

Recently, it has been proposed a new theory (i.e., ATOM) that expands the analog magnitude representations' application to those dimensions that can be experienced as "more than" and "less than": time, space, and quantity (Walsh, 2003). Four aspects distinguish this new theory: 1) involving ordinal processing of magnitudes, 2) obeying Weber's law, 3) operating from birth, and 4) proposing that the apparent specialization for time, space, and quantity develops from a generalized magnitude system (Walsh, 2003).

Only a handful of studies have directly addressed the development of ordinal numerical knowledge in the first months of life (e.g., Brannon, 2002; Cooper, 1984; Feigenson, Carey, & Hauser, 2002; McCrink & Wynn, 2004; Wynn, 1992, 1998) suggesting that at least from 9 months of age, infants are able to detect and elaborate spatial ordinal information (i.e., area). These results converge with the numerous evidence that show that 6-month-old infants are able to represent discrete quantity as well as continuous quantity, as time and space, presenting the same ratio effects (i.e., 1:2 is the smallest discriminable ratio between magnitudes) (e.g., Brannon, Lutz, & Cordes, 2006; Clearfield, 2003; Xu, Spelke & Goddard, 2005). Altogether, the data reviewed strengthen the ATOM model's suggestions of an inborn ordinal representational system of magnitudes, which might precede the numerical representation of spatial magnitudes (Brannon, 2002).

The topic of this chapter will be to investigate the nature and the development of infants' abilities to process spatial ordinal magnitudes (i.e., area) in the first months of life. More specifically, the hypothesis that ordinal knowledge of continuous magnitude might be present in the early first months of life will be investigated. To this purpose, three experiments will be carried out with newborns and 3-month-old infants, using familiarization techniques. Newborns' (Experiment 8) and 3-month-olds' (Experiment 9) ability to discriminate between a monotonic continuous magnitude ordinal sequence (e.g., going from the smallest magnitudes to the largest) and a non-monotonic sequence (random order) will be explored. Furthermore, newborns' discrimination of ordinal sequences will be tested using habituation technique (Experiment 10)

Experiment 8

The goal of Experiment 8 was to investigate whether newborns are able to recognize a spatial sequence arranged in according with ordinal principles. Babies were familiarized with a configuration composed by three figures which had the same geometrical shape (e.g., square), but which presented different size (i.e., 4, 12, and 36 cm^2). During the test phase two novel configurations were simultaneously presented: Both configurations shared a new geometrical shape (i.e., rhombus), however only in one configuration the familiar monotonic sequence was maintained, whereas in the other configuration a random sequence was presented. It was hypothesized that if newborns are able to detect the spatial sequence arranged in according of ordinal principles, then they should look longer at the non-monotonic sequence.

Method

Participants

Six-teen healthy, full-term newborn infants (mean age = 40.1 hr, *SD* = 16.4) were recruited at the maternity ward of the Paediatric Clinic of the University of Padova. All infants met the screening criteria of normal delivery, a mean birth weight of 3397 g (*SD* = 489), and a 5 min Apgar score above 7. One infant did not complete testing due to fussiness, and one presented a strong position bias during the preference test phase, looking 80% of the time in one direction. Therefore, the final sample consisted of 14 infants (9 female, 5 male), randomly assigned to two different familiarization conditions: Ascending monotonic condition and descending monotonic condition.

Stimuli

The stimuli were created using the software Paint Shop Pro 7.02. Each configuration was composed by three black rectangles (8.67 cm wide x 9.17 cm high; about 16.57° x 17.53°) depicted on a grey background (27.5 cm wide x

10.67 cm high; about 52.5° x 20.4°), with a distance of 0.5 cm (about 0.96°) between them. A white geometrical shape was centered in each rectangle. The shapes used during the familiarization phase were triangle, circle, and square. In each sequence, the same geometrical shape was presented in three different sizes (i.e., area): The biggest shapes presented an area of 36 cm^2, the medium 12 cm^2, and the smallest 4 cm^2, regardless of the specific geometrical shape used (Figure 1).

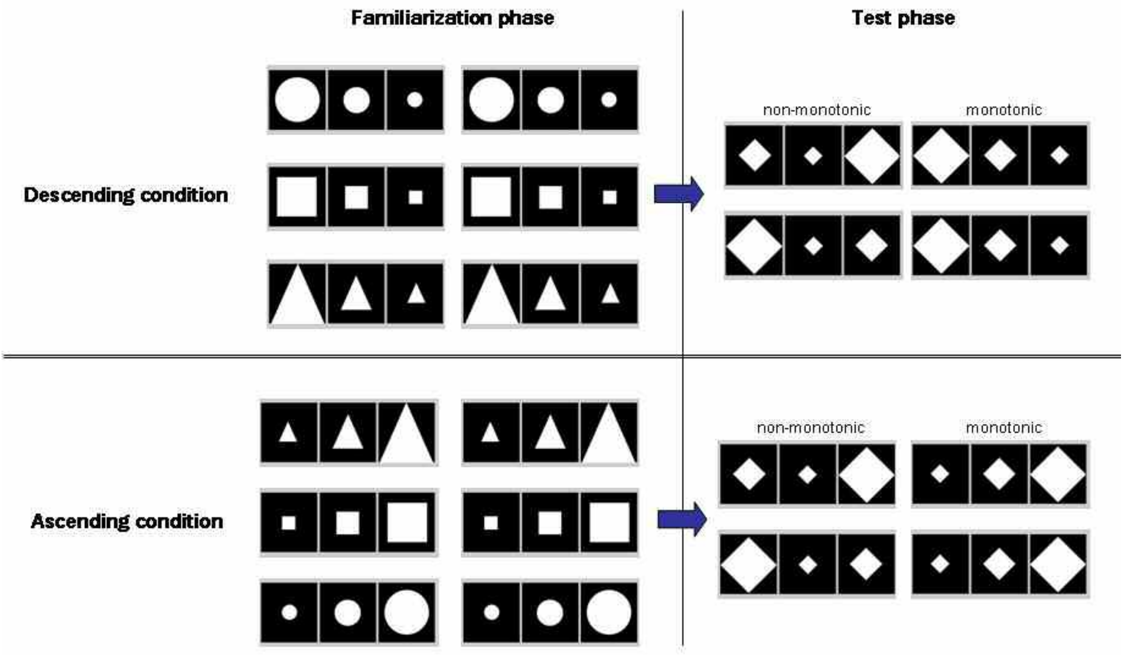

Figure 33: Sample of the stimuli used in Experiment 8.

Four of the presented sequences, referred to as belonging to the ascending monotonic condition, depicted the shapes from the smallest to the biggest from left to right. Similarly, the four referred to as belonging to the descending monotonic condition, depicted the shapes from the biggest to the smallest from left to right (Figure 1). The stimuli used in the test phase were a sequence of monotonic or non-monotonic rhombus. The non-monotonic sequences, used as novel stimulus in test phase, presented three rhombuses in a random order and they could present two different sequences: medium, smallest, and biggest (MSB non-monotonic sequence) or biggest, smallest, and medium (BSM non-monotonic sequence).

Apparatus

The infant was placed on an experimenter's lap, in front of a black panel, at a distance of about 30 cm. The panel had two square holes where the black screens of two computer monitors appeared. Infant's eyes were aligned with a red flickering LED, located in the centre of the screen. The LED was used to attract the infant's gaze at the start of both the familiarization and preference test phases and between each familiarization trial, subtended about 2° of a visual angle and, when turned on, blinked at a rate of 500 ms on and 500 ms off. Stimuli were projected at a distance of 4 cm from the central LED. To prevent interference from irrelevant distracters, two white panels placed on both sides of the infant limited peripheral vision.

Procedure

The procedure used in Brannon's study (2002) was partially replicated. However , based on the fragile perceptual and attentive competencies present at birth in the present study the procedure utilized by Brannon (2002) was simplified in two different ways:

1) Temporal information was excluded and only spatial information were preserved. Therefore, display simultaneously showed three different size figures (Figure 1).

2) Infants were required to recognize simply the presence or the absence of an ordinal relation between magnitudes, rather than the specific direction of the ordinal relation.

The familiarization phase began only when the infant was apparently at ease and his/her gaze was properly aligned with the central LED. Half of newborns (7 infants) were familiarized with three different ascending monotonic sequences (*Ascending condition*) and the other half (7 infants) with three different descending monotonic sequences (*Descending condition*). An experimenter recorded the duration of each fixation on the stimulus by pressing a push button that was connected to the computer. When a 20-sec total fixation time criterion was reached, the stimulus was automatically turned off and the central LED were turned on. As soon as the infants were realigned to the central discs, the subsequent trial began. At the end of the familiarization trials, a preference test phase started. Each infant was given two paired presentation of test stimuli. During the test phase, newborns were tested with two novel sequences: Both of them were composed by novel geometrical shapes (i.e., rhombus), but one presented the familiar monotonic sequence and the other a non-monotonic one. Half of the babies were tested with MSB non-monotonic sequence, and half with BSM non-monotonic sequence (Figure 1).

The two paired-stimuli were always shown in both the left and right positions, the positions being reversed from presentation 1 to presentation 2. The initial left-right order of presentation was counterbalanced across subjects. The experimenter recorded the duration of infant's fixations on each stimulus by pressing two different push buttons. A presentation lasted until each stimulus had been fixated at least once and a total of 20 sec. of looking had been accumulated.

Results

Preliminary statistical analyses showed no significant effect or interactions involving the distinct familiarization condition (i.e., Ascending condition vs. Descending condition, *t* (13) = 1.24, *p* > .05), and involving the different test non-monotonic sequences (i.e., MSB non-monotonic sequence vs. BSM non-monotonic sequence, *t* (13) = 1.18, *p* >.05). Therefore, data were collapsed across these factors.

Two paired-sample t tests were performed to determine whether newborns' number of discrete looks and total fixation time differed for the two stimuli presented. The difference was not significant for either dependent variable. Newborns looked 5.77 times (*SD* 1.3) at the novel non-monotonic sequence and 5.85 times (*SD* 2.11) at the monotonic sequence, *t* (13) = -.143, *p* > .05. Similarly, they spent 23.63 s (*SD* 9.7) and 22.87 s (*SD* 10.3) looking at the non-monotonic and at the monotonic pattern respectively, *t* (13)= .141, *p*>.05.

In addiction, a novelty preference score (percentage) was computed for each infants. Thus is, each infant's looking time at the novel non-monotonic sequence during the two test presentations was divided by the total looking time to both test stimuli over the two presentations and converted into percentage score. Hence, only scores significantly above 50% indicated a preference for the novel stimulus. Preference scores for the novel non-monotonic sequence (51.08%, *SD* = 20.9) were not significantly above chance *t* (13) = .186, *p* > .05.

Discussion

Overall, collected data demonstrated that newborns are not able to recognize a common perceptual characteristics shared by a sequences arranged in according with ordinal principles. These results suggest that quantity information is elaborated in a different way with respect to elaboration of spatial information. In fact, newborns ability to recognize spatial sequences well demonstrated in Study 2 fails when quantity information is introduced, regardless the same procedure was used.

Experiment 9

The aim of Experiment 9 was to test whether the ability to detect and elaborate a spatial sequence arranged in according with ordinal principles, is present at 3 months of age. For this purpose, Experiment 9 was replicated with 3-month-old infants.

Method

Participants

The experiment was carried out at Centre of Cognitive Neuroscience, Duke University. Participants were 23 healthy full-term 3-month-old infants (mean age: 3 months 1 day, range: 2 months 15 days – 3 months 17 days). Seven infants were not included in the final sample because of a strong position bias during the preference test phase, looking 80% of the time in one direction (5 infants), or due to technical problems (2 infants). Thus, the final sample consisted of 16 infants (9 females, 7 males), randomly assigned to two different familiarization conditions: ascending monotonic condition and descending monotonic condition.

Stimuli

The stimuli employed in the present experiment were identical to those used in Experiment 8 (Figure 1).

Apparatus

Infants were seated in a car seat 60 cm far from two computer monitors resting on a stage surrounded by blue fabric. Parents were seated next to their infants and instructed to keep their eyes closed and to refrain from talking to, touching, or otherwise interacting with their infant for the duration of the experiment.

Infant's eyes were aligned with the middle line of a zooming colored windmill projected in the center of each computer screen (Figure 2). The zooming windmills were used to attract the infant's gaze at the start of each familiarization trial at the beginning of test phases.

Figure 34: A frame of the windmill-attractor movie.

Procedure

The procedure adopted in the previous experiment was used. However since data of Experiment 9 were collected in a different laboratory to respect to those obtained in Experiment 8, the two procedures are not exactly the same.

The infant was seated on a car-seat in front of two computer monitors, on which a brief Sesame Street cartoon was projected (Figure 3), to attract baby's attention to the computer screens and to make her/him at ease. The total duration of the cartoon was of 51 sec, but the experimenter could stop it as soon as the baby was judged ready for starting the first session.

Figure 35: A frame of Sesame Street cartoon presented at the beginning of Experiment 9.

Therefore, the windmill-attractor was projected and the familiarization phase began only when the infant was properly aligned with the middle line of the attractors. As in Experiment 9, infants were distributed in two familiarization conditions: *Ascending condition* and *Descending condition.* A microcamera monitoring the infant's face and feed directly from the stimuli presentation computer were multiplexed onto a TV monitor and VCR. One experienced experimenter blind to the experimental condition recorded the infants' looking behavior while viewing the live video with the display occluded. Looking behavior was recorded by holding a button down when the infant was looking at the computer monitor and letting go when the infant looked away. The button input was fed into a Real Basic program, which calculated when a 15-sec total fixation time criterion was reached or when 60 sec were spent. Babies that did not reached the 15-sec time criterion in every familiarization session were not included in the final sample. The total fixation time criteria employed in the present experiment came from the procedure commonly used with 3-month-old infants familiarization tasks (e.g., Quinn, 2004). Then, the stimulus was automatically turned off and the windmill- attractors were turned on. As soon as the infants were realigned to the attractors, the subsequent trial began.

At the end of the familiarization trials, a preference test phase started. Each infant was given two paired presentation of test stimuli. As in Experiment 8, during the test phase, they were tested with two novel sequences, one of which presented a monotonic sequence and the other a non-monotonic one. Half of the babies were tested with MSB non-monotonic sequence, and half with BSM non-monotonic sequence (Figure 1).

The two paired-stimuli were always shown in both the left and right positions, the positions being reversed from presentation 1 to presentation 2. The initial left-right order of presentation was counterbalanced across subjects. The experimenter recorded the duration of infant's fixations on each stimulus by pressing two different push buttons. A presentation lasted until each stimulus had been fixated at least once and a total of 10 sec. of looking had been accumulated. Each trial ended after 60 sec if 10-sec of looking time criterion was not reached. As above, these criteria were established based on the literature on familiarization technique with 3-month-old infants (e.g., Quinn, 2004).

During the different sessions, the experimenter could play two different sounds, originated between the two computer screens, for attracting infant's attention to the displays.

Moreover, a second coder unaware of the stimuli presented subsequently analyzed videotapes of eye movements throughout the trial frame by frame. Inter-coder agreement was 1.00 (Cohen Kappa) for the number of orienting responses toward the stimuli and 0.92 (Pearson correlation) for total fixation time.

Results

Preliminary statistical analyses showed no significant effect or interactions involving the distinct familiarization condition (i.e., Ascending condition vs. Descending condition, t (15) = .608, $p > .05$), and involving the different test non-monotonic sequences (i.e., MSB non-monotonic sequence vs. BSM non-monotonic sequence, t (15) = .571, $p > .05$). Consequently, data were collapsed across these factors.

The average number of fixations to orient toward the two stimuli during the test phase was calculated. Infants did not look more often to the novel non-monotonic stimulus (5 average number of orientations, *SD* 1.75) than to the familiar monotonic one (4.75 average number of orientations, *SD* 2.595), t (15) = .513, $p > .05$. However, they looked longer at novel non-monotonic sequence (*M* 10.42 s, *SD* 4.7) than at monotonic sequence (*M* 7.49, *SD* 3.6), t (15) = 2.368, $p <.033$.

As in the previous experiments a novelty preference score (percentage) was computed for each infants, showing that the preference score for the novel stimulus (58.15%, *SD* = 13.6) was significantly above chance t (15) =2.375, $p < .032$.

Discussion

Collected data demonstrated that 3-month-old infants were able to recognize a perceptual similarity between monotonic sequences. This evidence suggests that at 3 months of age, infants are able to recognize an ordered spatial sequence composed by different sizes, arranged in according with ordinal principles.

These results replicate those obtained by Brannon’s study (2002) even if some relevant differences between the two studies are present.

For example, white and black stimuli rather than rainbow shapes were utilized, in order to facilitate the detection of the configuration to the very immature visual system of young infants, ill-equipped with acuity, contrast sensitivity, and color sensitivity (Banks & Bennet, 1988; Slater, & Johnson, 1998).

Moreover, a 1:3 ratio instead than the 1:2 ratio used by Brannon was utilized. Finally in this study any temporal information was enclosed and only spatial information were preserved. Spatial information was emphasized, depicting each figure in a single black frame, generating spatial landmarks between each figure (Figure 1).

In spite of these differences, we believe that data of Experiment 9 suggest that even at 3 months of age infants posses ordinal abilities.

Conversely, newborns did not show this ability. Experiment 8 showed that newborns did not discriminate between a stimulus depicting a higher familiar monotonic sequence and a stimulus depicting a non-monotonic sequence.

However, an alternative interpretation of newborns’ data might be proposed. In the experiment described above, during the test phase, newborns were required to discriminate between stimuli very similar, that is between stimuli belonged to the same perceptual category. Nonetheless, some studies have demonstrated that at birth infants are able to detect perceptual similarity between stimuli belonged to different perceptual categories (Quinn, Slater, Brown, & Hayes, 2001; Turati & Simion, in press), whereas this capacity fails in matching stimuli belonged to the same perceptual category (Quinn, et al., 2001). In other words, it seems that newborn is only able to form global-level perceptual categories, thus are categories perceptually different between them (i.e., closed vs. open geometric forms). For instance, even if newborns are able to discriminate between stimuli perceptually very similar (e.g., to discriminate between squares with different contours), they are not able to trait these stimuli as belonging to the same class (i.e., square class) when they are required to match them with an exemplar of a new class (i.e., circle class), belonging to the same basic-level category (i.e., closed geometric forms). Quinn and colleagues (2001) posit that the ability to form only global-level perceptual categories derives from the fact that global-level categories include stimuli easily distinguishable even for the newborn's immature visual system, whereas the basic-level categories include instances too similar.

In the light of these data, it has been hypothesized that the ability to recognize an ordered sequence might be facilitate when newborn is required to discriminate, instead to categorize, a monotonic sequence from a non-monotonic sequence.

Experiment 10

The aim of Experiment 10 was to verify whether newborn infants are able to detect and elaborate a spatial sequence arranged in accordance with ordinal principles, in an easier task, thus is using only one monotonic sequence during the familiarization phase. It was predicted that if newborns were able to extract and recognize a basic perceptual invariance related to the ordinal relations between sizes, during test phase, they would look longer to the non-monotonic sequence.

This result would confirm also that newborns were able to detect a difference between sizes presented within a sequence. Alternatively, if newborns were not able to extract and recognize a basic perceptual invariance between monotonic sequences, they would perceive the two test stimuli as equally novel, not showing any novelty preference in test phase.

Method

Participants

Twenty-two healthy, full-term newborn infants (mean age = 42 hr, *SD* = 18.2) were recruited at the maternity ward of the Paediatric Clinic of the University of Padova. The screening criteria were the same as those used in the previous experiments. Six infants were not included in the final sample: two did not complete testing due to fussiness, three presented a position preference and one was excluded for technical problems. Therefore, the final sample consisted of 19 infants (7 females, 12 males), randomly assigned to 2 different habituation conditions. About half of sample (10 infants) were habituated to ascending monotonic sequence, and the other half (9 infants) were habituated to descending monotonic sequence.

Infants were tested only if awake and in an alert state, after the parents gave their informed consent.

Stimuli and apparatus

Stimuli and apparatus were identical to those employed in Experiment 8, with the exception that in this study only sequence composed by triangles and rhombus were used (Figure 4).

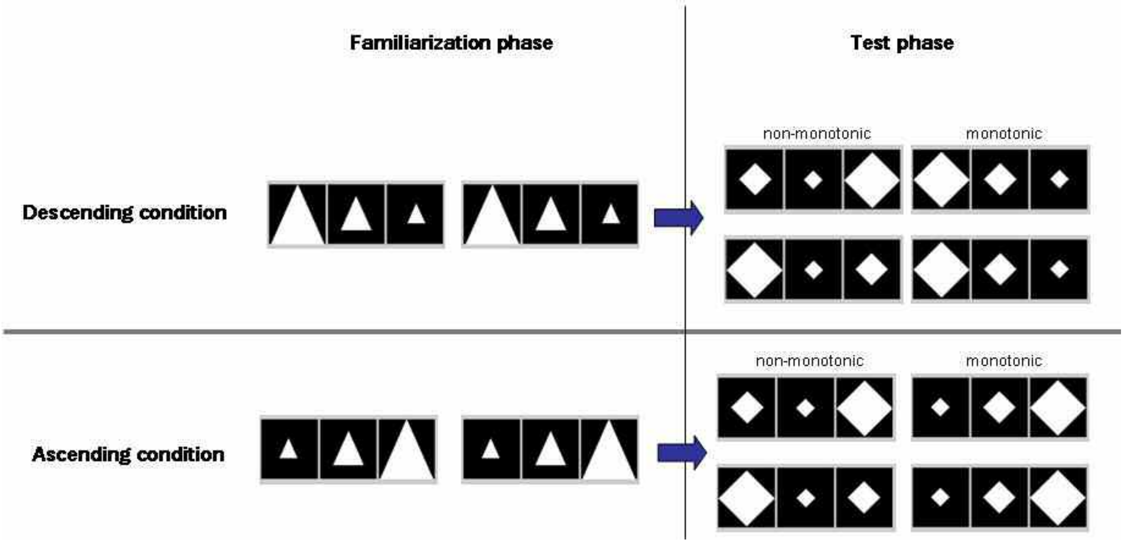

Figure 36: Sample of the stimuli used in Experiment 10.

Procedure

All newborns were habituated to a monotonic sequence; about half of them (10) belonged to the *Ascending condition*, and the other half (9) to the *Descending condition*. In both conditions (i.e., Ascending or Descending), half newborns saw a sequence composed by triangles, and the other half saw a sequence composed by rhombuses (Figure 4).

As soon as the infants were apparently at ease and their gaze was properly aligned with the central LED, the habituation phase was begun, by pressing a key on the keyboard. This automatically turned off the central fixation point and activated the habituation stimuli. A monotonic sequence was projected bilaterally, on each side (i.e. left and right) of the central LED.

The duration of each fixation was coded on-line by an experimenter, who could not see the display and was blind with respect to the specific left/right position of the familiar and novel stimuli in test trial. A look-away criterion of 2 s was used to determine the end of each fixation. In order to be sure that this criterion was strictly respected, the software was planned so that it automatically compacted two consecutive fixations that were not separated by a time interval of at least 2 s.

The stimuli remained on the screen until the habituation criterion was reached. The infant was judged to have been habituated when, from the fourth fixation on, the sum of any three consecutive fixations was 50% or less than the total of the first three (Horowitz, Paden, Bhana, & Self, 1972). Only when the habituation criterion was reached, the stimulus was automatically turned off and the central fixation point was turned on.

As soon as the infant's gaze was realigned to the central fixation point, a preference test phase started. Each infant was given two paired presentations of the test stimuli. During each presentation, infants were simultaneously presented with the familiar stimulus (i.e., monotonic sequence) and a novel stimulus in which the shapes appeared in a random order (i.e., non-monotonic sequence). The two paired stimuli were always shown in both left and right positions, the position being reversed from presentation 1 to presentation 2. The central fixation point flickered between the first and the second test trials, but did not flicker when the test stimuli were on.

The experimenter recorded the duration of each fixation on the stimuli by pressing two different push buttons depending on whether infants looked at the right or left position. Each presentation lasted when a total of 20s of looking to the novel and/or familiar stimuli had been accumulated.

Results

All the infants reached the habituation criterion. The average total fixation time to reach habituation was 108.72 s (*SD* = 45.77). The average number of fixations during the habituation phase was 8.58 (*SD* = 3.78). Preliminary statistical analyses showed no significant effect or interactions involving the distinct conditions (Ascending condition vs. Descending condition, *t* (18) = .112, *p* > .05), and the distinct shapes used (triangle vs. rhombus, *t* (18) = .154, *p*, > .05). As a consequence, data were collapsed across these factors.

The average number of fixations to orient toward the two stimuli during the test phase was calculated. Newborns did not look more often to the novel non-monotonic stimulus (5.00 average number of orientations, *SD* 1.8) than to the familiar monotonic one (5.47 average number of orientations, *SD* 1.95), *t* (18) = -.891, *p* > .05. However, total fixation time was longer for the monotonic sequence (*M* 27.82 s, *SD* 6.96) than for the novel non-monotonic sequence (*M* 19.69, *SD* 7.6), *t* (18) = -2.763, *p*<.014.

In order to test whether newborns were able to recognize the monotonic sequence to which they were habituated, a novelty preference score (percentage) was computed. As in the previous experiment, each infant's looking time at the new stimulus during the two presentation sessions was divided by the total looking time at both stimuli, and subsequently converted into a percentage score. To determine whether the novelty preference score was significantly different from the chance level of 50%, a one-sample t-test was applied. Preference scores for the stimulus with the novel position of the square were significantly above chance (*M* = 41.16%, *SD* = 12.16), *t* (18) = -2.988, *p*< .009.

Discussion

The results of Experiment 11 demonstrate that newborns showed a preference for the familiar monotonic sequence, at least in lower perceptual-variability.

This finding appears in line with previous studies that tested newborns' ability to recognize a learned stimulus over strong modifications, such as rotation, or photonegative and size transformations, and obtained a familiarity preference (Walton, et al., 1992; Walton, Amstrong, & Bower, 1997; Gava, Valenza, Turati & de Schonen, in press). These results suggest that a preference for the familiar stimulus reflects a difficulty to recognize the modified familiar stimulus: Newborns react to significant perceptual changes in the visual stimulus with a persistent and extensive visual exploration of the familiar configuration. Indeed, models on infants' habituation profile state that, at the beginning of the recognition process, infants look longer at the familiar stimulus and that, only later, when recognition is well established, a shift from a familiarity to a novelty preference is observed (Roder, Bushnell, & Sasseville, 2000; Hunter, Ames, & Koopman, 1983; Rose, Gottfried, Melloy-Carminar, & Bridger, 1982; Fantz, 1964; Sirios & Mareschal, 2002, 2004). Since the perceptual difference between geometrical shapes presented in habituation phase and the ones shown in test phase produces a very important perceptual discrepancy, it might be inferred that newborns had difficulty to recognize the modified familiar monotonic sequence, fixating the familiar sequence for a prolonged period. These findings suggest that newborns are able to detect a perceptual invariant monotonic sequence, but that this ability is not yet enough develop to produce a novelty preference. Consequently, the non-preference obtained in Experiment 8 might be not due to newborns' perceptual inability to process the ordinal continuous sequences presented, but it might be a consequence of a heavy requesting in memory and/or attentional cognitive resources in processing ordinal information, which is overcome 3 months later.

Conclusions

In conclusion, Study 3 has demonstrated that from birth some foundations of ordinal knowledge of continuous magnitude are present. Moreover, it has highlighted that ordinal competence develops in the first 3 months of age, at least for continuous magnitudes.

Altogether, the results of Study 3 demonstrated a very early ordinal ability with respect to evidence present in literature (Brannon, 2002). It is relevant to stress however that these results narrowed to the specific stimuli used, that is spatial sequences lacking of any temporal attributes .

Findings from this study are consistent with the ATOM model's proposal that time, space and quantity are part of a generalized magnitude system, which applies to those dimensions that can be experienced as “more than” and “less than” (Walsh, 2003).

However, it is necessary to investigate the nature and the interactions of ordinal knowledge of numerosities and time information for obtaining a more robust confirmation of this model.

General conclusions

Over the past 30 years, several studies have provided evidence that from 6 months of life young infants can discriminate the numerosity both of large and small collections (i.e., up to three elements). Two predominant models of the development and structure of numerical knowledge in the first year and months of life were proposed, that posit two inborn system implied in numerical performance: An object-tracking system for object representation, called Object-file system (e.g., Carey, 1998; Uller, et al.1999), and a numerical estimation system, called Analog magnitude system (e.g., Dehaene & Changeux, 1993). Recently, a new theory (i.e., ATOM model) has extended the application of analog magnitude system to continuous as well as numerical quantities, based on ordinal knowledge (Walsh, 2003). These systems differ considerably: Object-file system detects and represents objects with their spatio-temporal features and only subsequently extracts numerosity information, and presents the constriction of the absolute set size ($n < 4$); Analog magnitude system is specifically implied in the elaboration of quantity information, and its application is modulated by the numerical ratio of the values compared (i.e., ratio effects).

Strikingly, despite the assumption that both of these systems are innate, no studies have explored if the specific abilities required for object representation by Object-file system (e.g., Simon, 1999) and for quantity elaboration by Analog magnitude system (e.g., Gelman & Gallistel, 1978; Walsh, 2003) are present in early life (but see, Antell & Keating, 1983). Starting from this lack, the present research has intended to contribute to the study of numerical abilities' origins. For this purpose, three different studies have explored the presence of some foundations of object representation, involved by Object-file system (Study 1 and 2), and quantity processing, involved by Analog magnitude system and ATOM model (Study 3), in the first months of life.

Study 1 has investigated the presence to form categorical representations of spatial relationships at birth. Five different experiments have demonstrated that newborns not only are able to discriminate an object's position with respect to a landmark (Experiment 1, 2, and 5), but also to recognize a perceptual invariance between left/right spatial relations in condition of low (Experiment 3) and high-perceptual variability (Experiment 4) of the object. Altogether, evidence from Study 1 reveals that from birth, infants are able to treat spatial relationship between objects in a categorical manner; at least when the spatial relationship involves only two objects and they are easily discriminable from each other. These results suggest that from birth human cognitive system detects, processes and represents object based on their visuo-spatial features.

Study 2 supports and extends these results showing that newborns are able to detect spatial ordered sequences of objects. Specifically, the results of Experiments 6 and 7 have shown that 3-day-old infants are able to detect a spatial order sequence based on the spatial relations between three elements at least, when temporal information are not available.

Altogether, the findings obtained in Study 1 and Study 2 support the hypothesis of the existence of an early general and automatic attentive system of object tracking based on visuo-spatial processing (e.g., Scholl & Leslie, 1999; Simon, 1997; Uller, et al., 1999). Furthermore, the data obtained in Study 2 give some important indications on the capacity of visual memory store in the first days of life, which are involved in another aspect of Object-file system: the comparison process 1-to-1. This process is directly involved in the implicit extraction of the numerosity of a set. Given that the discrimination of small numerosities implies object-file representations (e.g., Feigenson & Carey, 2005; Spelke & Kinzler, 2007; for a review see Chapter 3), and given that newborns show the ability to represent objects in accordance with object-file representations, it could be expected that even newborns could be able to discriminate small numerosities. Future researches should be addressed to investigate the presence of this ability. For instance, after been familiarized with visual patterns that display small set of elements (e.g. 3 dots) in different spatial arrangements, newborns should prefer a pattern with a novel numerosity (e.g. 2 dots) instead that a new exemplar of the familiar numerosity. Crucially, continuous variables should be strictly controlled through the trials in order to be sure that infants discriminate the two configurations only based on numerical information.

On quantity processing, Study 3 has explored the nature and the development of infants' abilities to process spatial ordinal magnitudes (i.e., area) in the early months of life. To this end, the presence and the features of a representational system of ordinal continuous magnitudes at birth and at 3 months of life have been tested. Specifically, Study 3 has ascertained when the ability to detect ordered sequence of continuous magnitudes arises. Collected data have demonstrated that 3-month-old infants (Experiment 9) were able to discriminate between a monotonic continuous magnitude ordinal sequence (e.g., going from the smallest magnitudes to the largest) and a non-monotonic sequence (i.e., random order). This evidence suggests that at 3 months of age, infants are able to recognize an ordered spatial sequence composed by different sizes, arranged in accordance with ordinal principles. Conversely, newborns did not show this ability (see Experiment 8), even if they have showed the ability to recognize a spatial ordinal magnitude sequence when they are required to discriminate a monotonic from a non-monotonic sequence, in conditions of lower perceptual variability (Experiment 10).

Altogether, the data from Study 3 have demonstrated that some abilities of detecting ordinal continuous magnitude are present even in the first days of life, earlier than evidenced in literature (Brannon, 2002). Moreover, these data allow outlining the developmental trend of ordinal knowledge in the first months of life, highlighting that ordinal competences develop in the first 3 months of life, at least for continuous magnitudes. Even if these findings have to be limited to the specific stimuli used, they strengthen the hypothesis of the existence of an early and general representational system of non-numerical magnitudes, proposed by ATOM model (Walsh, 2003). Future researches could be addressed in order to discover whether the ability to process continuous ordinal sequences can be extended to discrete sequences. For example, infants familiarized with an ordinal sequence composed by discrete quantity (i.e., number of elements: 4, 12, 36), with all continuous variables controlled, should yield the same performance manifested with continuous ordinal sequence.

In conclusion, overall the present research has provided evidence that from birth infants posses some visuo-spatial competencies, such as to form categorical representation of spatial relation and to detect spatial order sequences, that fail when quantity information are introduce, as in the case of detecting spatial order sequences of continuous magnitudes. These data seem suggest that, at birth, the human cognitive system elaborates objects, whereas the ability to elaborate quantities appears very fragile. Consequently if the capacity for objects processing develops before quantity processing, it is arguable that from the first days of life, infants posses the abilities necessary to elaborate small numerosities, yielded by an Object-file system, and that subsequently the ability to elaborate analog magnitudes develops. Future researches should be addressed to solve this open question.

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