UNIVERSITY OF TRENTO

DEPARTMENT OF PSYCHOLOGY AND COGNITIVE SCIENCES

DOCTORAL SCHOOL IN
PSYCHOLOGICAL SCIENCES AND EDUCATION

Doctoral Dissertation in the subject of Cognitive Sciences

The two core systems of numerical cognition in infants and developmental dyscalculia

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GENERAL INTRODUCTION

Two different systems grounding numerical cognition

Numbers are everywhere. We spontaneously use numbers in our everyday life, buying something at the market, interpreting a graph, looking at the clock and calculating how many minutes to go for a meeting. These operations are done automatically and almost without awareness.

But how do we acquire this knowledge? How do children learn such basic mathematical abilities? How do they make sense of numbers? Is the sense of number innate or acquired? Why do some children present difficulties only in the mathematical domain and not in other areas?

One of the most basic numerical skill that humans display early in life and that they share with most non-human animals, with no need for language or formal instruction, is the ability to quantify sets on the basis of the number of objects they contain. It has been recently suggested that there are two distinct systems at the basis of this intuitive quantification skill: that of approximate number estimation and that of precise number quantification (Feigenson, Dehaene, & Spelke, 2004; Burr et al., 2010; Hyde, 2011; Piazza, 2010; Piazza et al., 2011; Cutini, Scatturin, Moro, & Zorzi, 2014). These two systems are respectively defined as Approximate Number System or ANS (Halberda et al., 2008; Dehaene, 1997) and Subitizing, or Object Tracking System, OTS (Piazza 2010; Trick & Pylyshyn, 1994; Xu, Spelke, & Goddard, 2005;). In the following sections I will describe each of them with their main features.

1. The Approximate Number System (ANS)

1.1 Development of ANS during infancy

The Approximate Number System[1] (ANS) is a system that allows the estimation and discrimination of different numerosities without counting. It is thought to be present very early in development (e.g. Izard, Sann, Spelke, & Streri, 2009), shared with non-human species (e.g. Brannon & Terrace, 1998; Cantlon & Brannon, 2006; Feigenson, Dehaene, & Spelke, 2004; Gelman & Gallistel, 2004; Nieder, Freedman, & Miller, 2002; Nieder & Miller, 2003; Rugani et al., 2007) and active in individuals from cultures with a limited counting system (e.g. Pica, Lemer, Izard, & Dehaene, 2004). Furthermore, the ANS increases in precision during the life-span, and it is ratio-dependent: the capacity to discriminate two arrays of different numerosities depends on their ratio. In the case of high ratios (i.e. 1:2 ratio) it is easy for adults to discriminate the difference between two numerosities and to judge which one contains more dots, while in the case of small ratios the task becomes more difficult (for example 7:8 ratio). The minimal discriminable difference can be described in terms of Weber fraction (w). The Weber fraction is the difference between the two closer discriminable numerosities normalized by the magnitude of the smallest one. Performance in comparison or in discrimination of dot patterns (or sequences of visual or auditory objects) can also be fitted with psychophysical functions, where a key parameter (the slope of the psychometric function) may be interpreted as

[1] Some authors refer to this system as Analog Magnitude System (e.g. Carey, 2009; Wagner & Johnson, 2011), due to it's ratio-dependent signature, indicating an internal analogue (continuous, non-discrete) representation.

reflecting the precision of the internal representation of estimated numerical magnitude. The weber fraction can also be estimated using this approach. The weber fraction is an inverse index of precision: better performances in dots comparison/matching task (where you have to choose which one of the two arrays contains more dots, or to evaluate the numerical equivalence across sets) corresponds to a lower Weber fraction and vice versa.

Recent research focused on the development of ANS and found its activation from the first hours of life (Izard et al., 2009). Newborns were first familiarized with fixed number of sequences of 4 or 12 syllables (see Fig. 1), and then were shown images that could either match with the number of syllables heard or not. Infants looked significantly longer at the image that was congruent with the auditory sequence compared to the incongruent image. The authors found this preference only for a numerical ratio of 1:3, but not for a ratio of 1:2. Using this inter-modal paradigm, they provided evidence for a numerical discrimination that emerges for a ratio of 1:3 but not for closer ratios.

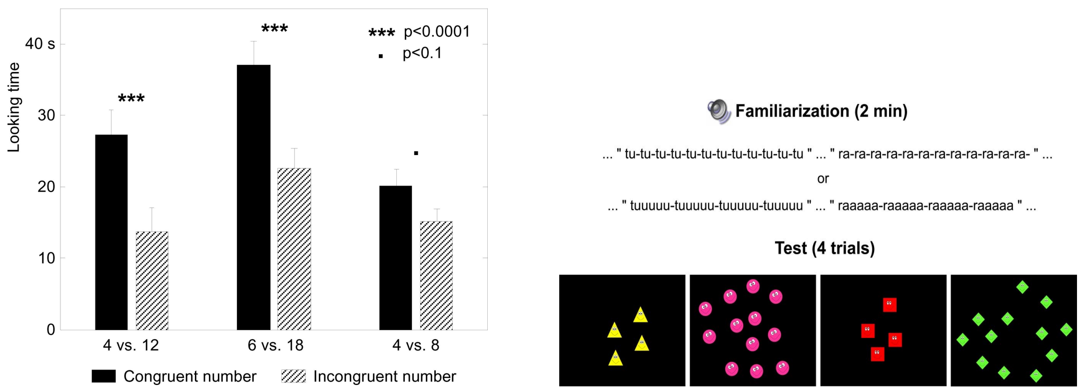

Fig. 1 Schematic illustration of the paradigm used by Izard and colleagues and their results. Newborns looked more at the congruent image with the sound heard in 1:3 ratio but not in 1:2 ratio.

The ANS acuity (the ability to perceive the difference between two numerosities) improves very quickly in the first months of life. Xu and Spelke (2000), using the habituation paradigm, observed that 6-month-old infants looked longer at the numerically new arrays after they had been habituated either with 8 or 16 dots. The numerical acuity at this age is therefore determined by the 1:2 ratio (Xu, Spelke, & Goddard, 2005). Then, it develops from a ratio of 1:2 to a ratio of 2:3 before the end of the first year of life (Lipton & Spelke, 2003): infants of 6 month-old can discriminate 16 versus 8 dots but not between 16 and 12 dots, whereas 9 month-old discriminate both ratios.

In the next steps of development, children progress from the perception of numerosities differing by a 3:4 ratio at the age of 3 years (e.g. 12 dots versus 9 dots) to 5:6 (e.g. 12 dots versus 10 dots) at the age of 6 years, up to 10:11 ratio in adulthood (Halberda & Feigenson, 2008).

More recently, some authors reported a phenomenon defined as "hysteresis" (Odic, Hock, & Halberda, 2014; Wang, Odic, Halberda, & Feigenson, 2016), where this normally thought fixed ratio-dependent acuity can actually be rapidly improved. In one study (Wang, Libertus, & Feigenson, 2018, Fig. 2) 6-months-old infants were trained with 10 trials in the following sequence of ratios 1:6, 1:3, 1:2, 3:5, 3:4, observing a progression on difficulty. After the training trials, participants were presented with two test trials only with the 2:3 ratio. In this case, already at 6 months, infants can discriminate numerosities that differ for a ratio of 2:3. These results show how the ANS can be modulated by previous experience not only in older children (Odic et al., 2014) but also in infants.

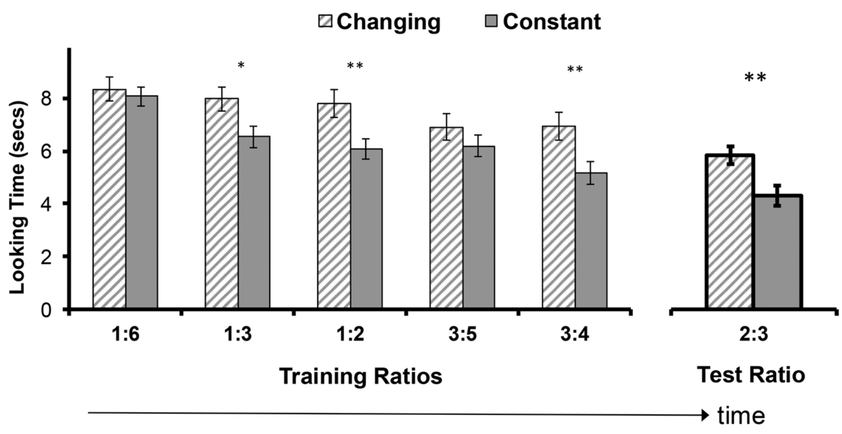

Fig. 2 Results obtained in Wang and colleagues (2018) testing the "ANS hysteresis" with the change detection paradigm.

1.2 The link between ANS and mathematical abilities

The acuity of the ANS is also thought to be predictive of mathematical capacities in pre-school aged children (for a meta-analysis: Schneider et al., 2017). In one study (Libertus, Feigenson, & Halberda, 2013) the authors assessed the ANS acuity, math ability and expressive vocabulary of preschool-aged children in a longitudinal study. They found that early ANS acuity predicted performance in math six months later and this ability was the only predictor above expressive vocabulary, attention and memory span.

Another study investigated this relation. Mazzocco and colleagues (2011) observed ANS precision in 3/4 year-old children with a non-symbolic comparison task; then they measured the same mathematical abilities after two years. The results showed that the ANS precision of 3/4-year-old children predicted their school mathematics performance at 6 years old. All these findings demonstrated the tight correlation between ANS acuity and further mathematical abilities. Other studies found similar results in high school students (Halberda, Mazzocco, & Feigenson, 2008), in college students (Libertus, Odic, & Halberda, 2012) and in gifted adolescents (Wang et al., 2017). Complementary lines of research have also demonstrated improvements in arithmetic performances with ANS specific trainings in college students (Park & Brannon, 2013, 2014) and in pre-schoolers (Park et al., 2016). However, other authors tested 3-to-4-year-old children with 7 months of interval in a numerosity comparison task, counting task, give a number task and symbolic battery and they provided evidence for a predictive role of cardinality proficiency and symbolic number knowledge on accuracy in number comparison. Therefore, the direction of the link between ANS acuity and symbolic skills does not appear so clear (for a review of this relationship: Feigenson, Libertus, & Halberda, 2013).

Moreover, most longitudinal studies (that are key in demonstrating that the ANS is foundational for subsequent language-based math skills) have measured the ANS in children having already approached some form of mathematical education, for example having learnt the verbal counting principles: it is therefore difficult to systematically discern the direction of the causality link between the ANS and symbolic numeracy skills reported. Is the greater acuity the one which leads to better mathematical performances or vice versa? This question is crucial not only to understand which is the basis of math but also to prevent/rehabilitate difficulties in this domain.

To my knowledge, only one study has assessed this relation with a longitudinal study in children before approaching any form of mathematical learning (Starr et al., 2013). The researchers have tried to understand whether the precision of preverbal number sense in the first year of life predicts later mathematical abilities. They used a change detection paradigm to examine ANS acuity: newborns of 6 months observed two streams of different arrays presented on different monitors on the left and on the right of the infant, one screen showed images that change in numerical values while the other stayed numerically fixed and changed only in dot size and arrangement. At 3.5 years of age the children were again assessed in numerical and mathematical capacities. The results demonstrated that ANS acuity at 6 months of age is predictive of math achievement, number word knowledge and numerical acuity at 3.5 years of age.

However, the size of the correlation was small and the numerical ratios used to estimate the ANS acuity at T1 differed from child to child (some were presented with ratios of 1:4, others 1:3, or 1:2), leaving open the possibility that at least some part of the results may reflect the effect of this confounding variable. Other weaknesses of the study involve the infants' age (they were very young with attention span limits) and the different control task used to estimate perception abilities.

In addition to this gap of longitudinal studies in early links between ANS and math, some researchers have failed to find significant correlations (e.g. Holloway, & Ansari, 2009). Other authors (Gilmore et al., 2013) speculated that the correlation actually reflects the capacity to inhibit other non-numerical factors such as the total area occupied. There is therefore a lack in this domain and it is difficult to determine the direction of the link between the preverbal ANS acuity and symbolic numerical abilities.

1.3 The role of ANS in developmental dyscalculia

Developmental dyscalculia (DD) is defined as a specific learning disorder in the mathematical domain and in particular in calculation abilities. According to the Diagnostic and Statistical Manual of Mental Disorders – V (American Psychiatric Association, 2013) individuals with DD present specific impairments in processing numerical information and learning arithmetic facts and the prevalence is estimated from 5% to 15% in the school-aged population. These percentages support the importance and the necessity of making progress in understanding DD. Indeed, the core deficits causing this learning disorder still remain unclear and the literature is composed by various and often contradictory observations. One line of research proposed that one of the causes of DD is a deficit in ANS acuity. Piazza and colleagues (2010) found, for the first time, a strong association between dyscalculia and ANS acuity. In this study, dyscalculic children of ten years of age were tested with a standardized battery probing knowledge of symbolic number, a calculation task and with a dots comparison task (children were asked to indicate which of two arrays contains more dots). The results demonstrated that numerical acuity was severely impaired in children with DD compared to the performance of controls and it was showed 5 years of delay in ANS acuity development. Other studies provided further support to the hypothesis of an ANS deficit as underlying DD (Mazzocco et al., 2011; Mussolin et al., 2010).

Nevertheless, some authors failed to find impairments in non-symbolic numerical acuity (DeSmedt & Gilmore, 2011; Rousselle & Noël, 2007).

Other studies have hypothesized specific impairments in working memory (WM) at the origin of DD (McLean & Hitch, 1999; Geary, Hoard, Byrd-Craven & DeSoto, 2004); however, also in this case results appear controversial (see Landerl, Bevan, & Butterworth, 2004).

Related to this, some authors suggest a defective inhibitory mechanism in interaction with WM: if this cognitive ability is impaired, irrelevant information or inappropriate arithmetic strategies are not inhibited in favour of more appropriate ones (Gilmore et al., 2013). Szucs and colleagues (2013) compared five different theories of dyscalculia (magnitude representation, WM, inhibition, attention and spatial processing) in 9-10 year-old children of primary school. They supported the idea that visuo-spatial STM and WM with inhibition impairments are the most relevant dysfunctions in DD. Inhibition impairment, for these authors, is related to the disruption of central executive memory function. According to them, DD should be characterized by a specific deficit in visuo-spatial STM and by a specific inhibition impairment relevant to visuo-spatial central executive memory function, resulting in poor WM. This complicated scenario is also connected with the heterogeneity of DD. For instance, Kaufmann and colleagues (2013) support the idea of DD as a heterogeneous disorder, resulting from individual differences that occur in multiple levels (such as neuroanatomical, neuropsychological, behavioural etc.). In line with these authors multiple deficits can co-occur in DD and the heterogeneity could not be explained by a single core deficit.

All these studies show how this topic is still debated. Contrasting findings indicate that the relation between primitive abilities and dyscalculia is still unclear. Some authors support the idea that mathematical abilities are related to

WM and/or inhibition abilities; on the other hand there is evidence in favour of ANS theory and its role in mathematical knowledge. This scenario clearly calls for more investigations.

2. The Object Tracking System (OTS)

2.1 Development of OTS during infancy

Another component of early numerical abilities is the Object Tracking System (OTS). The OTS is a mechanism for representing multiple objects in parallel, and it is a capacity limited system which underlies many aspects of perception, including not only numerical tasks, but also visuo-spatial attention and WM (Alvarez & Cavanagh 2004; Luck & Vogel, 1997). This system allows tracking a limited number of objects in space and time and it seems to reach maturity by the first year of life (Revkin et al., 2008; Ross-Sheehy et al., 2003; Rose et al., 2001; Vogel & Machizawa, 2004).

However, at its maximum development this capacity is limited to 3-4 items. This capacity limitation was demonstrated using different paradigms. In one experiment (Feigenson, Carey, & Hauser, 2002), for example, 10-12 month-old infants were shown with two empty buckets and the experimenter filled each bucket with crackers of different numerosities. Then infants were free to choose one of the two buckets: in the case of 1 vs. 2 and 2 vs. 3 crackers, infants chose the greater quantity, but in the case of 3 vs. 4, 2 vs. 4 and 3 vs. 6, they randomly reached one bucket or the other. Using the manual search technique these results were confirmed also in 14 month-old infants (Feigenson & Carey, 2003). Infants can therefore discriminate sets of objects up to 3 and the OTS doesn't follow the ratio-dependence as in the case of the ANS. This suggestion is supported by the fact that infants would succeed also with 2 vs. 4 crackers or 3 vs. 6 if we consider the ratio: we have already seen that infants of 6 months old can discriminate numerosities for a ratio of 1:2.

Further evidence is provided by studies assessing the memory span capacity and the subitizing. Regarding the former aspect, studies of adults found that the capacity to individuate multiple items is limited to 3-4 items and the performances decreased systematically with more than 3-4 objects at a time (e.g. Luck & Vogel, 1997). For infants a crucial moment of improvement is outlined between 5 and 12 months, where they quickly developed span capacities (for a review see Reynolds & Romano, 2016; Ross-Sheehy et al., 2003; Rose et al., 2001). A paradigm used to assess the visual STM in infancy is the change detection paradigm: participants observed two sets of stimuli, presented on the right and on the left, one of them changes at each presentation while the other remains constant. For example, in assessing WM span of three objects, one monitor always shows three squares with the same colors, while the other presents three squares but one of them changes color at each new presentation. The hypothesis behind this paradigm is that infants would prefer the changing set when it remains under the limit of their WM span. When the set size exceeds this limit, infants shouldn't manifest a preference. Using this paradigm, Ross-Sheehy and colleagues systematically assessed memory span in infants from 4- to 13- month-old. Findings revealed a span of 1 in 4- and 6.5-month-old infants, while 10- and 13-month-old infants showed a span of 3. Moreover, when tested with 4 objects at a time, infants of 10 months old preferred to look at the changing stream. These results lead to important assumptions. First of all, infants' memory span develops very quickly, starting from one item and reaching to four items before the end of the first year of life. Secondly, this capacity remains fixed until adulthood, as adults have a limited memory span of 4 items. Unlike the ANS, which continues to develop until adulthood, the OTS grows exponentially in the first year of life and then stops until adulthood (see also Cutini et al., 2014; vanMarle et al., 2018). More recently, some authors (Ross-Sheehy et al., 2011) found an enhancement of WM span in 10 month-olds when providing spatial cues and in 5 month-olds with motion cues.

A parallel line of research found convergent results indicating capacity limited numerical processing in adults. These studies evaluated the subitizing capacity, i.e. the rapid naming of the exact number of the presented objects. The OTS is supposed to be at the base of the ability to perceive the precise quantity of small sets (from 1 up to 3-4 items). For example Revkin et al., (2008) tested participants with a rapid naming task in 1-8 and 10-80 items. The findings indicated more precise performances for 1-4 numerosities but not for 10-40 numerosities. Thus, the subitizing range reaches up to 4 items and it is a qualitatively different process if compared to large numerosity estimation.

2.2 The link between OTS and individuation process

In the previous section we have seen that the OTS is involved in tracking objects through space and time. But how does it assign an index to these objects? Which are the relevant features that allow it to discriminate multiple entities as different? On what basis do infants manage to count one, two or three objects? The aim of the studies in object individuation is exactly that of trying to give an answer to these questions (e.g. Baillargeon et al., 2012; Kibbe & Leslie, 2011;

Wilcox & Biondi, 2015; Stavans & Baillargeon, 2018). The violation of expectation is usually used to assess infants' knowledge: infants are shown one occluder on the scene and a sequence of object emergences that conduct them to create expectations about how many entities are hidden behind the occluder. Then, in the test phase infants observe either an expected or unexpected outcome.

Using this technique, some authors demonstrated that infants can rely on spatio-temporal information to discriminate two objects. For example, when infants of 4 months observed a discontinuous movement[2], they looked longer at the one-object rather than the two-objects outcome (Spelke et al., 1995). Infants have early access to spatiotemporal information to perceive different objects. However, they find it difficult to bind featural information. In a seminal study, Xu and Carey (1996), demonstrated that without spatiotemporal cues infants as young as 10 months failed to bind featural information to individuate different objects. Nevertheless, other studies have shown that the individuation process might be facilitated by language acquisition (Xu, 2002; Xu, Cote, & Baker, 2005). For example, 12-month-olds can succeed in a searching manual task, using the number of labels pronounced by the experimenter to determine the number of objects hidden in a box.

Thus, language has an important role in facilitating the object-kind categorization. In line with these results, another source of facilitation is found to be the functional uses of the objects. In one study, (Futò et al., 2010) participants observed occlusion events including two objects with their distinct functions and

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[2] In the discontinuous movement condition two screens were presented. From one screen an object emerged and then returned behind it; from the opposite side an identical object emerged from the other screen and returned behind it. The expectation is to observe two objects behind the occluders because no object appeared in the space between them.

with ostensive signals (i.e. “Hi, baby, hi” and “Watch this!”). 10-month-old infants showed the violation of expectation when the screen was removed revealing only one object; but when no ostensive signals or no distinct functions were presented infants didn’t assign objects to different categories. The relevant contribution of functional demonstrations was also supported by a more recent study (Stavans & Baillargeon, 2018).

However, other authors found that infants before the first year of life can assign different categories on the base of human-like or non-human-like information without linguistic cues or functional demonstrations (Bonatti et al., 2002, 2005; Surian & Caldi, 2010). These studies are the only ones to have investigated the role of “human” and “dynamic” (in terms of “agent” vs. “inert” object) information in the individuation process. More research should clarify the importance of this information when infants have to track different objects.

2.3 The role of OTS in developmental dyscalculia

As described in section 1.3, the underlying causes of dyscalculia are still unclear. Some authors proposed an ANS deficit (Mazzocco et al., 2011; Mussolin et al., 2010; Piazza et al., 2010), whereas other researchers supported more domain-general theories (e.g. Andersson & Lyxell, 2007; Andersson, 2010; Geary, 1993; Szucs et al., 2013; see for a review Träff, Olsson, Östergren, & Skagerlund, 2017).

Another line of research has also tested the hypothesis of a deficit in the subitizing task, i.e. the rapid naming of numerical small sets of number (Desoete & Gregoire, 2006; Moeller et al., 2009; van der Sluis et al., 2004). In a longitudinal study, (Landerl, 2013) children with dyscalculia and controls were followed for 2 years, from Grade 2 to Grade 4. The author observed systematically larger slopes (for inverse efficiency scores) of the subitizing range in dyscalculics than in controls.

In another experiment (Schleifer & Landerl, 2011), enumeration skills were tested in dyscalculic children and in controls matched for age, IQ, visual-STM, attention and response speed. Dyscalculics displayed steeper reaction times (hereafter RTs) slopes in the subitizing range (1-3), but similar RTs slopes in the counting range (4-7). These results were later replicated by Andersson & Östergren (2012), who found specific impairments in the exact representation up to three objects but not above this subitizing range. Thus, according to them, children with dyscalculia show a deficit in the OTS for representing and tracking from 1 to 3 objects, but no impairments in the counting of larger numerosities.

Contrary to this hypothesis, other studies failed to demonstrate a deficit in the subitizing capacity (De Smedt & Gilmore, 2011; Iuculano et al., 2008; Landerl, Bevan, & Butterworth, 2004). Recently, Ceulemans and colleagues (2014) administered a subitizing test to 18 adolescents with dyscalculia. Comparing dyscalculics and controls, they did not find significant differences either in accuracy or in reaction times.

In sum, the research in this field is limited and leads to divergent conclusions about the OTS deficit hypothesis in DD. It's therefore important to propose studies that aim to elucidate whether children with DD present or not impairments in the subitizing range.

The content of the present dissertation

The present dissertation collects several works that aim to examine multiple aspects of ANS and OTS during infancy. In particular, the predictive role of ANS on mathematical abilities, the importance of dynamic information in OTS and the role of OTS and ANS in developmental dyscalculia.

CHAPTER 1: I report the results obtained in T1 of a longitudinal study where we assess ANS acuity in 12-month-old infants and their relation with parents' performances. I also present the findings in the control task (face perception), relevant to observe the dissociation between this ability and future math' acquisition. Finally, the correlations between infants and parents performances are presented.

CHAPTER 2: in this part I present the findings of three experiments where we test the role of motion information on 10-month-olds' and adults' object individuation process. This allows discriminating how many objects are involved in an event and it is directly connected with the OTS. Using the violation of expectation we extend the knowledge in this field by demonstrating the key role of motion information in the individuation process.

CHAPTER 3: I describe the study that aimed to test the role of each system in developmental dyscalculia (specific learning disability in mathematical field). In particular, the goal is to explore in which domains dyscalculic children differ from typically developing controls. In this study, we assess the two groups in tasks involving the ANS (non-symbolic comparison task), the OTS (enumeration task), symbolic comparison ability and visual short-term memory (STM).

CHAPTER 1

1.1 Study 1: the assessment of ANS and face perception during infancy

Preverbal infants are endowed by the ability to discriminate numerosities without counting. This ability, supported by what has been named by Halberda and colleagues, the "Approximate Number System", is found to be present from the first hours of life (Izard et al., 2009). A relevant feature of the ANS is its ratio-dependence. Indeed, six-month-old infants can discriminate a 1:2 ratio (for example 8 vs 16 dots) but not a 2:3 ratio (for example 8 vs 12 dots), whereas 9-month-olds succeed in both ratios (Libertus & Brannon, 2010; Lipton & Spelke, 2003; Xu & Spelke, 2000; Xu, Spelke & Goddard, 2005). Its precision (indexed by the minimal discriminable ratio) improves during childhood and adolescence until adulthood (Halberda & Feigenson, 2008; Halberda, Ly, Wilmer, Naiman, & Germine, 2012).

Moreover, a line of research has considered the idea of an important role of the inter-individual differences in ANS acuity for the development of later mathematical achievement. Indeed, some studies found a correlation between ANS and math (e.g., Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson and Halberda, 2011; Libertus, Odic, & Halberda, 2012; Mussolin, Nys, Leybaert, & Content, 2012; for a meta-analysis: Fazio, Bailey, Thompson, & Siegler, 2014) and a longitudinal relation with later symbolic math skills (Gilmore, McCarthy, & Spelke, 2010; Libertus, Feigenson & Halberda, 2013; Mazzocco et al., 2011). However, other studies failed to observe this relation (Holloway & Ansari, 2009; Nosworthy et al., 2013; Sasanguie, Defever, Maertens, & Reynvoet, 2014;) or reported mixed results. Bonny and Lourenco (2013) found a difference in this association that emerged only in children with lower math scores. In another study, (Inglis, Attridge, Batchelor, & Gilmore, 2011) the relation between ANS acuity and calculation was found in 7- to 9-year-old children but not in adults. These mixed findings lead to the question whether the ANS could be considered a predictor of later mathematical abilities or not. In the attempt to solve the debate, in a recent meta-analysis Schneider and colleagues (2017) investigated the reliability of such link between non-symbolic/symbolic numerical acuity and mathematical abilities. The results confirmed a small but statistically reliable association (even though symbolic magnitude comparison displayed a stronger correlation with school-based math compared to non-symbolic magnitude skills).

Most longitudinal studies (that are key in demonstrating that the ANS is foundational for subsequent language-based formal math skills) have measured the ANS in children with some form of math education (e.g. verbal counting principles): it is therefore difficult to determine the direction of the causality link between the ANS and later mathematical skills.

To the best of my knowledge, only one recent study has tried to deal with the question of causality in a direct way. Starr and colleagues (2013) measured number sense acuity extremely early, at 6 months of life, in a group of infants, whom they tested again when they were 3.5 years old, using symbolic math tests. In order to examine the ANS acuity in the first year of life, they devised a new numerical change detection paradigm (Libertus & Brannon, 2010): infants observed two streams of different arrays, presented to the left and to the right on a screen, one of which changed in numbers while the other stayed numerically constant (and changed only in dot size, density, and spatial arrangements). The results demonstrated that ANS acuity at 6 months of age is predictive of symbolic math achievement and number word knowledge at 3.5 years of age. However, although significant, the size of the reported correlation effect was extremely small ($r = 0.28$, $p = 0.03$).

Moreover, there were several methodological limitations that need to be corrected in the attempt at replicating the results:

1. the infants at T1 were very young (6 months) and the estimate of ANS acuity may have been inaccurate due to the limited attention span of the infants;

2. the numerical ratios used to estimate the ANS acuity at T1 differed across infants (some were presented with ratios of 1:4, others 1:3, or 1:2), thus potentially including confounding elements in the ANS estimation across infants;

3. the control task used to estimate perception differences at T1 differed across infants (some had a color and some a size perception task), thus potentially injecting spurious differences across infants that may have influenced the correlational results.

The current study

Given the contrasting findings and the paucity of early longitudinal research, the present study aims to lay the bases for a longitudinal assessment of the hypothesis of the ANS as an early precursor of later mathematical abilities. We developed a study where infants will be assessed at 12-months old (T1) and two-three years later at about 3.5 years old (T2). For the present dissertation, I will present the T1 results, which I started in July 2016 and finished in August 2017, because the T2 will take place in 2019, when the children are 3.5. Our study includes important changes compared to the study of Starr and colleagues that will overcome its limitations:

1. at T1 we tested slightly older, but still non-numerically literate infants (12 months old) obtaining potentially more stable estimates of their skills;

2. at T1 we used the same trials across infants so that the inter-individual differences were readily interpreted;

3. at T1 we used the same control task (face perception) for all infants in order to have a homogeneous control of perceptual skills outside the number domain, and therefore

4. at both T1 and T2 we will measure the same control skill (face perception), and this will serve for inferences on the specificity and selectivity of the relation between ANS and formal math skills.

To address the question of this relation, at T1 we administered one numerical task and one face perception task. The latter is relevant to verify the longitudinal specificity of ANS as a unique predictor of early symbolic and non-symbolic numerical achievement. The aim is to understand whether a positive correlation could be liable to differences in discrimination of quantities or to more general perceptual abilities. Positive correlations with both ANS and face perception would suggest that mathematical abilities rely more on general perceptual processing. On the other hand, if symbolic math skills selectively correlate with numerical acuity, this would give further support to the hypothesis of a specific association between ANS and math acquisition.

We decided to assess infants' face processing because it is considered a separated ability from numerical cognition, tapping on different neurocognitive systems and connected with a different cortical processing stream (ventral for faces *vs.* dorsal for numbers) (e.g. Chinello et al., 2013; Cohen & Dehaene, 2004; Golarai et al., 2007;). The dorsal stream is mainly involved in processing spatial/numerical information while the ventral stream is important for identification of objects and face recognition. For example, Chinello and colleagues (2013) found distinct developmental trajectories of face recognition abilities within the ventral stream on one side and numerosity comparison abilities within the dorsal stream on the other. The distinction between these abilities leads us to assess face perception as a control task for our longitudinal study.

ANS acuity task. We tested the ANS acuity at the end of the first year of life using the change detection paradigm (Libertus & Brannon, 2010) that provides an index of individual differences in numerical acuity. Infants were presented with two arrays containing dots, in one of which the numerosity changed at each presentation while in the other the numerosity remained constant. We explored infants' numerical acuity using multiple ratios presented to each child: we explored the numerical discrimination with an easy (1:4) and a more difficult ratio (1:2).

In previous studies (and especially in our reference study by Starr et al.) authors analysed the numerical sensitivity to different ratios in different groups of infants. Only very recently, the ANS precision has been examined in the same participants with different levels of difficulty (Wang et al., 2018). In this study, 6-month-old infants were familiarized first with highly discriminable ratios and then progressively with harder ones. However, the aim of this study was to investigate hysteresis, thus whether numerical acuity could be trained with easy ratios, in which infants were explicitly reinforced when looking at the numerical changing stream.

Face processing task. For this task, we focused our attention on the kind of features and configurations infants rely on in order to process and recognize different faces. Many authors proposed a distinction between *featural processing*, which refers to the sensitivity to the shape of eyes, nose and mouth, and *configural processing*, which involves the perception of relations among these features (Carey & Diamond, 1977; Maurer, Le Grand, & Mondloch, 2002; Quinn et al., 2013; Schwarzer, Zauner, & Jovanovic, 2007).

One type of configural processing concerns the *sensitivity to second-order relations*, i.e. processing the distances among features (e.g. Mondloch et al., 2002). Some authors provided evidence of more difficulty in tasks that require sensitivity to *second-order* changes than to *featural* ones (e.g. Freire & Lee, 2001). For example, Mondloch and colleagues (2002) demonstrated a late development of *configural* process, in particular *second-order* relation, compared to the *featural* one in children aged 6, 8 and 10 years. However, only few studies investigated the sensitivity to these changes during infancy and all of them (Bertin & Bhatt, 2004; Hayden et al., 2007; Thompson et al., 2001) tested the *second-order* change detection without a parallel assessment of the *featural* change detection.

To our knowledge, only one study proposed a task for investigating the two processes in the same infants. 3-4-month-old and 6-7-month-old infants (Quinn & Tanaka, 2009) were administered a modified version of the Face Dimensions Test (Bukach et al., 2008). Infants were exposed to a woman's face in the familiarization phase and then they were presented with the familiar image and the new image that could differ in the distance between the eyes, distance between the nose and the mouth, size of the eyes and size of the mouth. The authors reported a preference of the infants for the novel image in the cases of a different distance among eyes, nose/mouth and different features in the eyes but not in the *featural* change of the mouth. Thus, the sensitivity for the change depends not only on the *featural*/*second-order* arrangements but also on the part of the face involved in the task. Moreover, and more interestingly for our investigation, contrary to previous results (e.g. Cashon & Cohen, 2004) the authors found higher mean percentage looking time for the novelty in the *second-order* change relative to the *featural* one.

Given that these results seem to contradict those reported above (e.g., *featural* changes are more easily perceived compared to *second-order* changes), it is still unclear whether infants can better discriminate *featural* or *second-order* changes. Therefore, in assessing face processing we aimed to first provide a control task for the longitudinal study and in parallel examine (a) the *featural* and *second-order* process in 12-month-old infants (b) in a within subject design to test the inter-individual differences that occur in infancy (c) using children faces. To test the infants' individual differences, we implemented the same paradigm used for assessing the infants' numerical acuity (Libertus & Brannon, 2010), and we tested them with two levels of change: one that we assumed, following Mondloch and colleagues (2002), to be an easy level (*featural* change), where we showed two different faces in the changing image stream, and one, assumed to be a more difficult level, where we changed the *second-order* features of the same images (we started from a reference face and generated the novel one by separating the distance between the eyes and between the eyes and the mouth).

Materials and methods

Participants

We tested 60 full-term infants of 12 months (*M* = 12 months and 4 days, *SD* = 24,4 days). We recruited this sample size considering the previous longitudinal study of Starr and colleagues (2013) where the authors assessed sixty-six infants. Nine infants were excluded due to fussiness, cry or distraction. Parents of all children provided written informed consent, approved by the Ethical Committee of the University of Trento, before the infant's participation. Infants received a small gift as a compensation for their participation.

Design

To assess ANS acuity we used a modified version of the change detection paradigm (Libertus & Brannon, 2010). Infants were on a parent lap and in front of three different monitors. They observed two streams of images of dots placed on the left and on the right of a central black screen: the non-changing image stream showed the same numerosities over time, while the changing image stream showed different numerosities over time (see Fig. 1). The arrays were generated to be equated on half the trials in dot size and in the other half in total occupied area.

Infants observed four trials, presented in the same fixed order: first, two streams of 1:4 ratio (5 and 20 dots, 20 images for each stream) and then four of 1:2 ratio (5 and 10 dots, 30 images for each stream). An attractor appeared between each stream of images. The side of the changing image stream was counterbalanced within participants: if in the first stream the changing image stream was presented on the left, in the following stream it was presented on the right. Half of infants observed first the changing on the left monitor and half on the right monitor.

In the face processing task (see Fig. 2) infants were presented with two streams of images of faces, where one stream showed the same identical face, while the other showed two alternating faces which key elements (eyes, nose, and mouth) differed either in their shape (so called *featural change*) or in their relative position (i.e., the distance across the eyes, and distance between eyes, nose, and mouth; so called *second order change*).

Infants observed four streams, two streams of *featural* changes and then two streams of *second-order* changes. In the first and third block stimuli were male faces, while in the second and fourth block female faces.

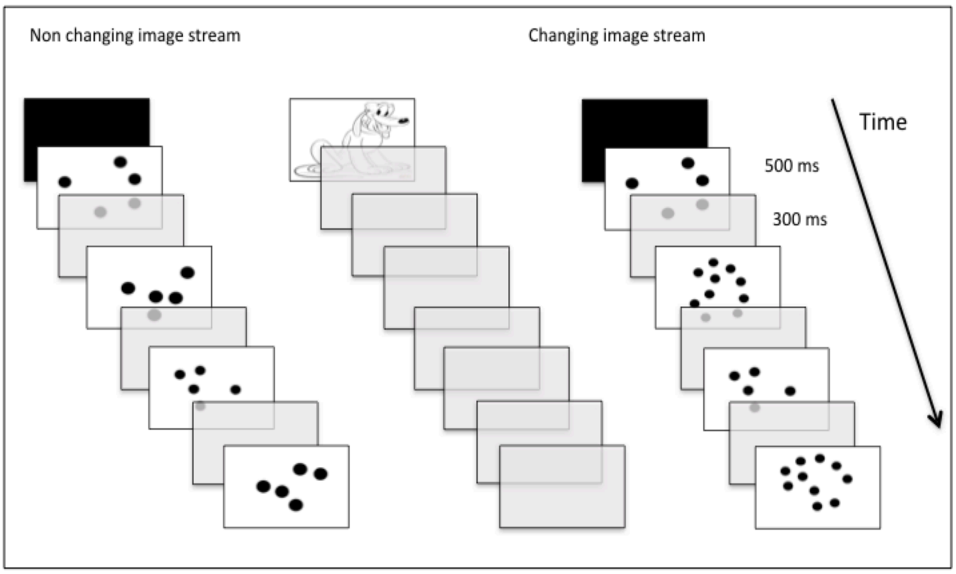

Fig. 1 Schema of the change detection paradigm used for assessing 1:4 ratio and 1:2 ratio. One stream shows images that change in numerosity, while the other stream shows the same numerosity over time.

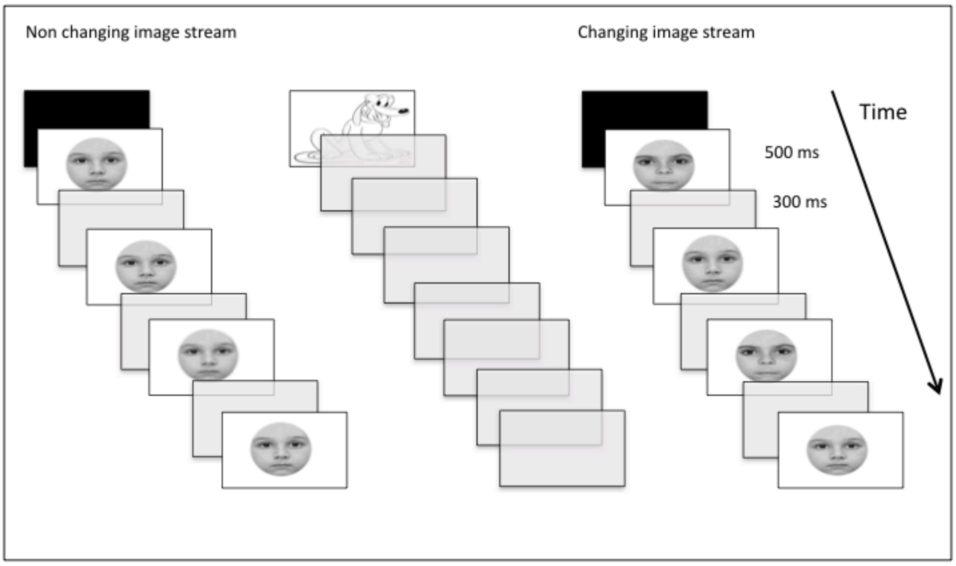

Fig. 2 Schema of the change detection paradigm used for assessing face processing. On one monitor there are images with different faces while on the other there is the same image.

Stimuli, apparatus and procedure

The images in the ANS acuity task were composed by dots of different numerosity. For the 1:4 ratio infants were shown 20 and 5 dots in the changing image stream and 5 dots in the non-changing image stream. For the 1:2 ratio, infants observed 10 and 5 dots in the changing stream and 5 dots in the constant one. Both streams showed the same image but one array alternated with the changing numerical image while the other presented the same numerical image.

In the face processing task, stimuli consisted in pictures of four children's faces (males' age: 4 years old and 11 years old, females' age: 5 years old and 9 years old). Parents gave written consent to use and transform the images. The children's hair was put up using an elastic band and the children wore no external objects (such as jewelry or glasses). The original pictures were greyscaled, cropped in order to leave only the oval part of the faces and equalized in luminance. The female and male faces had approximately the same size (male faces: 12.5 cm wide and 17.1 cm high; female faces: 12.1 cm wide and 17.6 cm high). In order to generate the stimuli for the second order change condition we followed the method used in Mondloch and colleagues (2002): starting from each of the four original faces, we generated four new ones where the eyes were moved 1.2 cm further apart and the mouth was moved 1.2 cm further down compared to the original, corresponding to an approximate 2% change in spatial separation across the facial features.

Stimuli for both tasks were presented for 500 ms followed by 300 ms of a blank image. Infants sat on a parent's lap in front of three 17-inch monitors (resolution, 1280x1024), in a quiet room at the Baby Lab of the Department of Psychology and Cognitive Science in Rovereto. The chair was positioned 105 cm from the central monitor and the monitors were placed at a distance of 55 cm from each other. A black panel was arranged to cover the lights present on the monitors, leaving visible only the screens. On the middle monitor a small webcam was also placed, oriented in the direction of the infant. The webcam was attached to a laptop placed on a desk, behind the table with monitors. The experimenters were hidden by a curtain, which was placed behind the table with the screens. Parents were instructed at not pointing at the screens. Moreover, they did not know the goal of the study (they were only informed that infants would observe arrays of dots or faces) so they could not unwittingly orient the attention of the infant towards one screen or the other. After instructing the parents not to point at the monitors with the stimuli, the experiment started with an attractor shown in the central monitor. Once the attention of the infant was captured, the experimenter pressed a button on the keyboard, starting the trials. The side of the changing stream (left or right monitor) alternated across trials, and its order was counterbalanced across participants: half of the infants started the first block with the changing image stream on the right, while the other half started with a changing image on the left.

Infants' fixations were recorded online by an expert observer. A second observer coded offline infants' fixations. The average of inter-observer reliability was r=0.95.

Results

The final sample was composed by 51 infants and we calculated for each infant a preference score: the proportion of looking time to the changing stream minus the proportion of looking time to the non non-changing stream. Thus, a positive preference score indicates that the infant looked longer at the changing stream of images, while a negative preference score indicates more looking times to the non-changing stream. Before performing the analyses, we excluded infants that were distracted and fixations under 1.6 seconds, as infants needed this time to observe a minimum of two images in each stream. Indeed each image is shown for 500 ms followed by a blank image for 300 ms.

ANS acuity task. Preliminary analyses showed that preference scores were normally distributed in 1:4 ratio and 1:2 ratio (Shapiro-Wilk test, 1:4 ratio: W = .97, p = .238; 1:2 ratio: W = .98, p = .69). Descriptive analyses revealed that infants preferred to look at the changing more in the 1:4 ratio (*M* = .22, *SD* = .37) than in the 1:2 ratio (*M* = .09, *SD* = .32). The difference between the two levels of difficulty however, only approached significance ($t(50) = -1.85$, $p = .07$). We then compared each level of difficulty with zero (as in the study of Libertus & Brannon, 2010) in one-sample t-tests and we found significant preference for the changing both in the 1:4 ratio and in the 1:2 ratio ($t(50) = 4.19$, $p < .001$; $t(50) = 2.08$, $p < .05$, Fig. 3). 39 infants out of 51 preferred to look at the changing image stream compared to the non-changing in the 1:4 ratio, while 33 infants preferred the changing in the 1:2 ratio. Separated analyses for the first and the second 1:2 trials revealed no significant difference between preference scores and zero in the former ($t(50) = 1.01$, $p = .31$) and in the latter ($t(50) = 1.93$, $p = .058$).

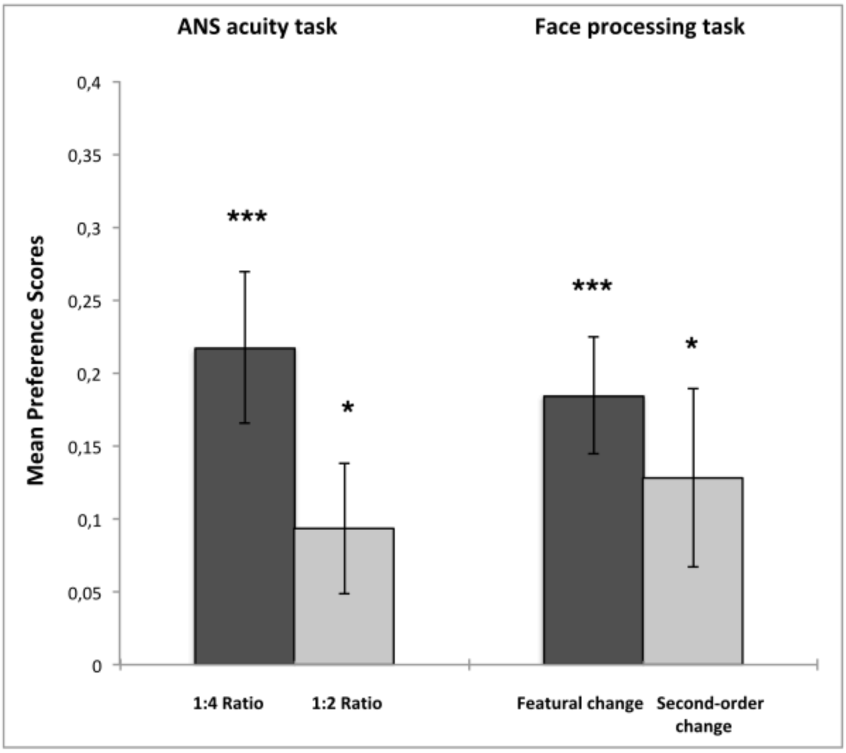

Fig. 3 Mean preference scores for ANS acuity task (1:4 ratio and 1:2 ratio) and for the face processing task (featural change and second-order change). Infants looked significantly longer at the changing image stream for all the levels of difficulty (1:4 ratio and featural change: *** = $p < .001$; 1:2 ratio and second-order change: * = $p < .05$). Error bars represent standard error.

To assess the reliability of our measure we performed a correlation between the two levels of difficulty (2 trials of 1:4 and 4 trals of 1:2). We didn't find a significant relation between the two ratios (*r* = .05, *p* = .71, Fig. 4).

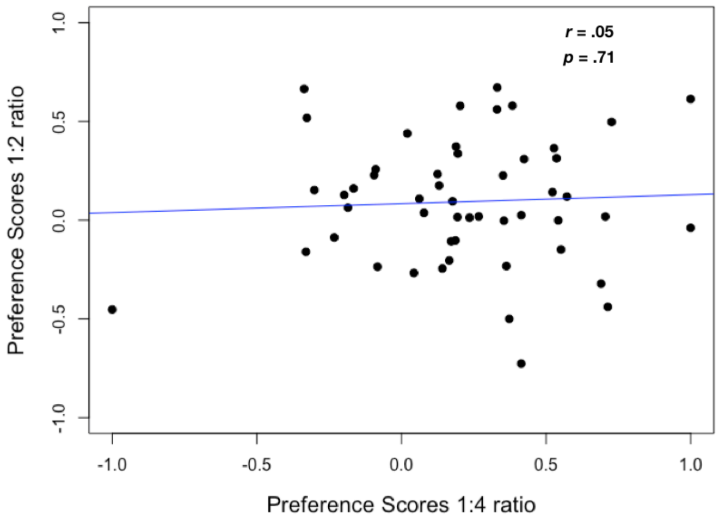

Fig. 4 Correlation between Preference Scores in the 1:4 ratio and in the 1:2 ratio.

Face processing task. Preliminary analyses showed that the preference scores were normally distribuited both in *featural* and *second-order* conditions (Shapiro-Wilk normality test, *featural* change: W= .98, p= .45; *second-order* change: W= .96, p= .08). Infants preferred more the changing in the *featural* condition (M = .18, SD = .29) than in the *second-order* condition (M = .13, SD = .44). However, the two conditions did not significantly differ from each other ($t(49) = 2.07$, p = .35).

We then compared the preference scores for each level of difficulty with zero in one-sample t-tests (see Fig. 3); we found a significant preference both for the changing image stream in the *featural* condition ($t(50) = 4.59$, $p < .001$) and in the *second-order* condition ($t(49) = 2.07$, $p < .05$). Specifically, 42 infants out of 51 preferred to look at the changing compared to the non-changing stream in the *featural* change, and 32 infants preferred to look at the changing stream in the *second-order* condition.

To assess the reliability of our measures we performed a correlation between the two levels of difficulty. This revealed a significant relationship between the preference scores in the *featural* and in the *second-order* change ($r = .29$, $p < .05$). Importantly, we also computed separated correlations between numerical and face perception preference scores for both levels of difficulty and we did not find a significant correlation either in the easy levels (Ratio 1:4 and *featural* change: $r = -.07$, $p = .62$) or in the difficult levels (Ratio 1:2 and *second-order* change: $r = .15$, $p = .28$).

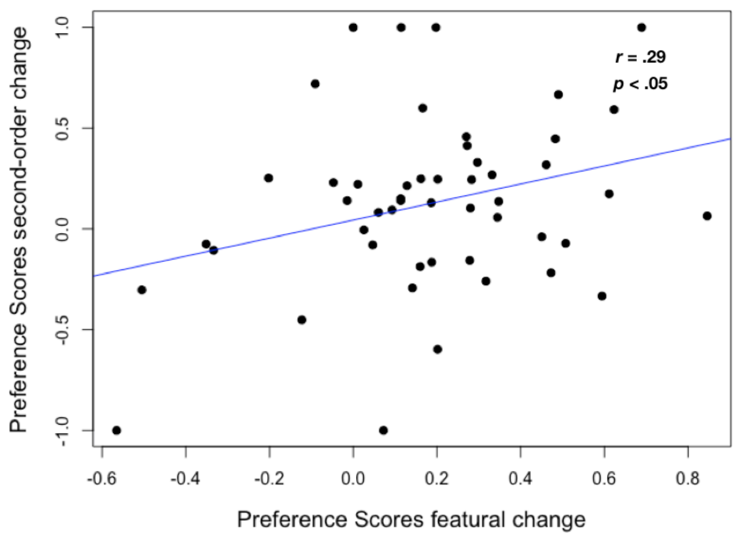

Fig. 5 Correlation between Preference Scores in the *featural* and *second-order* change.

Discussion

Here I presented the results of T1, collected in 2016/2017. We used a modified version of the change detection paradigm (Libertus & Brannon, 2010) where 12-month-old infants observed two streams of images, one of them changed in numerosities or in facial components while the other showed the same image over time. Moreover, we manipulated the levels of difficulty for both tasks: 1:4 ratio (5 and 20 dots)/1:2 ratio (5 and 10 dots) for the ANS acuity task and *featural* (different eyes, noise and mouth)/*second-order* (different spaces between the eyes and between the eyes and the mouth) change for the face processing task. We then calculated for each participant a preference score (proportion of looking time to the changing minus proportion of looking time to the non-changing) that could be positive when infants looked longer at the changing or negative when they observed more the non-changing stream.

In the ANS acuity task, our results revealed higher looking times at the numerical changing in both ratios. These findings are in line with previous studies, confirming that infants in the first year of life develop an ANS acuity that allows them to discriminate numerosities when the ratio is 1:4 and 1:2 (Brannon, Abbott, & Lutz, 2004; Lipton & Spelke, 2003; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). Moreover, the positive preference scores varied as a function of the different ratios between the numerosities shown in the changing stream. In particular, infants preferred more the numerical changing in the case of greater ratio (i.e. 5 vs. 20, M = .22) compared to the smaller one (i.e. 5 vs. 10, M = .09).

However, we didn’t find a significant reliability between the two levels of difficulty in the paradigm. Indeed, in a previous study, Libertus and Brannon have assessed infants at 6 months of age using the change detection paradigm with trials of 60 seconds for a total of 4 trials for each infant. The same participants were then tested again at 9 months. 6-month-old infants, who had a strong preference for the changing, more likely preferred to look at the changing also at 9 months. They provided therefore evidence for inter-individual differences that are stable in the first year of life.

In our study we failed to replicate such results. Infants who observed more the changing in the 1:4 ratio were not the same infants who had high positive preference scores in the 1:2 ratio. There are two possible interpretations for the failure of replication. Firstly, in our study we used easier ratios compared to Libertus and Brannon. Indeed, in their experiment infants observed multiple ratios at 6 months (1:4, 1:3, 1:2) and the preference scores were normalized for the maximum preference score in the linear regression. Then, at 9 months they observed only one difficult ratio. The variability in the preference scores at 6 months, connected with the use of multiple ratios, and the use of a single difficult ratio at 9 months, could be at the base of the correlation emerged from their data. On the contrary, we used two easy ratios that should be well established in 12-month-old infants. In particular, in the 1:4 ratio the majority of the infants preferred to look at the changing and we didn't find a high variability across subjects. The low variability in the preference scores could be considered as a less reliable threshold for distinguishing the performances across infants and, in parallel, this could explain the result of our correlation.

Another explanation could be the amount of data that we collected. We obtained less looking times compared to previous study (Libertus & Brannon: 240 seconds for one ratio; our study: 80 seconds for one ratio), earning more information about infants' preferences.

Finally, a more qualitative interpretation might be the infant fatigue. In Libertus and Brannon study infants observed the same ratio over time. In our study, we used a within subject design where infants observed first the easy ratio for two trials and then the difficult ratio in the last two. Infants might be more tired when the task started to be more difficult for them.

Future research should expand these results. To our knowledge, few studies investigated the correlation in the preference scores obtained in a within subject design with multiple ratios. Indeed, all recent studies proposed multiple ratios in the same participants but they examined only whether there is a facilitation effect in presenting first the easy ratios and then the most difficult one, without directly testing for a correlation across levels of difficulties (Odic, Hock, & Halberda, 2014; Wang, Odic, Halberda, & Feigenson, 2016; Wang, Libertus, & Feigenson, 2018). There is therefore a gap in the assessment of the change detection as a reliable measure with multiple ratios.

In the face processing task, the first interesting finding was the sensitivity of infants for *second-order* relations. Our results showed that infants looked significantly longer at the changing stream when the changes consisted in differences in spaces between facial features. This confirms evidence from previous studies demonstrating that infants in the first year of life can already rely on *second-order* changes (Bertin & Bhatt, 2004; Hayden, Bhatt, Reed, Corbly, & Joseph, 2007; Thompson, Madrid, Westbrook, & Johnston, 2001).

Importantly, infants preferred more the changing in the *featural* condition than in the *second-order* condition. They better discriminated the differences in faces when the change involved features, such as eyes or nose. These findings are in line with other studies reporting an earlier sensitivity to the *featural* change in children and infants (Bhatt et al., 2005; Cashon & Cohen, 2004; Mondloch et al., 2002; Schwarzer, Zauner, & Jovanovic, 2007). Importantly, we demonstrated that a similar effect is present using children's faces, expanding our knowledge on *featural vs. second-order* processing in 12-month-old infants.

However, these data show an opposite trend compared to the study of Quinn and Tanaka (2009). They assessed *featural* and *second-order* sensitivity at different ages, and their results revealed no significant differences between the mean preference and the chance level (50% of preference) in the *featural* change, whereas a significant difference emerged in the *second-order* change. The authors concluded that infants were more sensitive to the configural aspect than to the featural changes. However, it's difficult to compare our findings with the ones by Quinn and Tanaka for the following reasons. We tested older infants (12-month-old infants) while they assessed younger participants (3-to-4-month-old and 6-to-7-month-old infants). Moreover, they separated the changes into different facial regions (upper *vs.* lower) and this separation might result more difficult for infants to perceive, in particular in the featural level. In contrast we did not manipulate separately the two facial regions. All these methodological differences make the two studies not really comparable.

Another important finding of our study with respect to the face processing was the significant positive correlation across the two levels of difficulty in the face trials: inter-individual differences in infants' preference scores persisted across conditions. Contrary to the numerical change detection, infants who preferred the changing image stream in the *featural* condition were more likely to observe the changing in the *second-order* condition, supporting the evidence of high reliability in the measures obtained with the use of the change detection. Related to this, these findings lead to the suggestion that this task produces reliable measures and consequently can be used to assess not only numerical cognition but also face processing during infancy. These results added new evidence in literature about the stability between *featural* and *second-order* processes, since to our knowledge no previous studies have been conducted using the change detection paradigm.

Comparing face processing and numerical preference tasks, we observed different correlational trends. We found more reliability for faces than for numbers. An explanation is that in the numerical change detection there were more variables that we manipulated in the changing and in the non-changing streams, such as total occupied area and size of the dots. These visual controls could have created more noise in the numerical infants' preference scores. We also performed separated correlations to test whether face processing and numerical acuity tapped on different cognitive paths. Specifically, we found no significant correlations neither in the easy levels (1:4 ratio and *featural* change) nor in the difficult levels (1:2 ratio and *second-order* change), providing evidence for a dissociation between numerical acuity and face processing ability, and suggesting that they rely on separated pathways (e.g. Chinello, Cattani, Bonfiglioli, Dehaene, & Piazza, 2013). These results are promising for the longitudinal study that will be conducted in 2019 and allow us to hypothesize the same dissociation at T2. At T2 we will propose tasks that aim to investigate early cardinality principles, spontaneous attention to numerosity, ANS acuity and mathematical acquisition, as well as normative tests for general intelligence. We will correlate an index for each task with the preference scores obtained in the first part of the study.

Our study has the potentiality to elucidate whether there is a correlation between the results at 12 months of age in discrimination of different numerosities and the performances at 3 years old in mathematical tasks. If our hypotheses are confirmed, the ANS acuity could be assessed early in life facilitating the precocity of diagnosis. Moreover, these findings would improve the knowledge of intervention in dyscalculia: children with this deficit could be helped in developing the ANS acuity in order to attenuate the effects of the neurodevelopmental disorder.

1.2 Study 2: Is there a parental influence on infants' ANS acuity and face processing?

Little is known about the relation between infants' and parents' perceptual skills in the numerical cognition and in the face processing domain.

In the numerical cognition field, few correlational studies have explored this relation (Brown, Mcintosh & Taylor, 2011; Crane, 1996; Blevins-Knabe, Whiteside-Mansell & Selig, 2007; Duncan et al., 2005). For example, evidence was found in a correlation between parental mathematical scores during childhood and math scores of their children at the same age (Brown et al., 2011). However, it is still unclear which factors influence this relation. Some authors using twin studies demonstrated the weight of both genetic and environmental factors (e.g. Hart, Petrill, Thompson, & Plomin, 2009; Kovas et al., 2007). In the genetic domain authors supported the idea of a set of genes that would influence both reading and mathematical disabilities (Kovas et al., 2007). Considering the environmental factors, some focused their attention on parent "number talk" (e.g. Levine, Suriyakham, Rowe, Huttenlocher, & Gunderson, 2010; Elliott et al., 2017) or on socioeconomic background (e.g. Saxe et al., 1987), revealing a predictive role in the achievement of early mathematical principles. However, all these studies have never examined the link of ANS acuity in parents and children.

Only recently one study (Braham & Libertus, 2017) considered the inter-generational association in discrimination of quantities, examining the influence of ANS parental acuity on their children's performances. 45 children of 5-8 years old and their parents completed an ANS acuity task, where they had to determine which one of two arrays contained more dots. They found a predictive role of parent mathematical abilities on children's ability in multiple math measures and, more interestingly, ANS parental acuity correlated with children's ANS acuity. This is the unique study assessing specifically the correlation of parent-offspring in ANS. However, since the children involved were already numerically literate, especially thanks to parental education, we cannot conclude that there is a genetical influence. No studies have yet considered this relation in pre-verbal, pre-litterate infants.

In the field of face processing, researchers have focused their attention mainly on twin studies and studies of prosopagnosia. The idea behind the twin studies is that monozygotic twins totally share their genes, while dizygotic twins share only half, so if there is an important contribution of genes than monozygotic twins should perform more similarly than dizygotic ones. Indeed, findings indicate that performances in monozygotic twins correlate more than in dizygotic twins, providing evidence for face recognition as a highly heritable ability (e.g. Zhu et al., 2010). Some authors using a twin design proposed a specific gene for face perception (Wilmer et al., 2010; Zhu et al., 2010), in contrast to the idea of a "generalist genes hypothesis" (Kovas & Plomin, 2006), where other authors supported the idea of a gene that affects several areas of the brain and, by extension, different cognitive processes. In line with the hypothesis of a specific gene, Shakeshaft and Plomin (2015) measured face recognition, object recognition and general cognitive ability obtaining data from about 2000 twins in the United Kingdom. They first replicated the higher correlation in monozygotic twins than in dizygotic ones. Secondly, they showed that heritability of face recognition is linked to a specific genetic influence, not shared with object recognition or general ability.

The second line that leads us to test the parents-infants link is the highly hereditability of prosopagnosia. The impairments in face recognition could be present from birth and run in families (Duchaine, Germine, & Nakayama, 2007; Kennerknecht et al., 2006; Grueter et al., 2006; Schmalzl, Palermo, & Coltheart, 2008). We know that participants affected by congenital prosopagnosia have a first-degree relative who presents the same face-recognition difficulties (Behrmann & Avidan, 2005).

All these studies in ANS and face processing domain conduct us to test not only infants' performance but also parents' abilities to investigate whether there is or not a relation in the first steps of development. Thus, we correlated the infants' preference scores of the previous study with the data obtained by their parents. They were assessed with a dots comparison task for testing ANS acuity and with the Cambridge Face Memory Test (CFMT; Duchaine and Nakayama, 2006) for testing face recognition abilities. Moreover, we separated the analyses for fathers and mothers because no studies have alredy assessed the distinct contribution of each parent in these two abilities.

Method

Participants

Forty-seven mothers and thirty-seven fathers participated at this study. The mean age of mothers was 33 years (range = 22 years to 46 years) and the mean age of fathers was 38 years (range = 29 years to 48 years). The parent who accompanied his/her child at the lab did the task there, while the other parent was asked to complete it at home. For the final analyses we decided to include only the data obtained by both parents of the same infant and not partial data of a single parent. The final sample was composed by 34 pairs of parents.

Apparatus and Procedure

Parents were assessed in a dots comparison task and in a face processing task. Participants who completed the tasks at the lab were in front of a Lenovo 80H8 with resolution 1366 x 768. The experimenter gave them verbal instructions and then the experiment started. Each task lasted about 10/15 minutes.

In the dots comparison task (Fig. 1), participants were presented with pairs of arrays of dots (black on white background), presented laterally to a central fixation cross. The task was to press the response-key located on the same side of the larger array. Stimuli were controlled for size and total occupied area and involved pairs of arrays, one of which (n1) always presented either 16 or 32 dots. Stimuli paired with arrays of 16 dots (n2) could contain 12, 13, 14, 15, 17, 18, 19, 20 dots, while stimuli paired with 32 dots could present 24, 26, 28, 30, 34, 36, 38 or 40 dots. We then calculated the internal Weber fraction (w) for each participant and the overall accuracy.

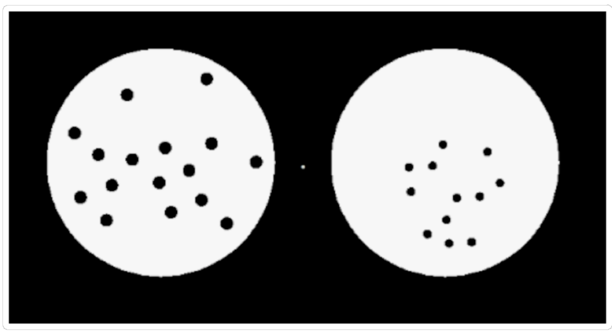

Fig. 1 Example of stimuli used for assessing ANS acuity in parents. They had to choose the array containing the greater quantity of dots.

Parents were also administered the Cambridge Face Memory Test (CFMT, Duchaine & Nakayama, 2006) to assess their face recognition ability. The stimuli consisted in faces of men without visible hair and with neutral expressions. The CFMT was divided into 3 sections (with a practice part before these) and was composed by a memory phase and a test phase: in the first one, participants memorized a face-item and in test phase they were instructed to recognize it by choosing one of three options.

As mentioned, the first part was the *Practice* where participants observed for three seconds the cartoon character Bart Simpson in three different positions, a left 1/3 profile, a frontal view and a right 1/3 profile. Then in the test phase 3 images were presented for 3 times and participants were instructed to press the number (1, 2 or 3) on the keyboard corresponding to the chosen face. One of these three images was the target-face, previously memorized, while the other two were distractors (Fig. 2A). This section served to familiarize participants with the schema of the test.

In the first test section, defined as *Same images* (see Fig. 2B), participants were shown the first target face for three seconds in the different profiles. Later, the test phase presented three items one of them was identical to the faces' profile that participants had memorized. In the memory phase and in the test phase the image that participants had to memorize and recognize was exactly the same. The procedure was repeated for 5 times.

In the *Novel images* (see Fig. 2C) participants were presented 6 faces in frontal profile in the same screen for 20 seconds. In this case, the test phase contained three images one of them was the right face but proposed in a different lighting, pose or both compared to the memory phase image.

Finally, in the *Novel images with noise* participants memorized again 6 faces for 20 seconds; in the test phase images consisted of novel images with noise (see Fig. 2D). The difficulty increased progressively across the sections, so that the *Novel Images with noise* was the most difficult one to recognize the right face.

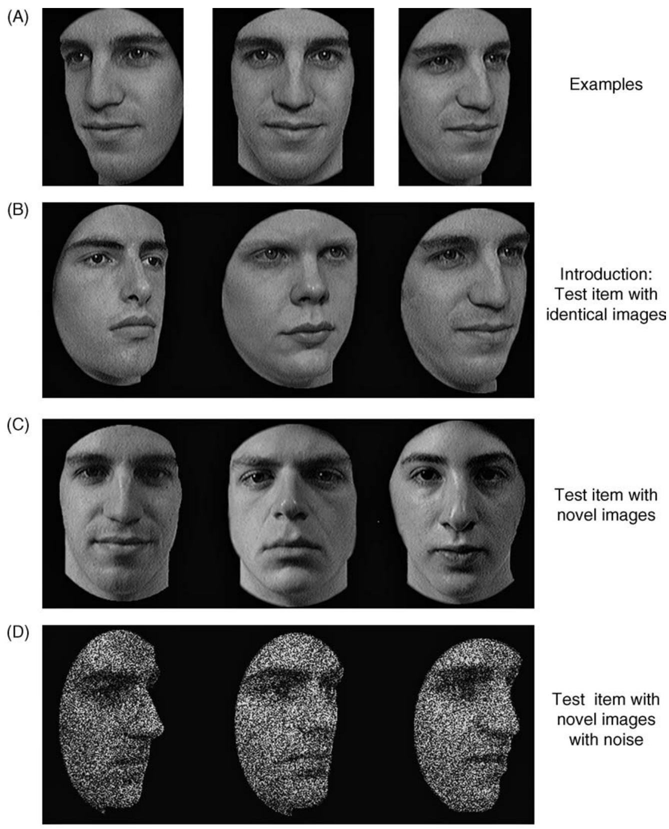

Fig. 2 Schema of the stimuli presented in the Cambridge Memory Test (Duchaine & Nakayama, 2006). A) Example of the images that participants memorize in the memory phase. B) Example of the stimuli used in the *Same images* section, where faces were the same in the memory and test phase. C) Example of the stimuli used in the *Novel images* section, where faces in the test phase are presented differently than in the memory phase. D) Example of the stimuli used in the *Novel images with noise*, where faces in the test phase are not only different from the memory phase but also with noise.

Results

In the dots comparison task, we calculated for each parent the accuracy and the *w* fraction. Accuracy was significantly higher for mothers than for fathers (M_{mothers} = 77.96, SD = 9.23; M_{fathers} = 69.62, SD = 10.33; $t(66) = 3.51$, $p < .001$). However, the comparison between the *w* fractions only approaches significance: mothers had an internal *w* fraction of 0.2 (that reflects a better numerical estimation) while fathers 0.35 ($p = .067$).

We performed separated correlations to test the hypothesis of a link between parents' and infants' performances for 1:4 and 1:2 ratio (see Fig. 3). Analyses revealed no significant correlations between mothers and infants in the 1:4 ratio nor in the 1:2 ratio ($r_{1:4\ \text{ratio}} = -.06$, $p = .74$; $r_{1:2\ \text{ratio}} = .10$, $p = .56$). We did not find significant correlations even between fathers and infants ($r_{1:4\ \text{ratio}} = -.13$, $p = .45$; $r_{1:2\ \text{ratio}} = .02$, $p = .89$).

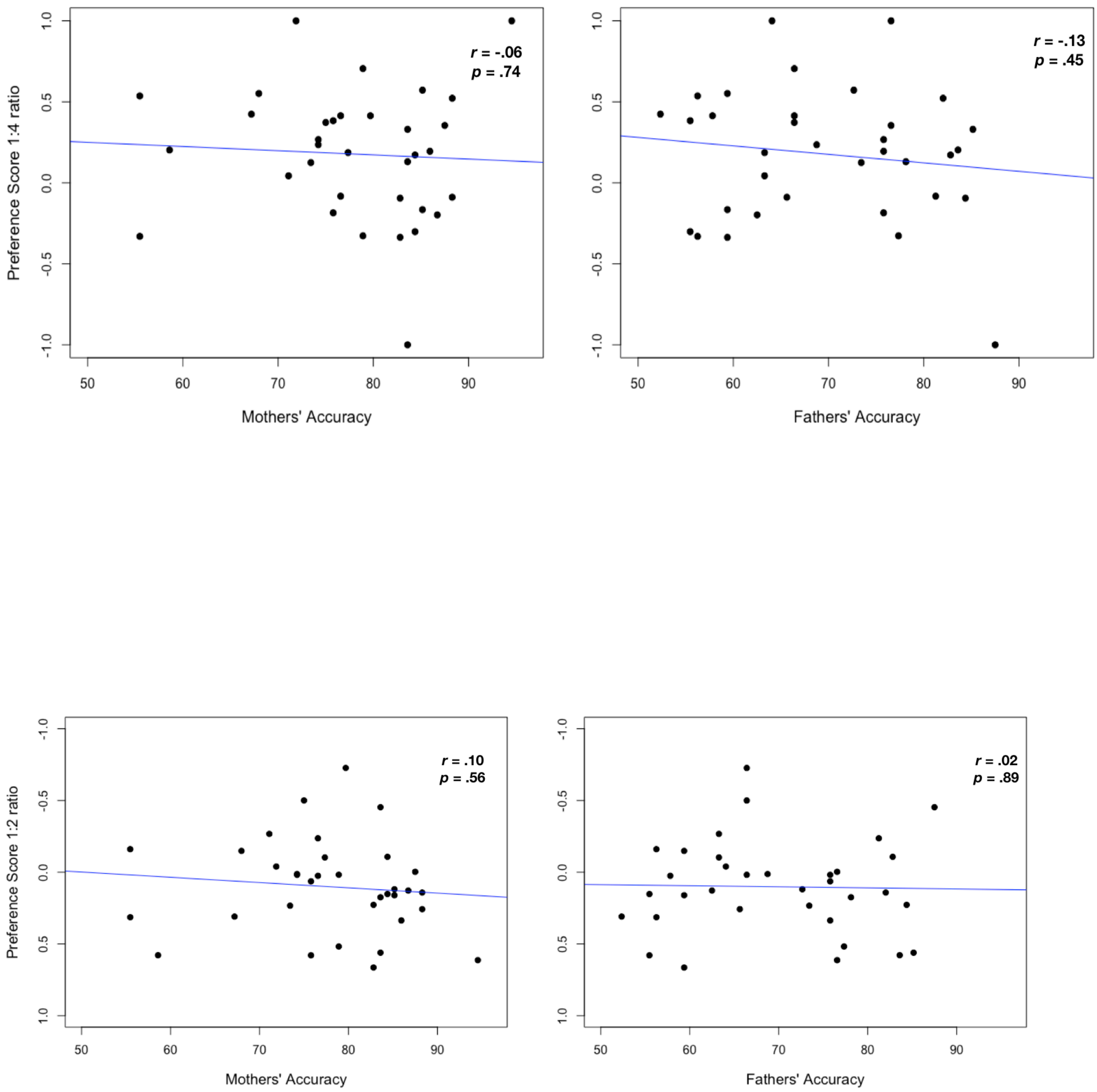

Fig. 3 Correlations between fathers'/mothers' accuracy and infants' preference scores in the 1:4 ratio and in the 1:2 ratio.

Considering the face processing task, we calculated the accuracy score for each parent, summing the correct answers at the CFMT. The scores ranged from 31 to 70 and the average of total score was 49.38 out of 72 with standard deviation of 9.82.

We found similar performances between mothers and fathers (M_{mothers} = 50.22, *SD* = 8.94; M_{fathers} = 48.54, *SD* = 10.68). We then compared each mean with the probability of giving random answers and the difference between means and chance level (24) was significant (mothers: $t(36) = 17.84$, $p < .001$; fathers: $t(36) = 13.98$, $p < .001$). Therefore, parents performed well beyond chance.

Moreover, we plotted the average of cumulative scores with standard deviation divided into sections (see Fig. 4); the black lines indicated the ideal and linear performance with the sum of the correct answers. We replicated overall the results obtained by Duchaine and Nakayama. As showed in Fig. 4, in the first section performances were good with very few mistakes, because participants were presented with the same image in memory and test phase. However, the performances started to be worst in the second and third section (*Novel Image* and *Novel Image with Noise*). The slope became increasingly flat and deviated from the ideal line. Participants made more errors and the standard deviations were larger in these sections. Indeed, as mentioned in Apparatus and Procedure, in the test phase individuals found more complicated to recognize faces with different lighting, pose or both; this level of difficulty was emphasized by the addition of the noise. Indeed, in the *Novel Image with noise*, faces were presented differently from the memory test and reduced in quality by the noise, making more difficult for individuals to compare the image they had previously memorized with the one presented in the test phase.

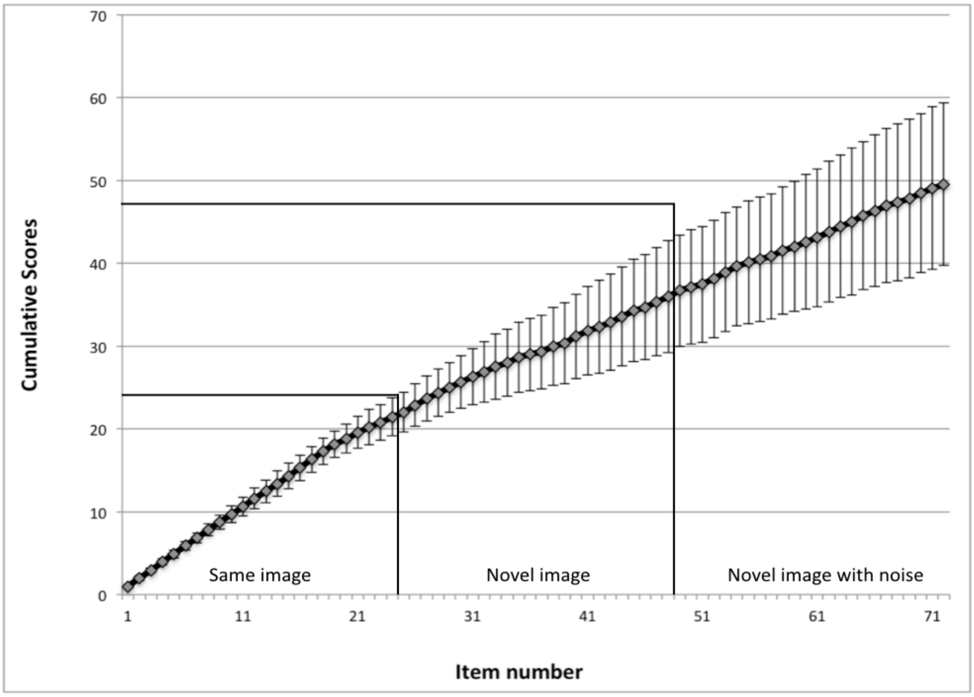

Fig. 4 Total average of cumulative scores for each test item in the CFMT. Points represents the means for each item; error bars represent the standard deviations. It is divided into the three sections of the test by lines that display the ideal performance (with all correct answers). The more the slope deviates from these lines, the more errors participants have done.

Separated correlations were performed to test the hypothesis of a link between parents' and infants' performances (see Fig. 5). We separated analyses for *featural* and *second-order* change. Regarding the first one, correlations revealed a positive significant correlation between fathers and infants (r = .36, p < .05, see Fig. 5), whereas there was no significant correlation between mothers and infants (r = -.20, p = .229). In particular, the correlation affected more females than males. Indeed, there was a significant correlation between daughters and fathers (r = .52, p < .05) and no correlation with sons (r = .21, p = .44). Using the Fisher r-to-z transformation we tested the significance of the difference between mothers' and fathers' correlations and we found a significant difference (Z = -2.77, p < .01).

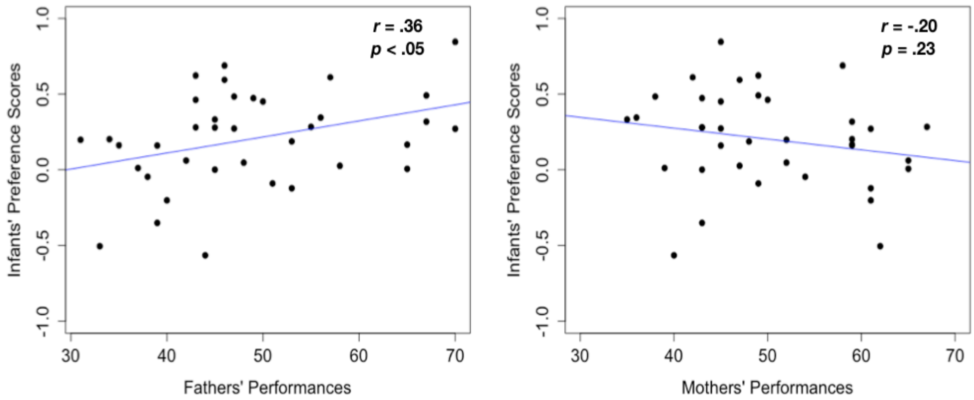

Fig. 5 Correlation between fathers'/mothers' and infants' performances in the *featural* change.

In the *second-order* change the correlations for mothers and fathers were not significant (r_{mothers}= .08, p = .632; $r_{fathers}$ = -.01, p = .941, Fig. 6). In sum, we observed a significant relation in the performances of fathers-infants in the *featural* change and this is true in particular for females, whereas no significant correlations were found in the *second-order* change.

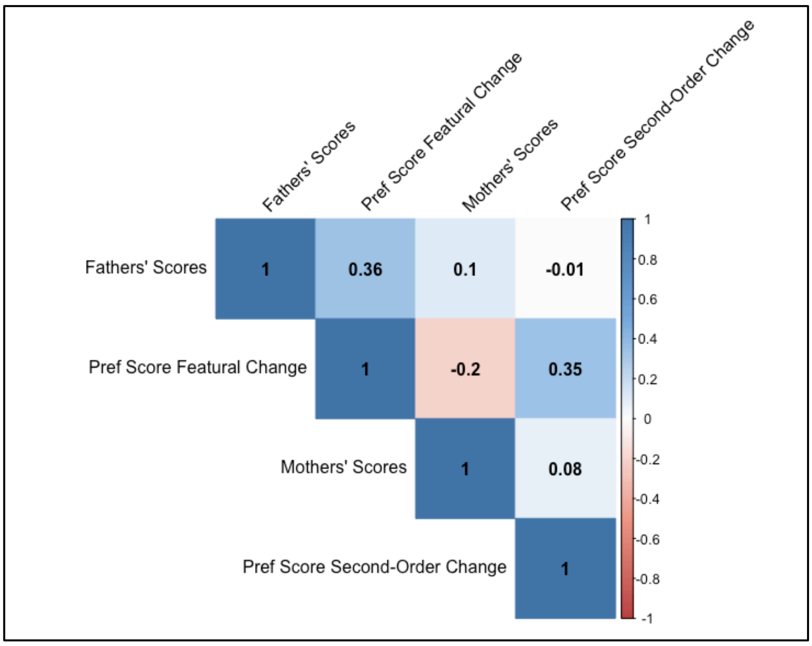

Fig. 6 Correlation matrix for fathers' and mothers' performances and infants' preference scores for both levels of difficulty (easy level = *featural* change, difficult level = *second-order* change)

Discussion

In Study 2 we presented the data obtained by the infants' parents of Study 1. In particular, we aimed to explore whether there is a relation between parents-infants in numerical acuity and face processing. Parents were administered an ANS task and a face recognition standardized test (CFMT).

Considering the ANS part, we found no significant correlations neither in the 1:4 ratio nor in the 1:2 ratio. The present results suggest that numerical acuity in the first steps of development is not influenced by parental acuity. Considering our data there does not seem to emerge a genetic influence in the acquisition of this ability. Indeed, a recent genetic investigation (Tosto et al., 2014) found low heritability of numerical acuity in 16-year-old twins. However, no studies have yet demonstrated a genetic role in the first years of life and further studies are needed to clarify this aspect.

On the other hand, many studies provided evidence for the malleability and the improvement through specific trainings of ANS. For example, Park and Brannon (2013, 2014) showed that non-symbolic approximate arithmetic trainings administered in multiple sessions enhanced symbolic arithmetic abilities. Moreover, many studies demonstrated the positive link between children's mathematical abilities and math-related practices at home (Anders et al., 2012; Lefevre et al., 2009; LeFevre, Polyzoi, Skwarchuk, Fast & Sowinski, 2010b; Kleemans, Peeters, Segers & Verhoeven, 2012). It is therefore plausible to support the idea that environmental influences become active later in development, through activities and conversations that can be related or not to mathematics. Future studies should systematically investigate the role of socio-economic status and numeracy experiences (with observational techniques) in ANS acquisition during infancy. Complementary to this, research could focus its attention on genetic influences in the first years of life.

However, another possible explanation for the absence of correlation is that the infants' measure of the numerical task is not a reliable one. Indeed, infants' preferences could be influenced by other non-numerical variables, such as size and density that were controlled in the images. Future studies should concentrate on understanding the reason why the current experimental parameters do not allow for a reliable estimate of the subjects' number acuity.

On the other hand, we have also assessed parents' performances in face processing. Participants were instructed to memorize a face (or six faces in the Novel Image and Novel Image with Noise sections) and then tested with a three-alternative forced choice task, where one of them was the right face. Our results indicated that participants made more errors in the Novel Image and Novel Image with Noise sections compared to the Same Image section as evidenced by the trend in the cumulative scores showed in Figure 4. Indeed, parents found tougher the recognition of the same face when presented in a novel position, lighting or both. This difficulty still increases with the addition of the noise as presented in the third section of the test (see also McKone, Martini, & Nakayama, 2001).

More interestingly, no studies have already investigated the correlation between parents and infants in the first year of life, separating mothers' and fathers' performances. Findings revealed a significant relation between fathers and infants in the *featural* change, whereas there wasn't a significant correlation with the mothers.

Moreover, this significant link appears stronger for females than for males. These findings raise the question whether this correlation reflects genetic or social components or an interaction of both. Noteworthy, studies on prosopagnosia (Duchaine, Germine, & Nakayama, 2007; Grueter et al., 2006; Kennerknecht et al., 2006; Schmalzl et al., 2008) and twin studies (Zhu et al., 2010; Wilmer et al., 2010) highlight the influence of genetic aspects on face perception. For example, studies on prosopagnosia have found that this deficit is linked to hereditary traits and is better explained by an autosomal dominant pattern. However, the specific influence of gender was not studied in depth. Moreover, to our knowledge, there are no studies that have investigated the genetic role in normal development of face processing.

Another line of research has tested the effects of experience on face perception. We know that in the first years of life face recognition becomes more and more precise for particular categories of stimuli. Indeed, infants begin to develop biases towards their own species and own races, showing advantages for these groups in face recognition. Macchi Cassia, Kuefner, Picozzi and Vescovo (2009) assessed two groups of children, with and without an older sibling, and found that 3-year-olds without siblings presented age bias for adults face whereas children with siblings did not display this bias. Therefore, the experience during the first year of life plays a relevant role in shaping infants' knowledge of the outside world.

Future research could enhance the potentiality of these preliminary results in multiple directions. Firstly, from this study the necessity of a replication with a bigger sample of our findings to test whether the link between fathers and infants is confirmed or not emerges. Moreover, prosopagnosia and twin studies can focus their attention not only on the heritability of face perception abilities but also on the gender to investigate the different influences of mothers and fathers on infants' performances.

CHAPTER 2

2.1 Infants' ability to rely on self-motion information in object individuation

This chapter is based on the following original article:

Decarli, G., Piazza, M., Franchin, L., & Surian, L. (2018). Infants' ability to rely on self-motion information in object individuation. Manuscript submitted.

Abstract

We investigated 10-month-old infants' and adults' numerical expectations in scenarios in which information on self-moving and static object features may give rise to numerically incongruent representations. A red circle (or a blue box with yellow stripes) appeared on the left side of an opaque screen, moved autonomously sideways and then moved back behind the screen. Next, on the opposite side, an identical object was first brought in view by a hand and then pushed back behind the screen (Experiments 1 and 2). The screen was finally removed revealing either one or two objects. Infants looked longer at one-object test events, suggesting that they expected to find two objects. Adults were also shown these animations, and they were asked for their numerical expectations. Contrary to infants, they expected one single object (Experiment 3). While infants' numerical expectations appeared to be dominated by information on object self or induced motion, adults' expectations were mainly guided by information on object static features such as shape, size and color. These findings are discussed in relation to current models on the development of object individuation processes.

Keywords: object individuation; object-tracking system; dynamic features; infancy.

Infants' ability to rely on self-motion information in object individuation

The ability to establish how many objects are present in a scene is a crucial aspect of humans' cognitive system. This ability is present very early in humans, indicating its pre-verbal nature. It was proposed that two distinct pre-verbal systems underlie infants' numerical skills: the Approximate Number System and the Object Tracking System (Feigenson et al., 2004; Piazza, 2010). The first system allows individuals to estimate numerosities without counting and it is imprecise but has no limit as for the set size to which it applies, whereas the second one allows exact and precise quantification. Carey (2009) postulated a specific system of parallel individuation processes that is present in young infants. According to this theory, infants can generate WM models where individuals (e.g., objects) are represented by non-numerical mental symbols. Each symbol corresponds one object in the world on the basis of the one-to-one correspondence principle. Therefore, infants can implicitly represent the numerical output by the 1-1 correspondence between WM symbols and the external individuals. However, differently from the approximate estimation, this system has a limited capacity. The WM models can contain up to 3 individuals. Using manual search task, some authors found that 12- to 14-month-old infants failed to correctly represent 4 objects in the box, whereas they succeeded with 1, 2 and 3 objects (Feigenson & Carey, 2003; see also Feigenson & Carey, 2005). These findings were also confirmed when 10- to 12-month-old infants were shown two filled buckets and they were free to choose one of them. Infants chose the greater quantity in the case of 1 vs. 2 and 2 vs. 3 crackers, but not 3 vs. 4, 2 vs. 4 and 3 vs. 6 crackers (Feigenson, Carey, & Hauser, 2002).

Small set quantification relies on object individuation processes (e.g., Baillargeon et al., 2012), the ability to track and locate a small number of objects through space and time (e.g., Baillargeon et al., 2012; Brower & Wilcox, 2013; Kibbe & Leslie, 2013; Woods & Wilcox, 2013; Xu & Carey, 1996). One key goal in individuation research is to determine which kind of information infants spontaneously use to individuate objects. In a seminal study, Xu and Carey (1996) started the systematic investigation of which factors determine the success of infants' individuation process, i.e. perceive objects as individual entities, traceable in space/time and countable. They showed two objects, emerging from behind a screen. In the so called 'property/kind' condition the objects were of different kinds (e.g., a truck and an elephant) and had different visual properties such as color and shape (e.g., one was red, the other blue), and alternately appeared from the left and the right side of the screen and came back behind it. The screen was then removed, showing either only one of the two original objects (e.g., the red truck) or both. In the 'spatiotemporal' condition, the same objects were presented together on the stage (thus each occupied a different spatial position) before disappearing behind the screen. In the test events, the screen was removed, revealing either one or two objects. Ten-month-olds failed to detect the numerical violation in the property/kind condition, showing that their individuation system had not generated two distinct representations for the two objects. On the contrary, they succeeded in the spatiotemporal condition, detecting the numerical violation when they were shown one-object test events. These findings led the authors to suggest that, before 12 months, infants can individuate multiple objects (at least up to two) when these objects are simultaneously shown, thus occupying different spatial locations; on the other hand, when objects are shown sequentially and the available spatiotemporal information on their identity is ambiguous, infants fail to individuate two distinct objects. This suggests that they could employ the very general sortal concept OBJECT, that is a representation coding spatiotemporal properties (the object location at a certain time), but they could not rely on other information such as shape, which are more specific than OBJECT. The 'object first hypothesis' posits that infants start with the sortal OBJECT and that before 12 months they cannot use more specific sortals in their individuation processes.

Leslie and colleagues (Leslie et al., 1998; Káldy & Leslie, 2005) proposed a neuropsychological model to explain these results. As a reference point they took Pylyshyn's model of individuation (Pylyshyn, 1989). According to Pylyshyn, individuation consists in applying attentional tags (so called indexes) to objects. During the first months of life these indexes are assigned on the sole basis of the location occupied by the objects, and only later can they be assigned by taking into account other perceptual features such as shape or color. This idea is somehow connected with the distinction between the 'what' and 'where' pathways in the brain (Ungerleider & Haxby, 1994). Within this framework, Leslie proposed that before the first year of life, objects' indexing is mostly guided by the 'where' system, while between 10 and 12 months it is also guided by information coming from the 'what' system. This explains why young infants might be unable to individuate two objects based only on feature differences such as shape or color, but they are able to in presence of relevant spatiotemporal information.

However, none of these models predict the results obtained in some other studies. For example, Bonatti et al. (2002, 2005) found that 10-month-olds individuate two objects when one looked like a human and the other did not, as well as when one was a canonically oriented face and the other an inverted face, even when they were not shown to occupy different spatial locations. These findings led to the proposal of the 'human first hypothesis', according to which before 12 months, infants can individuate objects on the basis of the sortal concept HUMAN (see also Galazka & Nyström, 2016). Another study found evidence suggesting the early use of the sortal concept AGENT (Surian & Caldi, 2010). In this study, one object (e.g., a green caterpillar) was self-propelled and it moved non rigidly, while the other one (e.g., a red cup) had a passive motion and was grasped and dropped by a hand. At the end of this familiarization phase, the screen was raised, revealing either one object or two objects. Participants looked longer at the one-object outcome, showing that they had individuated two objects. These findings support the idea that infants younger than 12 months can individuate two different objects when dynamic information indicating the presence of one agent and one inert object is available. A preparedness to pay attention to such information was also found in younger infants in studies that did not investigate object individuation. At seven months, infants quickly learn information about the self-propelled motion of novel wind-up toy animals, and retain it over a 15-min delay (Markson & Spelke, 2006) and even neonates display some sensitivity to information about self-motion (Di Giorgio, Longhi, Simion, & Vallortigara, 2017; see also Scholl & Tremoulet, 2000 for related findings).

One alternative account focuses on event complexity and information consistency (Baillargeon et al., 2012; Wilcox, 1999; Wilcox & Baillageon, 1998a, b). At its core there is the claim that young infants are able to encode both spatiotemporal and featural information (e.g., shape and color) in some simple individuation tasks, involving 'event monitoring', but not in other more complex tasks, involving 'event mapping'. These authors posit that individuation processes involve the representation of two types of information, structural and variable information. Structural information consists of spatiotemporal as well as categorical information concerning very general concepts, such as self-propelled and inert object, whereas variable information includes object perceptual features such as size, shape, color and pattern; these cues are typically diagnostic of more specific concepts, such as bird, dog, car and ball. The model also posits that infants at ten months are able to represent both types of information, as a host of research on infants' physical reasoning has shown. Moreover, according to this model, ten-month-olds' failure to generate numerical expectations in Xu and Carey (1996) property/kind condition was not due to a failure to represent featural information, but to the joint effect of two other factors: the inconsistency between the two information layers and the need to carry over object representations from one event (the object occlusion event) to the next (the screen removal event). They point out that the structural information leads to expect a single object while variable information leads to expect two. Due to this inconsistency, the carry over process that is required to transfer object representations from one event to the next breaks down, preventing infants from generating any specific numerical expectation.

The model proposed by Baillargeon et al. (2012) raises an interesting question. How would infants and adults respond to a complex, event-mapping scenario in which self-motion (structural information) and static (variable information, such as shape and color) information leads to opposite numerical expectations? Imagine that two objects differ only in their motion behavior, that is one displays self-propelled motion and another passive motion (e.g., Csibra, 2008; Gergely, Nádasdy, Csibra, & Bíró, 1995; Luo et al., 2009; Johnson et al., 2008; Luo & Baillargeon, 2005a; Markson & Spelke, 2006; Scholl & Gao, 2013; Surian, Caldi, & Sperber, 2007). Given the inconsistency between the structural and variable information, Baillargeon et al. (2012) model makes a clear prediction: young infants should not be able to generate any numerical expectations. By contrast, if infants before 12 months rely on the self-motion/passive motion contrast, but have difficulties in binding static features such as shape, color and size to their object files, they should generate specific numerical expectations, but their expectations may be different from those generated by adults. Since the objects that alternatively appear at the two sides of a screen are identical, but display different kinds of motion (self-propelled vs. passive movement, possibly activating the sortals AGENT and INERT OBJECT, respectively), infants should individuate two objects. By contrast, adults will have no difficulties in binding variable (static) feature information to their object files and this will lead them to see the scenarios as involving the same object behaving differently at the opposite sides of the screen. The main aim of this study was to test these predictions.

Experiment 1

Methods

Participants. Forty full-term infants participated in the experiment, 19 males and 21 females, with mean age 10 months and 13 days (Age range = 9 months, 6 days to 11 months, 20 days) and were randomly assigned to either the agency (*n* = 20) or the baseline (*n* = 20) condition. Seven additional infants were excluded due to parental interference (n = 1), fussiness (n = 4) or technical failure (n = 2).

Participants were recruited by obtaining the birth list from the Registry Office of the town of Rovereto (Italy). Parents were contacted by telephone and gave written informed consent to a protocol approved by the Ethics Committee of University of Trento.

Apparatus. The apparatus consisted of a wooden display booth with an iMac 27 inch monitor (resolution 2560 x 1440, display size 34 cm x 59 cm) positioned in the middle, on which the events were shown. A curtain was lowered on the monitor between trials and at both sides of the monitor two panels hided the rest of the apparatus. There was a webcam under the monitor to focus on the infant's face, in order to observe the infant's behavior and record looking time fixations. The experiment was conducted in a quiet and well lit testing room.

Stimuli and Events

We generated different animations for each condition. All animations were created with Adobe Flash CS6.

Introductory trials. These trials were proposed to all infants, and their aim was to introduce them to observe one or two objects behind the screen. The animations involved a yellow duck (4.50 cm x 3.40 cm) and a red car (5.30 cm x 3.50 cm).

At the beginning, an occluder (i.e., a grey screen, 16.00 cm x 14.50 cm) was presented in the scene for 3 seconds, a short sound (a bell) started to attract the attention of the infant, and a hand appeared to lower the screen (see Video 1). Then, the hand removed the screen and infants were shown either one or two objects (i.e., a yellow duck and a red car; see Figure 1). Each trial started and ended with the raising and lowering of a curtain.

Each infant observed four introductory trials and there were two orders of outcome presented after the removal of the screen (1, 2, 2, 1 or 2, 1, 1, 2), counterbalanced across participants. Each trial ended when the infant looked away for 2 consecutive seconds, after having looked at least for 8 cumulative seconds, or looked for a maximum of 16 cumulative seconds. The infants' looking times of each trial were taken starting from the removal of the screen, as soon as the object appeared at the view of the participant.

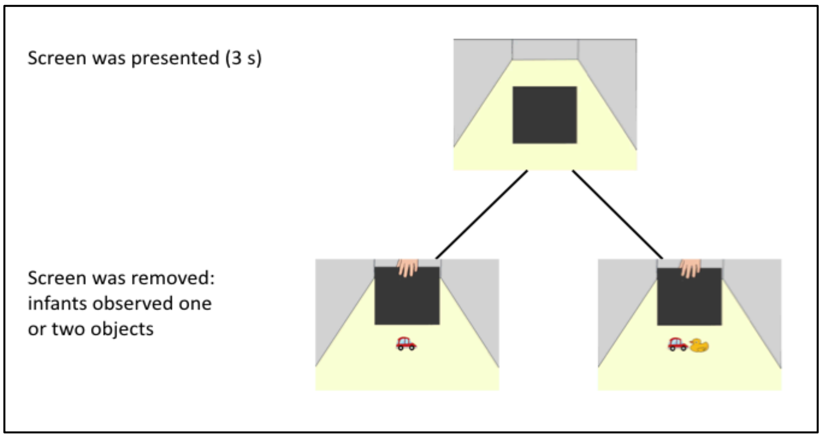

Figure 1. Schematic representation of the *Introductory trials*. Infants were shown a screen and then a hand removed it showing either a single object or two objects.

Test trials: Agency condition. The agency condition consisted of four trials. The first pair of trials involved a simple object (i.e., a red ball, 4.00 cm x 4.00 cm) and the second pair a different object (i.e., a blue box with yellow stripes, 5.00 cm x 1.70 cm). The order of objects' appearances was counterbalanced across participants.

Each trial included a *familiarization phase* followed by a *test phase*. In the *familiarization phase* a screen was presented in the middle of the scene. After 3 seconds an object (e.g., the red ball) emerged from behind the screen with an autonomous movement, it moved back and forth for three times, and then returned behind the screen, disappearing from the view (duration: 10 seconds, Fig. 2). In the same *familiarization* phase, from the opposite side a hand appeared on the scene, went behind the screen and grabbed an object (with the same features of the object with the autonomous movement). The hand dropped the object on the floor and pushed it behind the screen (duration: 9 seconds). The cycle of object appearances and disappearances was repeated four times for the first and third trial and twice for the second and fourth trials. The object that appeared on the left and right side of the screen in each *familiarization* trial was perceptually identical, it differed only in the type of motion to which it was associated: in one case it moved autonomously, while in the other it was grabbed by a hand, dropped and then pushed back behind the screen.

The *test phase* started with the removed of the screen, showing either one or two objects (see Video 2). Two possible orders of outcome (1, 2, 2, 1 or 2, 1, 1, 2) were counterbalanced across participants. Each test trial ended when the infant looked away for 2 consecutive seconds, after having looked for a minimum of 6 cumulative seconds, or looked for a maximum of 40 cumulative seconds. These criteria were the same as those used in Surian and Caldi (2010), except for the maximum of cumulative seconds that was lowered from 60 to 40 seconds in order to reduce the infants' drop-out rate due to fatigue.

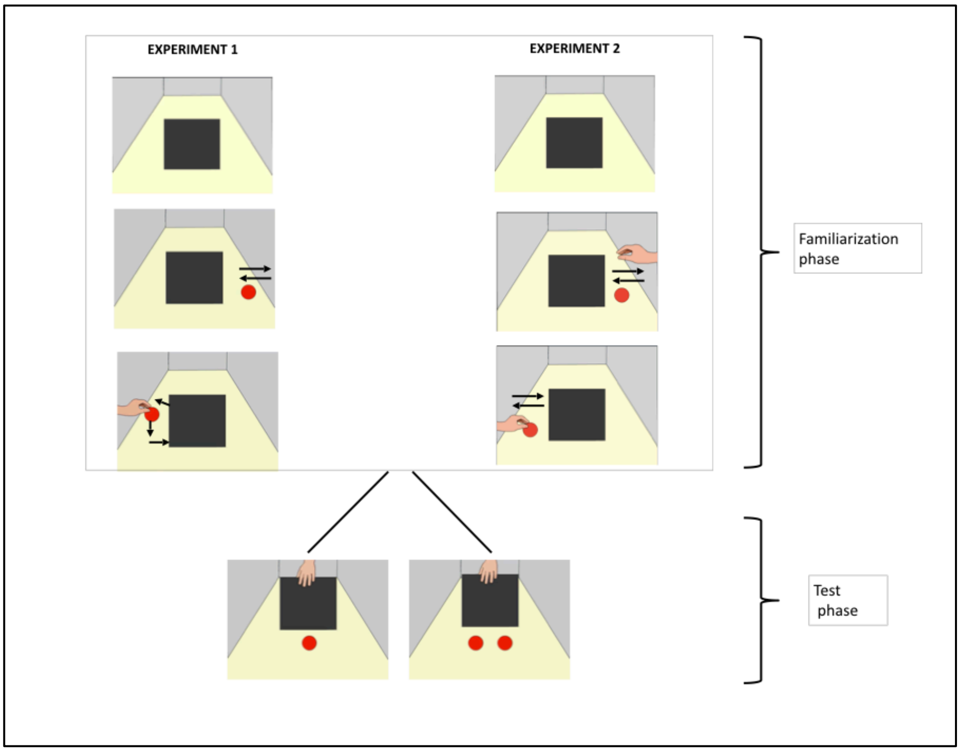

Figure 2. Selective frames presented in the *Agency condition*. Experiment 1: in the familiarization phase a screen was introduced on the scene, after a few seconds an object appeared and exhibited an autonomous movement. Then a hand appeared on the opposite side of the scene and grasped the object behind the screen, dropped the object on the floor and pushed it behind the occluder. Experiment 2: control for the Experiment 1, equating the left vs. right events in terms of movement type (horizontal for both self-propelled and the inert object) and visual features (the hand is present in both self-propelled and inert object parts). In the familiarization phase a screen was presented on the scene, a hand appeared and a self-propelled object came out from behind the screen, moved back and forth and disappeared behind the occluder. On the opposite side, a hand grasped an object and pushed it on the floor, reproducing the same movements as the first object shown on the scene. Then the hand put the object behind the screen. The test phase was identical for both experiments and consisted in the removal of the screen, showing either one object or two objects.

Test trials: Baseline condition. The baseline condition was identical to the agency condition except that participants were shown only the *test phase* (see Video 3).

In this case, no information on the number of objects hidden behind the occluder was provided.

Procedure. Infants sat on their parent's lap at a distance of approximately 60 cm from the central monitor. Parents were instructed to remain silent and not to point at the monitor during the *test phase*. Participants observed four introductory trials and four test trials in either the agency or the baseline condition.

Two experienced observers recorded the looking times and they were blind about the order of the test events that were presented. Each of them pressed a button when the infant was looking at the events. The looking times recorded by the primary observer were used to determine the end of each trial and in the data analyses.

The computer calculated the inter-observer agreement for each infant, first dividing each trial into 100 ms intervals, and then assessing within each interval whether the two observers agreed or not. Agreement percentage was obtained by dividing the total trials where the observers agreed by the total number of intervals within each trial. This index was measured for all the infants and the average agreement was 92% (range = 86% - 97%).

Results

Introductory trials. Looking times were analyzed in a 2 × 2 ANOVA with the outcome (one-object/two-objects) as within-subjects factor and the condition (agency/baseline) as between-subjects factor; there was a significant main effect of outcome ($F(1, 38) = 5.68$, $p = .022$, $\eta^2 = .13$) and a significant interaction condition × outcome ($F(1, 38) = 5.35$, $p = .026$, $\eta^2 = .12$). Planned comparisons indicated that whereas in the baseline condition infants looked longer at the two-objects outcome (M = 13.24 s) than at one-object outcome (M = 11.73 s), $t(19) = 3.1$, $p = .006$, in the agency condition they looked equally long at the two outcomes (M = 12.99 s; M = 13.01 s). Overall, infants looked longer at the two-objects outcome (M = 13.13 s, SD = 2.4) than at the one-object outcome (M = 12.36 s, SD = 2.15), $t(39) = 2.26$, $p = .029$.

Test trials. Infants' looking times were both averaged for all the trials and for each pair trial, as for the introductory events. Shapiro-Wilk tests revealed that half of the data that we use for the analyses were not normally distributed. We therefore performed both parametric and non-parametric analyses. Data were analysed in a 2 × 2 ANOVA with the outcome (one-object/two-objects) as within-subjects factor and the condition (agency/baseline) as between-subjects factor. The main effect of condition ($F(1, 38) = 4.2$, $p = .048$, $\eta^2 = .1$), and the effect of the outcome × condition interaction ($F(1, 38) = 6.17$, $p = .017$, $\eta^2 = .14$) were significant, while the main effect of outcome was not ($F(1, 38) = 2.32$, $p = .136$).

In the agency condition, infants looked significantly longer at the one-object outcome than at the two-objects outcome ($M_{one\text{-}obj.}$ = 16.97 s, SD = 8.63, $M_{two\text{-}obj.}$ = 12.62 s, SD = 4.91; $t(19) = 2.36$, $p = .029$, two-tails, see Fig. 3). In the baseline condition, looking times did not differ for the two outcomes ($M_{one\text{-}obj.}$ = 11.1 s, SD = 3.58; $M_{two\text{-}obj.}$ = 12.14 s, SD = 5.68; $t(19) = -.90$, $p = .377$). We found a significant difference between the one-object outcome in the agency and in the baseline condition ($p < .01$) but not for the two-objects outcome ($p = .78$).

Wilcoxon signed-rank test yielded results similar to parametric tests. We found higher looking times for the one-object outcome in the agency condition compared to the baseline condition ($W = 272.5$, $p = .051$); the same trend is present also comparing one-object outcome and two-objects outcome in the agency condition (V = 158, p = .048).

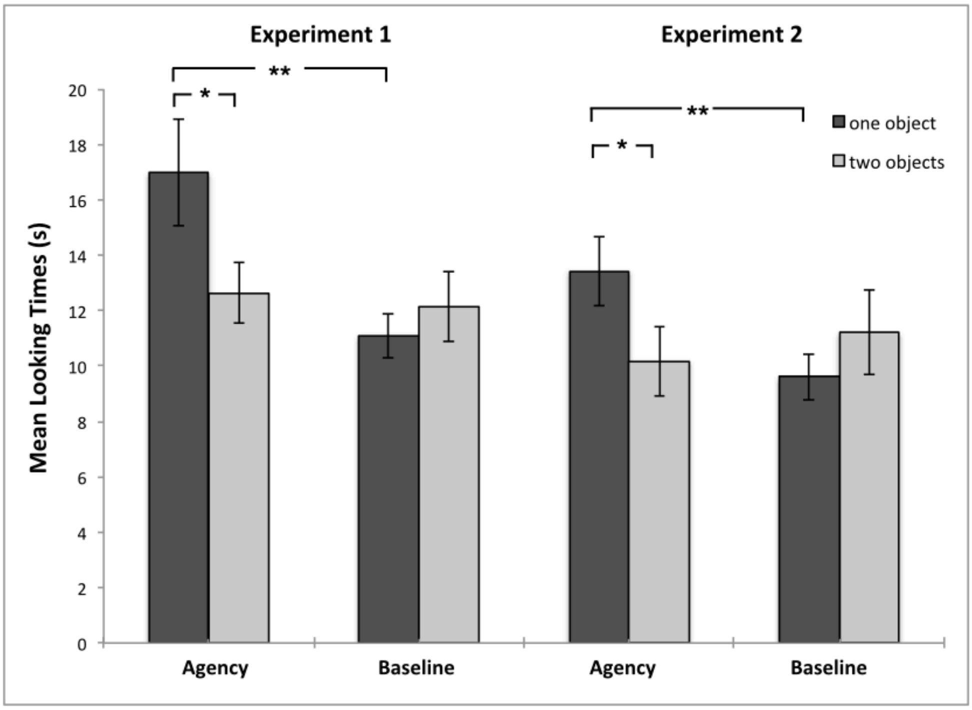

Figure 3. Mean looking times (and standard errors) at one- and two-objects outcomes in the agency and baseline conditions for Experiment 1 and Experiment 2. The asterisk (*) indicates p < 0.05 and two asterisks (**) indicate p < 0.01.

In sum, the results of this experiment clearly show that 10-month-old infants rely on different motion cues to individuate objects. Comparing these results with those obtained by Xu and Carey (1996), we can conclude that at 10 months, self-propelled and induced motion contrast is not only sufficient for individuation, but it is a more powerful cue compared to shape and color features.

However, these results could also be interpreted in a different way. Maybe infants individuate different objects based on different trajectories of the movements shown in the *familiarization* phase. Indeed, the self-propelled object moved horizontally back and forth, while the inert object was dropped vertically on the floor. Infants may have used these additional cues derived from object trajectories in order to individuate different objects. Therefore they might have looked longer at the one-object outcome not because of the contrast in the motion information, but simply because of their different trajectories. This suggestion seems to be supported by some findings demonstrating that 7-month-old infants succeed in individuating two objects when they are shown their different functional role, such as hammering and pouring (Wilcox and Chapa, 2004). Note that during the demonstrations, the objects not only displayed different funtions, but they also followed distinct paths.

A second issue is the presence of the hand appearing on one side of the screen and not on the other. The presence of the hand in one side of the screen could have influenced infants by creating the expectation of two different objects, one with the hand and the other without it.

The aim of Experiment 2 was to eliminate the differences in movement trajectory and the presence/absence of the hand in order to check whether these differences were responsible for the reported results of Experiment 1. In Experiment 2, the trajectories of the motions displayed by the self-propelled object and by the passive object were the same. In addition, we added a hand on the side of the screen where the self-propelled object appeared, but the hand never touched the object. If infants rely only on motion information and neglect non-motion information, we should observe similar results as in Experiment 1. If infants respond differently from Experiment 1, this indicates that they are influenced by other factors.

Experiment 2

Methods

Participants. Twenty-nine full-term infants participated in Experiment 2, 12 males and 17 females, with mean age 10 months and 3 days (Age range = 9 months, 1 day to 11 months, 6 days). Five additional infants were excluded due to fussiness (*n* = 3) or technical failure (*n* = 2).

Apparatus. The apparatus was identical to that in Experiment 1.

Stimuli and Events

Introductory trials. The Introductory trials were the same as proposed in Experiment 1. Infants observed a screen on the scene for 3 seconds. After the presentation of an auditory stimulus, a hand appeared to lower the screen. Behind the screen there could be one or two objects. The animations involved a yellow duck and a red car. At the end and at the start of each trial a curtain was raised/lowered, allowing the experimenter to change the animations.

Each infant observed four introductory trials with two orders of outcome presented after the removal of the screen (1, 2, 2, 1 or 2, 1, 1, 2), counterbalanced across participants. Each trial ended when the infant looked away for 2 consecutive seconds, after having looked at least for 8 cumulative seconds, or looked for a maximum of 16 cumulative seconds.

Test trials: Agency condition. The agency condition was composed by four trials. The objects involved in these trials were the same as in Experiment 1 (i.e. a red ball and a blue box with yellow stripes). The first pair of trials involved one object while the second pair the other one. The order of object appearances was counterbalanced across participants.

In the *familiarization* phase a screen was presented in the middle of the scene. A sound was played and simultaneously a hand appeared on the scene. Then an object emerged from behind the screen with an autonomous movement: it moved in the direction of the hand, which however never touched the object and remained fixed. The object moved back and forth and then returned behind the screen, disappearing from the view of the infant (duration: 13 seconds). The hand also disappeared from the scene (see Fig. 2).

From the opposite side of the screen a hand emerged and went behind the screen to grasp an object that presented the same features as the first object. The hand pushed it reproducing a movement that was symmetrical to the motion followed by the first object. Then the hand moved upwards and left the object on the stage; in this case the object remained stationary, showing that the object did not move unless it was pushed. Finally, the hand put the object behind the screen and disappeared from the scene (duration: 14 seconds). The cycle of object appearances and disappearances was repeated four times for the first and third trial and twice for the second and fourth trials. Differently from Experiment 1, the objects that are seen on the two sides of the screen present mirrored motion paths (in one case self-propelled, in the other case passive). The hand that pushed the object reproduces motions that were symmetrical compared to the motions reproduced by the self-propelled object (see Figure 2).

The test phase included the removal of the screen, showing either one object or two objects. As for Experiment 1, two possible orders of outcomes (1, 2, 2, 1 or 2, 1, 1, 2) were counterbalanced across participants. Each test trial ended when the infant looked away for 2 consecutive seconds, after having looked for a minimum of 6 cumulative seconds, or looked for a maximum of 40 cumulative seconds. These criteria were the same as Experiment 1.

Test trials: Baseline condition. In the baseline condition infants observed only the test phase.

Procedure. Infants sat on their parent's lap at a distance of approximately 60 cm from the monitor. Parents were instructed to remain silent and not to point at the monitor during the *test phase*. Participants observed four introductory trials and four test trials, in either the agency or the baseline condition as in Experiment 1.

Two observers recorded the infants' looking times and were blind about the order of the animations presented on the screen. The average of inter-observer agreement was 93% (range = 87% - 95%).

Analyses

For Experiment 2 we performed one-tail analyses because we already hypothesized the direction of the possible effect. Indeed, based on the results of Experiment 1, looking times at the one-object outcome are expected to be longer than looking times at the two-objects outcome.

Results

Introductory trials. We calculated for each infant the means of looking times for one-object and two-objects outcomes. Data were normally distributed ($W_{one\text{-}obj.}$ = .91, p = .05; $W_{\text{two-obj.}}$ = .926, p = .088) and infants looked equally longer at the one-object (M = 12.91 s, SD = 2.54) compared to the two-objects outcome (M = 12.85 s, SD = 2.33), $t(22)$ = .10, p = .919. A 2 (condition) × 2 (outcome) ANOVA yielded no significant main effects or interactions.

Test trials. Shapiro-Wilk test revealed that the majority of the data was not normally distributed (agency condition: $W_{\text{one-obj.}}$ = .943, p = .56, $W_{\text{two-obj.}}$ = .719, p < .01; baseline condition: $W_{\text{one-obj.}}$ = .76, p < .01, $W_{\text{two-obj.}}$ = .817, p < .05). We therefore performed as principal analyses non-parametric comparisons. In the agency condition, infants looked significantly longer at the one-object outcome than at the two-objects outcome ($M_{\text{one-obj}}$ = 14.09 s, SD = 4.06, $M_{\text{two-obj.}}$ = 9.83 s, SD = 4.76; V = 46.5, p < .05; parametric analyses approached significance: $t(9)$ = 1.87, p = .05). In the baseline condition, infants looked equally long at the one-object and two-objects outcome ($M_{\text{one-obj}}$ = 9.61 s, SD = 2.87, $M_{\text{two-obj.}}$ = 11.2 s, SD = 5.3; V = 31.5, p = .57; parametric analyses yielded similar results: $t(10)$ = -.807, p = .781). A significant difference was found when we compared looking times at the one-object outcomes in the agency and in the baseline condition ($M_{\text{one-obj,baseline}}$ = 9.61; $M_{\text{one-obj,agency}}$ = 14.09; W = 101.5, p < .01; parametric analyses: $t(20)$ = 2.98, p < .01), whereas there was no difference in looking times for two-objects outcome in the two conditions ($M_{\text{one-obj,baseline}}$ = 11.2; $M_{\text{one-obj,agency}}$ = 9.83; W = 52.5, p = .701; parametric analyses: $t(20)$ = -.634, p = .733).

In Experiment 2 we replicated the results of Experiment 1. Infants looked longer at the one-object outcome than at the two-objects outcome in the agency condition, whereas in the baseline condition they looked equally long at the two types of outcomes. Thus, we provide further evidence for the individuation process primarily based on dynamic information and rule out the role of other factors such as motion trajectory and presence of the hand.

While the results of the first two experiments suggest that self-motion features dominate the infants' object individuation processes, it is not clear whether such primacy would also be found in adults. It is possible that adults assign more weight to other non-motion visual features, which would lead them to see the scene as involving the same object that behaves quite differently on the two sides of the screen. In order to check whether the same primacy of motion cues over other visual features such as shape, size and color is also present in adults, we presented the same stimuli used in Experiment 1 to a group of adults and, since spontaneous looking times would not work as dependent variable with adults, we asked them explicitly about their numerical expectations.

Experiment 3

Methods

Participants. Eighty-three university students participated (M = 20.44 years, SD = 1.34). Participants volunteered their help and were not given credit for their participation. They were tested in groups and two experimenters observed them to ensure the independence of the answers.

Materials and procedure. Adults were presented the *familiarization* phase of the animation stimuli used in the agency condition of Experiment 1. At the end of that phase they were given a written question tapping their numerical expectation. Half of the participants observed the event involving the red ball and the other half the event involving the blue box with yellow stripes. Participants observed only one video. Animations were presented on a large projector screen. Half of the participants received the open query "*Numerical expectations: what do you expect to see behind the screen?*". The other half were asked, in the binary choice test question to say whether they expected to find one or two objects behind the occluder.

Results

The two types of questions gave rise to very similar response patterns. On the binary choice test question, 80.5% responded that they expected one object and the rest (19.5%) two objects, $p < .001$, binomial test, two tails. A similar strong bias was found in the responses to the open test question: 88.1% responded that they expected one object, $p < .001$, binomial test, two tails. The rest responded that they expected either two objects (7.14%), or "*at least one*" (4.77%).

General Discussion

In this study, 10-month-olds were shown objects that emerged and disappeared one at a time behind a screen. In the agency condition of Experiment 1, infants were shown one object appearing and moving autonomously on one side of the screen; then, on the opposite side of the screen, an identical object was grasped by a hand, dropped on the floor and pushed again behind the screen. In the test phase the occluder was removed revealing either one or two objects. Infants looked significantly longer at the one-object outcome, showing that that they had individuated two objects. However, in Experiment 1 infants may have paid attention to some irrelevant aspects, such as the fact that the two objects followed different motion paths (the self-propelled object moved horizontally right-to-left and back, the inert object was grasped and dropped on the floor) or the fact that a hand appeared on one side of the screen ('inert object side'), but there was no hand on the other side ('self-propelled object side'). In Experiment 2 we eliminated these differences and replicated the results found in Experiment 1. Finally, in Experiment 3, adults observed the same event stimuli used in Experiment 1 and were asked about their numerical expectations. More than 80% of them said they thought there was one object behind the screen. They clearly perceived the event as involving a single object that behaved autonomously on one side of the screen and passively on the other side.

These findings demonstrate that infants at 10 months can individuate multiple objects when they are not presented simultaneously (thus occupying two specific positions in space) and, crucially, even when they are perceptually identical, as long as they differ in the kind of movement (self-propelled vs. passive) that they exhibit. This is consistent with the claim that infants, as early as 10 months of age, spontaneously individuate objects by relying on sortal concepts more specific than OBJECT, such as AGENT, INERT OBJECT (Surian & Caldi, 2010) and HUMAN (Bonatti et al., 2002; Bonatti et al., 2005). It also highlights the important role of motion features in infants' individuation process.

The findings of the study are also consistent with Leslie and colleagues' (1998) neuropsychological model of the object tracking system. According to that model, infants first create a temporary object representation, an 'object file', mainly relying on spatiotemporal information processed by the 'where neural route' and only later they encode in the object file also featural information processed by the 'what neural route'. The two pathways would be completely connected only at the end of the first year of life. However, our results demonstrated that infants before 12 months can assign two different indexes when self-motion information is available. Previous neuroimaging studies have found that while features such as shape activates the 'what system' and motion the 'where system', a specific type of object motion, i.e. biological motion activates both what and where systems (e.g., Vaina et al., 2001). This suggests that the contribution of the where system to infants' object individuation processes may be richer than initially proposed by Leslie et al. (1998): it allows them to assign a new object index on the basis of spatiotemporal information, but it may also help binding crucial information on object motion type, information that is crucial in triggering some sortal concepts (such as AGENT or ANIMATE OBJECT).

The present findings also help to test a prediction derived from the recent developmental model on object individuation processes proposed by Baillargeon et al. (2012). A central aspect of this model is the distinction between structural and variable information. Structural information include both spatiotemporal and information that is diagnostic of very general concepts (e.g., the animate/inanimate distinction), such as self-propelled motion, whereas variable information include object features that are more likely to change contextually or that are typically diagnostic of more specific concepts, such as size, shape, color and texture. According to this model, young infants fail to generate numerical expectations in complex tasks, such as Xu and Carey (1996) property/kind condition because of (a) the inconsistency between the two information layers and (b) event mapping requirements (i.e., the need to carry over object representations from the event of object occlusion to the next event involving the screen removal). Structural information leads to expect a single object while variable information leads to expect two and this inconsistency prevents infants from generating any numerical expectation because it leads to the breakdown of the information transfer that is required in the event mapping tasks.

This account also predicts that infants will not generate numerical expectations in the agency conditions in Experiments 1 and 2 of the present study. In these conditions there was inconsistency between structural and variable information (i.e., structural information support two-object expectations whereas variable information support one-object expectations) and there were also event-mapping requirements (i.e., the need to carry over the relevant object representations from the occlusion event to the next, screen removal event). The crucial difference between the present study and previous works was the reversal of the numerical expectations supported by the two types of information. In the present study, structural information leads to expect two objects, while variable information supports the numerical expectation of a single object. In previous studies it was the opposite. Thus, a model that emphasizes the effect of the inconsistency between structural and variable information predicts, both for Xu and Carey's property/kind condition and for our agency conditions, that infants will not generate any numerical expectation. By contrast, our results clearly point out that both adults and young infants generated a specific expectation. Crucially, infants' expectation was consistent with self-motion ('structural') information whereas adults' expectation relied more on shape and color ('variable') information. The present findings therefore suggest that either the structural vs. variable information consistency plays a less important role that it is assumed in Baillargeon et al. (2012) model, or that such model needs to revise such distinction, perhaps by introducing a further differentiation between spatiotemporal and self-motion information, which, at present are lumped together into the structural information category.

In conclusion, our findings indicate that, lacking spatiotemporal information, two objects that only differ in motion cues, a crucial feature in the identification of agents and for the early animate/inanimate distinction, are individuated separately by infants. This suggests that motion information has a primary role in early object individuation processes. An interesting goal for future studies would be to test whether the infants' pattern of responses found in the present study could be generalized also to scenarios in which objects differ in other motion cues. For example in a context in which the contrast is not between autonomous vs. passive motion but between semi-rigid (e.g., bio-motion) and rigid motion, that is a contrast that is likely to activate, respectively, representations of living entities and mechanical artifacts.

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CHAPTER 3

3.1 The role of domain-general and domain-specific abilities in developmental dyscalculia

Introduction

Developmental dyscalculia (DD) is a neurodevelopmental specific learning disability in arithmetic skills that is unrelated to low IQ and to inadequate schooling and its prevalence is estimated ranging from 3 to 6% (Shalev, 2007). Although DD could present co-morbidity with other disorders (e.g. ADHD), in many cases it occurs separately from other abilities, such as reading and spelling. Dyscalculics can show a broad range of deficits that comprises difficulties in basic skills such as judging the greatest quantity or associating magnitudes to symbols, up to more complex abilities such as mental and written calculation.

Multiple hypotheses have been proposed to address the question of the origins of DD. On one hand, some authors highlighted the possibility that DD originates from dysfunctioning in domain-specific systems, while others hold the idea that dyscalculia results from a combination of domain-general ones. Here we review the two positions.

Hypotheses of domain-specific deficits

Domain-specific hypotheses posit that the core deficit of DD derives from deficit in the numerical components. In particular, two systems are considered fundamental in numerical processing, the Approximate Number System (ANS) for the estimation of large quantities and the Object Tracking System (OTS) for the spatio-temporal tracking and precise enumeration of small set of numbers (usually up to 3-4). In the first paragraph we will discuss the findings obtained in the assessment of ANS in DD, while in the second the results in the OTS field.

Some authors found evidence for a link between DD and ANS. In these studies children presented specific impairments in approximate processing of numerosities (Mazzocco et al., 2011; Mussolin et al., 2010; Piazza et al., 2010; but see also: Bugden & Ansari, 2016; Olsson, Östergren, & Träff, 2016; Skagerlund & Träff, 2016). Evidence was provided for a greater distance effect in dyscalculics than in controls in comparing non-symbolic quantities (Mussolin, Mejias, & Noël, 2010) and for a deficit in dots comparison task (Piazza et al., 2010). Although these studies demonstrated a specific deficit in the ANS acuity, others did not find differences in RTs and accuracy in non-symbolic comparison task with all the combinations of numbers from 1 to 9 (DeSmedt & Gilmore, 2011; Rousselle & Noël, 2007), but a deficit in the digits comparison task.

Another domain specific account of DD proposed impairments in the OTS. This line of research found deficits in mastering the exact number of objects in small sets (Desoete & Grégoire, 2006; Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009; Schleifer & Landerl, 2011; van der Sluis et al., 2004), reporting steeper RTs slopes and more errors in counting up to three objects in dyscalculics than in controls, but similar performances for counting large numerosities (Andersson & Östergren, 2012; Schleifer & Landerl, 2011). However, other authors failed to find similar results (Landerl et al., 2004).

A similar but distinct hypothesis proposed a deficit in manipulating exact numerosities, not only in the subitizing range (up to 3 or 4), but also above this range (Butterworth, 2011; Iuculano et al., 2008; Zorzi, Stoianov, & Umiltà, 2005). As regard to dyscalculia, these authors hypothesized a specific deficit in enumerating capacities and manipulating exact numerosities but, contrary to the OTS hypothesis, they did not assume limits in the range. Indeed, according to them dyscalculics could have impairments also with larger numerosities (7, 8, 9 etc.).

Finally, another line of research supported the access deficit hypothesis (Rousselle & Noël, 2007). According to these authors, the core deficit of DD would consist in connecting symbols with the corrisponding representation of numerical magnitude. As already mentioned above, some authors found impairments in children with DD in symbolic comparison tasks but not in non-symbolic ones (Rousselle & Noël, 2007; DeSmedt & Gilmore, 2011), supporting the lack of connection between symbols and magnitude representations.

In sum, while there seems to be some indications that the ANS and also potentially the OTS may be dysfunctional in dycalculia, the studies have lead to contradictory results and it is still unclear the influence of each system in this neurodevelopmental disorder.

Hypotheses of domain-general deficits

In executing mathematical tasks, many abilities are involved not only numerical ones. For example, we use WM for storing and manipulating information or inhibition skills for choosing which aspects of that information are relevant or not for the task (Baddeley, 1986; Miyake et al., 2000). Therefore, some authors tested the hypothesis that DD develops due to impairments in those domain general mechanisms.

Several studies provided evidence for a deficit in visuo-spatial WM (Ashkenazi et al., 2013; Rotzer et al., 2009; for its role in ANS acuity: Bugden & Ansari, 2016). For example, Ashkenazi and colleagues (2013) examined multiple components of WM and they found that dyscalculics showed lower arithmetic performances and lower scores on visuo-spatial WM task. Other studies have focused their attention on verbal WM. In particular, poorly performances were shown in processing linguistic and numerical information in children with DD (e.g. D'Amico & Guarnera, 2005; Passolunghi & Siegel, 2001).

Another line of research focused the attention on the role of shifting and inhibition skills in DD (Bull, Johnston, & Roy, 1999; McLean & Hitch, 1999). Passolunghi and Siegel (2004) showed that dyscalculic children presented more intrusion errors than controls in verbal WM tasks (e.g. listening span task, where children were asked to say if sets of sentences were true or false; at the end of each set they had to recall the final word of each sentence). The authors concluded that dyscalculics presented reduced capacities to manage irrelevant information. These findings were also suppored by another study (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013) where the authors demonstrated that visuo-spatial short- term memory and inhibition impairements were the most important dysfunctions in DD, thus supporting the hypothesis that DD emerges as a consequence of impairments in domain-general skills.

All the aforementioned studies supported the hypothesis of a domain-general deficit. Nevertheless, the results in this field appear controversial. Some studies found a specific deficit in visuo-spatial WM (Andersson, 2010; Schuchardt, Maehler, & Hasselhorn, 2008), whereas others failed to replicate such results (Andersson, 2008b). Moreover, some authors reported normal inhibition (Andersson & Lyxell, 2007) and shifting abilities (Andersson, 2010) in dyscalculic children.

Finally, some authors support the heterogeneity of DD as a result of individual differences in development, where domain-general problems and domain-specific deficits co-exist in the same disorder and lead to functional impairments (Kaufmann et al., 2013).

The present study

The main goal of the present study was to improve the knowledge in this field and to directly compare domain-general and domain-specific hypotheses. In particular, we tested a group of dyscalculics and matched controls using multiple tasks to assess a) the presence of deficits in magnitude representations assessing both the ANS and the OTS, b) the access hypothesis deficit by comparing symbolic and non-symbolic tasks, c) the domain-general hypothesis by testing visual and spatial STM.

Method

Participants

We tested thirty-two dyscalculic children and thirty-two typically developing children with no learning deficits. Parents gave written consent to participate at the study. Both groups were administered the following tasks:

- Non-symbolic comparison task
- Symbolic comparison task
- Enumeration task
- Visual short-term memory task (Visual STM task)
- Corsi block tapping task.

Selection of children with dyscalculia

Thanks to the collaboration with the "Azienda Sanitaria Beato de Tschiderer" (Trento, Italy), we selected 32 children with DD or difficulties in mathematical acquisition. The mathematical abilities were assessed by administering one of the following tests: the Battery for the assessment of Developmental Dyscalculia (BDE-2; Biancardi, Bachmann, & Nicoletti, 2016), that is divided into 3 areas, numerical processing, calculation and number sense or the AC-MT test (Cornoldi, Lucangeli, & Bellina, 2002), a standardized arithmetic battery for children aged 6 to 11. Participants included in the sample presented either the diagnosis of dyscalculia or severe difficulties in mathematical and calculation domains. Further criteria were: general intelligence, assessed with the Wechsler Intelligence Scale for Children (WISC IV, Wechsler, 1991), within the normal range; normal vision and hearing; normal schooling; no neurological or psychiatric disorders. The final group had a mean age of 9.51 (range 7.42 – 14) and average total IQ of 97 (SD = 9.48).

Selection of control group

Thirty-two children (mean age = 9.79, range 7.5 – 14.33) were selected from a sample of eighty-seven children of a primary school in Malo (province of Vicenza, in the north of Italy). Controls were administered WISC's subtests Similarities and Matrix Reasoning and their scores were used as measures of verbal and non-verbal IQ. The Similarities subtest measured logical and verbal thinking by asking children to tell how two objects or concepts were alike or different. The Matrix Reasoning subtest measured the visual processing and abstract/spatial perception; children observed matrices of images with a missing image and they were asked to choose the missing piece from a range of options. The final group matched to the group of dyscalculics for both age ($t(62) = -.71$, $p = .48$) and verbal and non-verbal IQ (Similarities: $t(59) = -.31$, $p = .76$; Matrix Reasoning: $t(61) = 1.68$, $p = .097$).

Procedure

Tasks

Non-symbolic comparison task

Participants were presented with pairs of arrays of black dots on white background, presented laterally on the screen. They were instructed to observe the two arrays and to judge without counting the greater one, by pressing the response-key on the mouse located on the same side of the larger array. The arrays remained on the screen until children gave an answer. However, children were instructed to give the answer as fast and accurate as possible to avoid the counting of the dots presented in the stimuli.

Stimuli were pairs of arrays, one of which (n1) always contained either of 16 or 32 dots. Stimuli paired with arrays of 16 dots (n2) could contain 12, 13, 14, 15, 17, 18, 19, 20 dots, while stimuli paired with 32 dots could present 24, 26, 28, 30, 34, 36, 38 or 40 dots. Stimuli were controlled for size and total occupied area. The task started with 8 training trials where a positive or negative feedback was given to participants, followed by 128 trials that were divided in 8 blocks. In the training trials, a feedback was given to participants to familiarize with the task. It lasted about 10 minutes. The task aimed to assess the ability to discriminate and compare two different numerosities without counting.

Symbolic comparison task

The task was similar to the dots comparison task described above. Participants were presented with pairs of stimuli, but contrary to the first task, the stimuli consisted in digits from 1 to 9. Participants were asked to decide as quickly as possible which of the two digits was the largest. Stimuli remained on the screen until participants pressed a response-key on the mouse. The task started with 8 training trials where a positive or negative feedback was given to participants, and then it comprised 128 trials divided in 8 blocks. It lasted about 10 minutes. The task aimed to measure the ability to compare symbolic numerosities.

Enumeration task

Participants were presented with arrays of colored dots appearing in a central grey circle and ranging from one to eight (Fig. 1). When the image disappeared, participants were asked to say aloud and as quickly and accurately as possible the precise number of dots. The responses were recorded via a michropone. Before starting the task, participants were instructed to pronounce numbers from one to eight in the microphone; this part was important to calibrate the microphone to the children's voice pitch for each numerosity. Stimuli were controlled for size and total occupied area; thus, across numerosities, half of dots were constant in dot size and the other half in dot total occupied area, to make sure that participants' estimation was based on numerosity and not on other factors.

The task comprised 10 training trials, followed by 128 trials divided in 4 blocks. It lasted about 30 minutes. The task aimed to measure the precise estimation of small numbers and it reflects the OTS capacity.

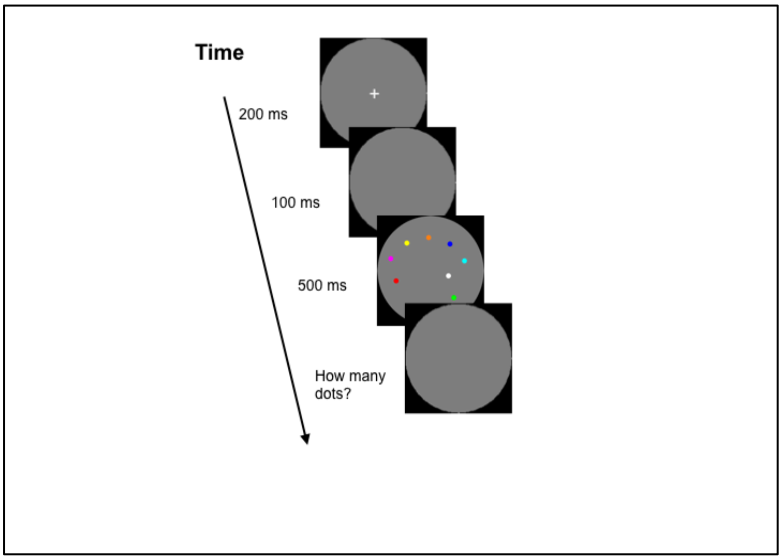

Fig. 1 Enumeration task: schema of timing and structure.

Visual STM task

Participants were presented with one image containing different colored dots, and then, after a 1s interval, with a second image that could be identical or different from the first one; each image was composed by dots from 1 to 8 (Fig. 2). The images used for this task were identical to the ones used for the enumeration task described above. Participants were asked to perform a same-different judgment aloud, while an experimenter pressed the corresponding answer given by participants on the keyboard. In half of the tests the two images were the same, in the other half one dot changed color. The experiment started with 10 training trials, followed by 128 test trials divided in 4 blocks. Only during the training trials participants got feedback (correct / wrong answer) about their performance.

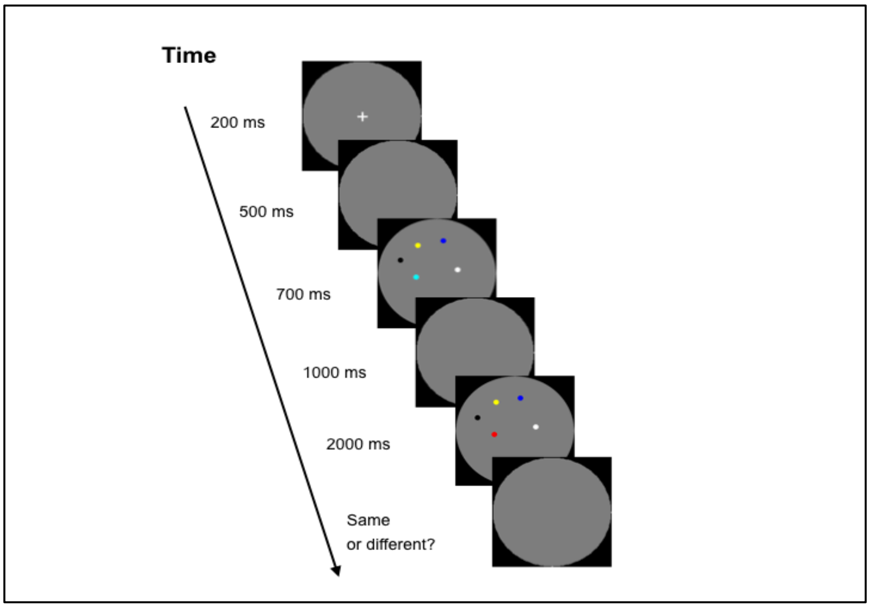

Fig. 2 Visual STM task: schema of timing and structure.

Corsi block-tapping task "forward" and "backward"

The test (Corsi, 1972) consisted of nine blocks placed on a board. The blocks are numbered from 1 to 9 only on one side of the block, visible to the experimenter but not to participants. The experimenter was seated in front of the child and tapped the blocks with the finger in sequence. Participants were instructed to observe carefully the actions of the experimenter and to repeat exactly the sequence with their fingers. For each level of touched block (e.g. sequence of two touched blocks) there were three trials and the task started with a sequence of two blocks touched by the experimenter. If participants succeeded in two out of three trials, the experimenter increased the level of the number of blocks to be touched. The test terminated in the case of failure in reproducing two sequences of a given level.

In the "backward" version, the experimenter touched a sequence of blocks as in the "forward" version, but participants had to repeat it in inverse order, i.e.

touching first the last one indicated by the experimenter. The test terminated when the child failed to reproduce the sequence in two trials out of three.

The test was interrupted when the child missed several sequences of the same number twice out of three. This task aimed to measure the visual WM.

Results

Non-symbolic comparison task

In the non-symbolic comparison task, we calculated mean accuracy and mean RTs for each participant. We also estimated the precision of the numerical representations by calculating the internal Weber fraction (hereafter *w*) for each participant that provides an index of the precision of the internal quantity representation (Piazza et al., 2004). Assuming the hypothesis that numerosities are internally represented by a logarithmic internal number line with fixed Gaussian variability, *w* corresponds to the standard deviation of the estimated Gaussian distribution of the internal numerical representation that generates the observed performance. Because this measure is dependent upon model fitting, we excluded the subjects for which the model did not fit well ($R^2 < 0.2$; for dyscalculics: n=4; for controls: n=2). The average of R^2 for dyscalculics was 0.47, while for controls was 0.57. Separated t-tests revealed that controls presented significantly higher accuracy (M_{contr} = 67.78, SD = 6.59; M_{dysc} = 63.84, SD = 7.8; $t(62) = 2.18$, $p < .05$, Fig. 3), resulting in a smaller *w* fraction (M_{contr} = .24, SD = .10; M_{dysc} = .32, SD = .14; $t(55) = -2.55$, $p < .05$, see Fig. 4). Importantly, the two groups did not differ in RTs (M_{contr} = 1595.79 ms, SD = 632.45; M_{dysc} = 1556.38 ms, SD = 624.91; $t(62) = .25$, $p = .803$).

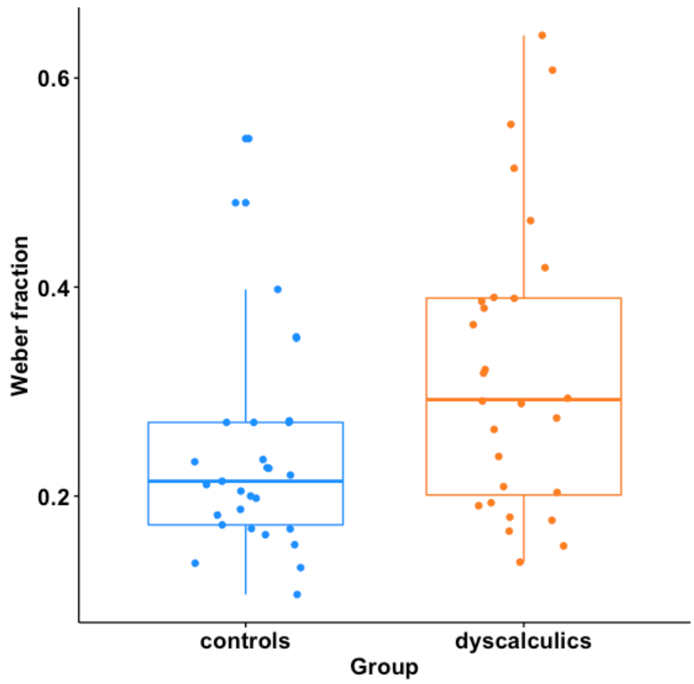

Fig. 3 Boxplot of *w* fraction in dyscalculics and controls.

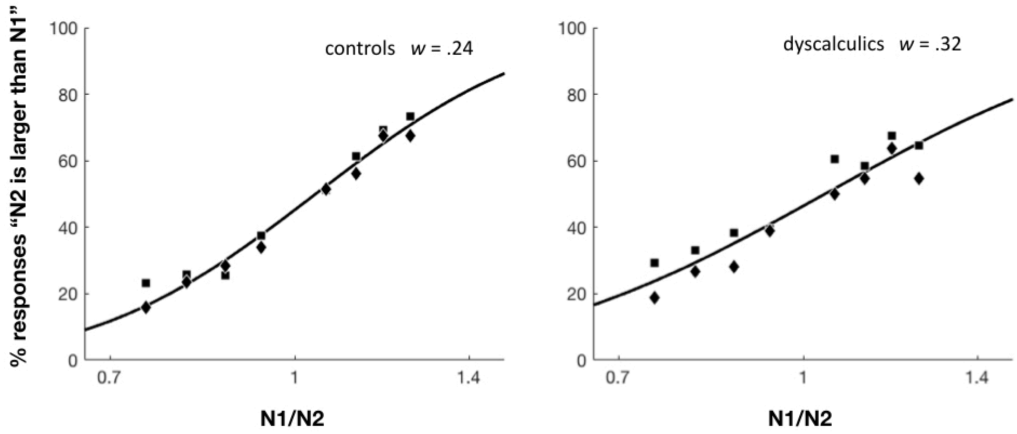

Fig. 4 Psychometric functions relating the proportion of trials in which participants responded that n2 was more numerous than n1 as a function of the logarithm of the ratio between n2 and n1. The fitted curves are derived from the equations described in (Piazza et al., 2004).

Symbolic comparison task

For the symbolic comparison task, we analyzed mean accuracy and mean RTs overall for dyscalculics and controls and for each distance between numbers (e.g. between 1 and 3 the distance was 2). Regarding the accuracy (see Fig. 5), we observed a clear differentiation between dyscalculics and controls in distances 1, 2 and 3. Overall, dyscalculic children made significantly more errors than controls (accuracy: M_{contr} = .97, SD = .02, M_{dysc} = .95, SD = .03; $t(62) = 2.75$, $p < .01$). A mixed ANOVA with distance (1-8) as whitin-subjects factor and group (dyscalculics and controls) as between-subjects factor yielded main effect of distance ($F(7,434) = 57.04$, $p < .001$, $\eta^2_G = .4$) and group ($F(1,62) = 8.94$, $p < .01$, $\eta^2_G = .04$), whereas the interaction only approached significance ($F(7,434) = 1.87$, $p = .07$, $\eta^2_G = .02$).

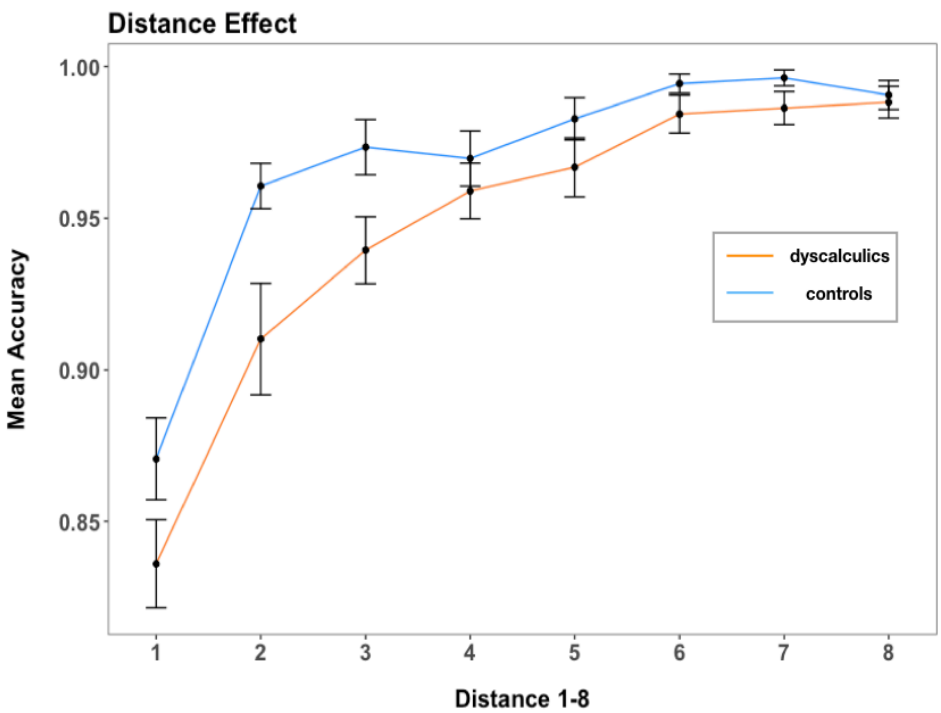

Fig. 5 Mean accuracy in the symbolic comparison task for distances 1-8 in dyscalculics and controls.

Moreover, dyscalculics were slower than controls (M_{contr} = 920.04 ms, SD = 238.26 ms; M_{dysc} = 1139.2 ms, SD = 321.49 ms; $t(62) = 3.09$, $p < .01$, see Fig. 6). We performed a mixed ANOVA with distance as within-subjects factor and group as between-subjects factor. We found significant main effects of distance ($F(7,434) = 53.7$, $p < .001$, $\eta^2_G = .1$), group ($F(1,62) = 10.07$, $p < .01$, $\eta^2_G = .12$) and significant interaction effect between distance and group ($F(7,434) = 2.48$, $p < .05$, $\eta^2_G = .005$).

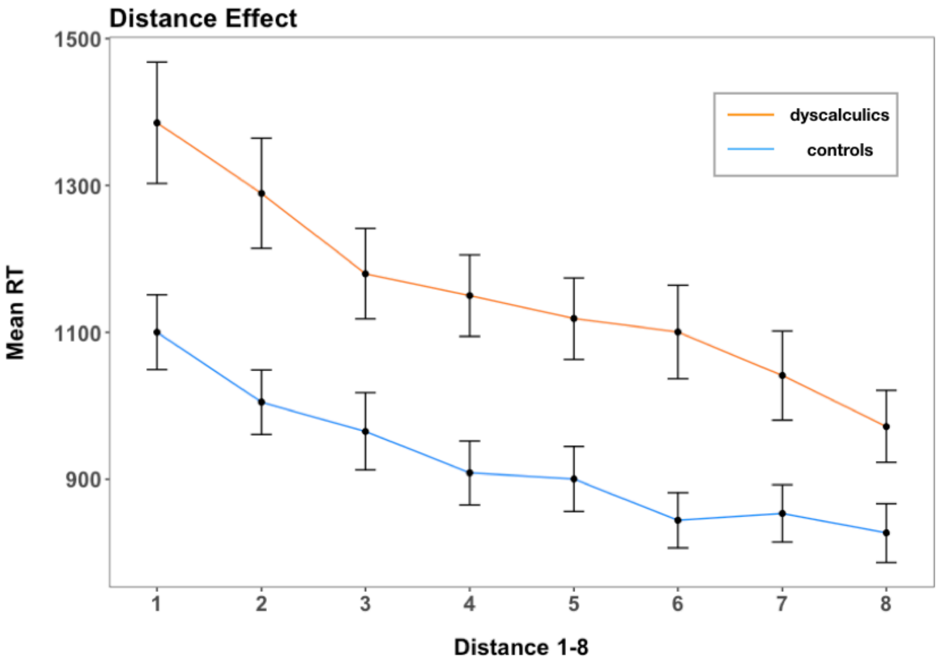

Fig. 6 Mean RTs in the symbolic comparison task for distances 1-8 in dyscalculics and controls.

Enumeration task

We first calculated mean accuracy and mean RTs overall, and then for each numerosity (1-8). Overall, dyscalculics were less accurate than controls ($t(62) = 2.17$, $p < .05$) but they did not differ in RTs ($t(62) = -1.95$, $p = .056$). We performed separated analyses for 1-3 (subitizing range) and 4-7 [3](counting range). The subitizing range was set a priori to 3 following the previous literature on subitizing in dyscalculics. However, we also confirmed it by analyzing the data from our control subjects that the "typical" subitizing range across subjects was 3: we conducted pairwise comparisons among the successive numerosities (1 vs. 2; 2 vs. 3; 3 vs. 4) and we found that significant differences in accuracy appeared only between 3 and 4 (3 *vs*. 4: $p < .01$, all previous pairwise comparisons $p > .05$). We thus proceeded performing separated analyses for the 1-3 (subitizing range) and 4-7 (counting range) trials. Across groups, there were no significant differences in accuracy ($M_{contr} = .99$, $M_{dysc} = .98$; $t(62) = -1.3$, $p = .197$) and RTs ($M_{contr} = .42$ s, $M_{dysc} = .39$ s; $t(62) = -.86$, $p = .39$) in the subitizing range, but significant differences in RTs in the counting range (accuracy: $M_{contr} = .64$, $M_{dysc} = .56$; $t(62) = -1.94$, $p = .056$, see Fig. 8; RTs: $M_{contr} = 1.05$ s, $M_{dysc} = 1.36$ s; $t(62) = 2.71$, $p < .01$, see Fig. 7).

[3] We decided to analyse up to numerosity 7, because children were informed that the number of dots presented could be from 1 to 8. Therefore the results of numerosity 8 were influenced by this information given to the participants. Indeed, the slope of RTs and error rate decreases in the last numerosity (see Fig. 6 and 7).

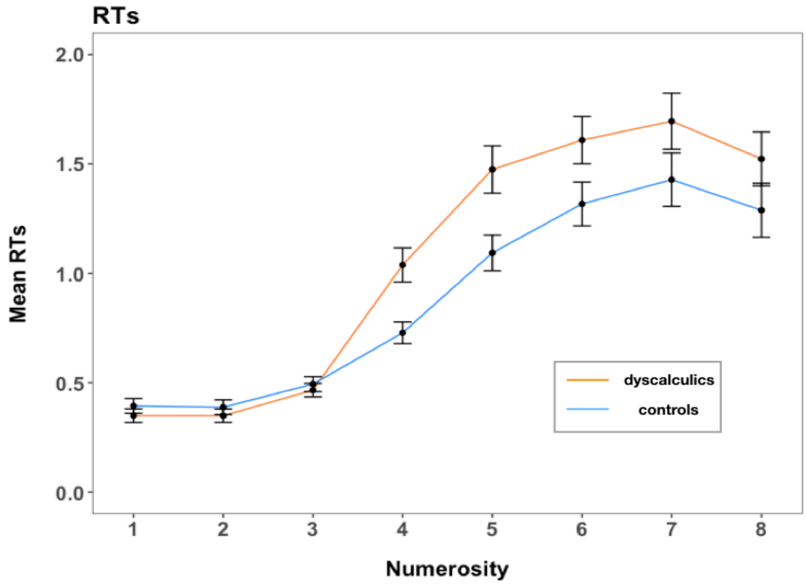

Fig. 7 Mean RTs in the subitizing task for distances 1-8 in dyscalculics and controls.

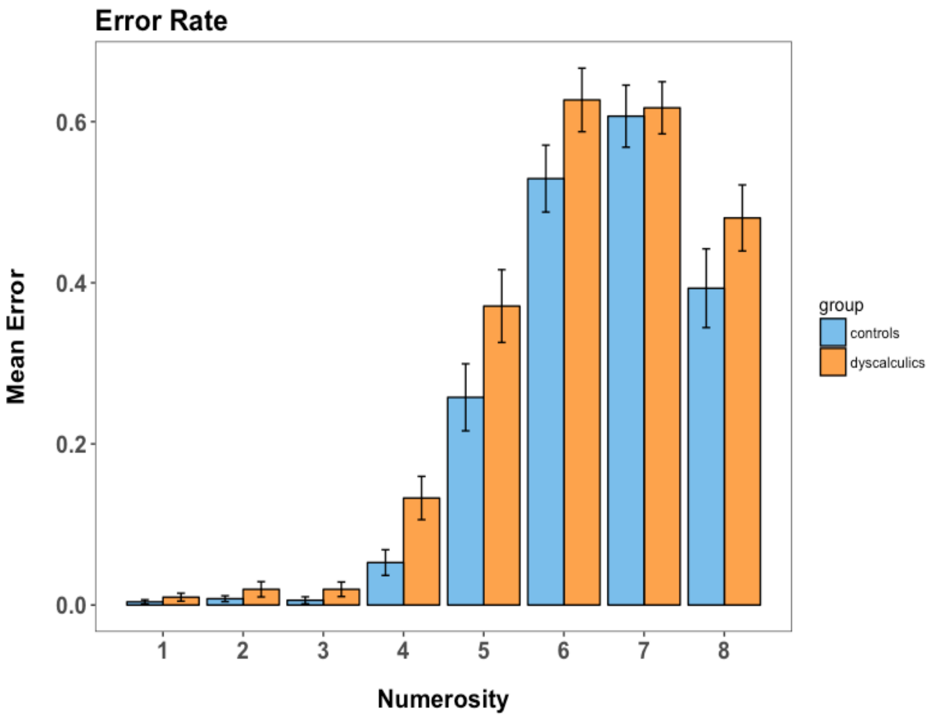

Fig. 8 Mean accuracy in the subitizing task for distances 1-8 in dyscalculics and controls.

In order to explore all possible features of our data, we also assessed the coefficient of variation (*cv*) calculated by dividing the standard deviation of the responses by the mean for each group (Ashkenazi et al., 2013; Gallistel & Gelman, 2000; Mazzocco et al., 2011). This index is approximately constant across variations in magnitude for scalar magnitude representations, and its value is a measure of the errors' extent. We found no significant differences between dyscalculics and controls in the subitizing range and in the counting range (subitizing range: $p= .42$; counting range: $p= .41$, see Fig. 9).

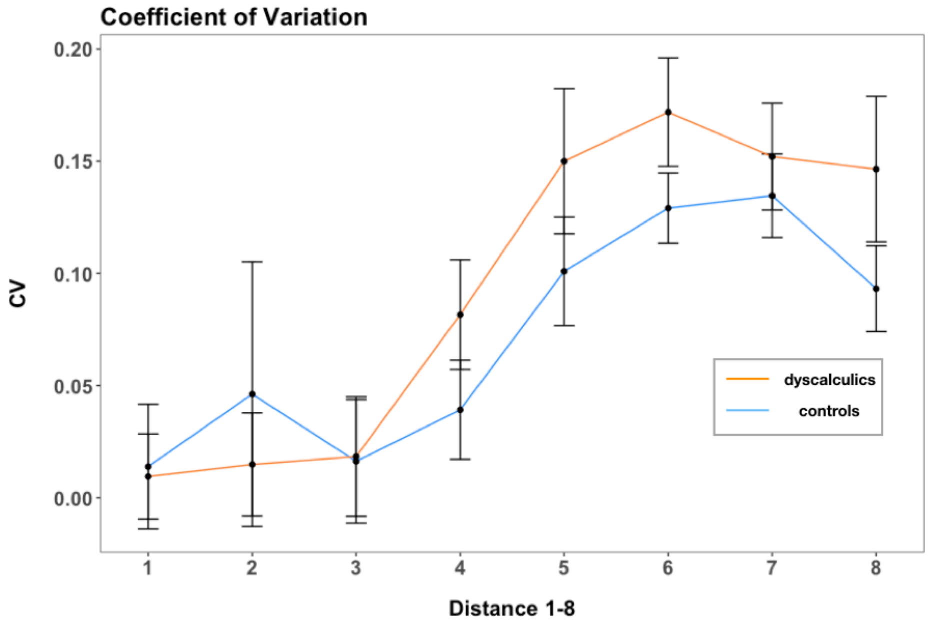

Fig. 9 Coefficient of variation (standard deviation of responses/mean of responses) for distances 1-8 in dyscalculics and controls.

Finally, following Reigosa-Crespo et al., (2013), we also calculated the efficiency measure (EM). The EM is an index that combines RTs and accuracy and it is calculated by extracting the mean of correct reaction times for numerosity 1 and 3 (or 5 and 7 for the counting range) for all participants and by dividing them by accuracy. Then, the EM of numerosity 1 is subtracted from the EM of numerosity 3 (or 5 from 7 for the counting range) and this index is divided by numerosity 3 (or 5). We compared the indices obtained for both groups, and we found a small but non significant difference between dyscalculics and controls in the counting range (subitizing range: $t(62) = 1.01$, $p = .32$; counting range: $t(59) = -1.68$, $p = .097$).

Visual STM task

Overall mean accuracy and mean RTs were measured for each participant and compared across groups. For each numerosity we also calculated Cowan's K (Cowan, 2001) (that allows the estimation of the number of objects encoded for each set size), and then computed the average K across set sizes for each subject as an estimate of the visual STM span (see Piazza et al., 2011).

Children with DD had an overall significantly poorer performances than controls both in accuracy and in RTs (accuracy: $M_{contr} = .81$, $M_{dysc} = .76$; $t(62) = 3.86$, $p < .001$; RTs: $M_{contr} = 870.59$ ms, $M_{dysc} = 1072.02$ ms; $t(62) = 2.47$, $p < .05$). We also found a strong group difference considering Cowan's K ($M_{contr} = 2.26$, $M_{dysc} = 1.76$; $t(62) = 3.85$, $p < .001$). As shown in Figure 10, the Cowan's K for controls was equal to about 2.5, while for dyscalculics it was smaller.

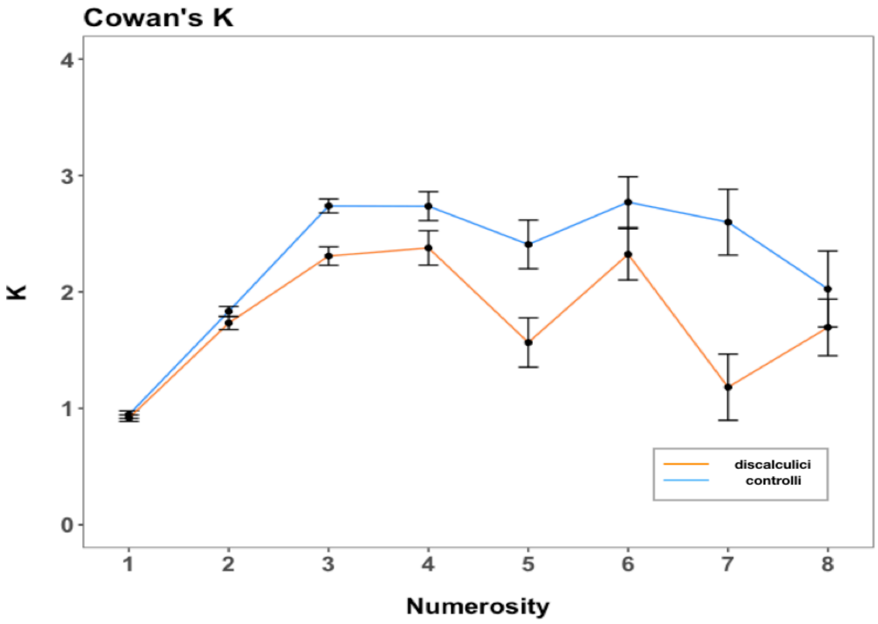

Fig. 10 Number of objects encoded for each numerosity (K Cowan) for dyscalculics and controls.

Corsi block-tapping test

Separated analyses were performed for Corsi task "forward" and "backward". Controls performed significantly better than dyscalculics, showing a more accurate visuo-spatial span (forward: $p < .05$; backward: $p < .001$).

Discussion

The present study aims to compare different hypotheses that have tried to propose at the origins of DD. In particular, given the tests we used, we can compare domain-specific and domain-general hypotheses. Within the former approach, different theories predict either a defective ANS and a non-impaired OTS (see Piazza, 2010), or defective both ANS and OTS (Butterworth, 2010), or problems in binding non-symbolic representations to symbolic ones (Rousselle & Noël, 2007). On the other hand, the theories whithin the latter approach predict a selective impairment in more general cognitive abilities, such as WM, visuo-spatial WM and inhibitory skills. In the present study, we assessed 32 children with dyscalculia and controls in multiple tasks: symbolic and non-symbolic comparison task, enumeration task, visual STM and WM.

Previous studies have found evidence for a defective ANS (Mazzocco et al., 2011; Mussolin et al., 2010; Piazza et al., 2010) and we replicated such results. Children without DD showed better performances in comparing non-symbolic numerosities (dyscalculics: w = 0.32; controls: w = 0.24). These findings closely replicated those by Piazza et al. (2010) reporting an internal w fraction of 0.34 for dyscalculics and 0.25 for controls of similar age. Moreover, as already demonstrated by these authors, although children with DD showed impaired number acuity, they did not present differences in RTs in this task compared to typically developing children, confirming that the two groups did not differ in the strategies used to perform the task. The data demonstrate that, while spending the same time to take a comparative decision, dyscalculics rely on a less precise internal representation of quantities. This result is at odd with theories that advocate a pure domain general origin of DD.

A second important finding was the significant impairment in the one-digit symbolic comparison task. Dyscalculic children performed poorly when they compared two symbolic magnitudes, and this was even more extreme in the case of small distances between them (1,2 and 3). This finding suggests that the mental representation of numerical symbols in DD is less precise (such that close numbers are less differentiated from each other) than in controls. These results were also confirmed by the analyses computed on RTs, where dyscalculics took significantly more time to decide which symbol was the greatest. The fact that dyscalculic children present impairments in symbolic comparison is part of the predictions of the access deficit hypothesis (Rousselle & Noel, 2007). However, this hypothesis predicts that the deficit should be limited to symbolic quantities and should not occur in non-symbolic comparison. The fact that DD show clear deficit in both symbolic and non-symbolic number comparison is therefore at odd with the access deficit.

In the enumeration task, that assessed the ability to name aloud the exact number of dots presented, we found overall differences between the two groups in accuracy and RTs. However, importantly, analyses computed only in the subitizing range (1-3) revealed no group differences. In fact, the group differed in both accuracy and RTs only in the counting range. Contrary to previous studies (Andersson & Östergren, 2012; Schleifer & Landerl, 2011), these results did not support the idea that children with DD present a specific deficit in the precise and exact estimation of small sets (within the subitizing range). In our study, children with DD present no deficit in tracking up to three objects, whereas they show more difficulties to identify larger quantities in the counting range. These results are therefore not in line with the OTS hypothesis and with the studies that support a specific deficit in manipulating exact quantities representations. However, the discrepancy with previous studies could be due to the differences in the task used. Indeed, our enumeration task was limited in time (children observed the images with colored dots for 500 ms) while in other studies that demonstrated a deficit in the subitizing range children had no limits for observing the images. Related to this, in these studies the authors did not analyse the accuracy, because the error rate was very low.

Finally, our results revealed better performances in controls in STM and

WM, both measured through our computerized change detection task and through the classical Corsi block test. In the first one, participants were asked to observe two images and to perform a same-different judgment, while in the second they had to repeat a sequence of previously shown touched blocks. In both tasks, they were dramatically less accurate compared to the controls.

These results indicate that dyscalculics present also deficits in the short-term encoding/storage/retrieval of visuo-spatial information. These results are consistent with previous studies that provided evidence of a defective visuo-spatial short-term memory (e.g. Szucs et al., 2013). It is plausible that impairments in visuo-spatial components would also affect performances in mathematical cognition. Indeed, many studies demonstrated its key role in calculation and arithmetic problem solving (e.g. Bull & Sherif, 2001; Furst & Hitch, 2000). Thus, this deficit should create difficulties in storing numerals, performing operations with symbols, retrieving of data etc.

In sum, the present study provides evidence for the ANS hypothesis and for the domain-general one, presenting defective numerical acuity, STM and WM in children with DD. Our findings only partially support the access deficit hypothesis by showing severe difficulties in symbolic comparison tasks in DD, but these comprise also non-symbolic magnitude representations. On the other hand, results are not consistent with the OTS hypothesis, because participants with DD in our study did not indicate a selective deficit in the subitizing range but a general weakness in the counting range instead. Considering our data, DD should be connected to multiple deficits rather then a single core deficit and this is consistent with the multiple deficits hypothesis (Andersson & Östergren, 2012; Dowker, 2005; Rubinsten & Henik, 2009; Kaufmann et al., 2013; Wilson &

Dehaene, 2007). Indeed, the present findings show that dyscalculics present domain specific deficits in symbolic and non-symbolic numerical acuity, as well as domain general deficits in STM. However, our data firmly dispute the idea that DD is associated with a deficit in subitizing ability.

GENERAL DISCUSSION

General Discussion

4.1 Main findings

The present work aims to extend our knowledge regarding the core systems of numerical cognition. In particular, the attention is focused on two systems grounding the numerical cognition, one for the approximate magnitude representation (Approximate Number System/ANS) and the other for the precise estimation of small sets of objects (Object Tracking System/OTS). This collection of works investigates specific aspects of these two systems. On one hand I have assessed the ratio-dependence of ANS, on the other hand, in parallel, the perception of faces in infancy. This chapter is relevant as a first step for a better understanding of ANS acuity in infancy. Moreover I implemented a modified version of the change detection paradigm, already used for numerosities but never for faces (our control task of the longitudinal study). In addition, parents' performance was measured for investigating its role in infants' performances. This part enhances the knowledge about the ANS in infancy and about the influence of parents in these two abilities. The latter hypothesis is particularly interesting due to the fact that only one study has investigated the correlation between children - parents ANS acuity; this is true also for face perception, where studies focused the attention only on twin studies and prosopagnosia.

On the other hand, in the second part of the thesis I presented the findings about the OTS in infancy. A crucial question concerns the kind of information infants needs to individuate and track different objects. Specifically, I tested the hypothesis that dynamic information is enough to create specific numerical expectations in 10-month-old infants. Indeed, previous studies have assessed agent and inert objects, not controlling for other variables (e.g. shapes changed too). Here I tested the dynamic information in infants with a systematic control of featural elements (the same red ball showing different patterns of movement).

Finally, another important aspect to be explored is the role of ANS and OTS in DD. Some authors found a specific deficit of ANS in dyscalculic children, while others demonstrated a specific deficit in OTS. In parallel, other studies supported the hypothesis of more domain-general deficits underlying DD. Therefore in the third chapter I compared this different theoretical positions to clarify the role of each component in mathematical disorders.

4.1 The assessment of ANS and face perception in infancy

In Chapter 1 I presented the results of the first testing session of a study that will be longitudinal, where we have tested the ANS acuity at the end of the first year of life using the change detection paradigm that provides an index of individual differences in numerical discrimination. Infants observed two arrays of dots, in one of them the numerosity changes over time while in the other the numerosity remains fixed. We explored infants' numerical acuity using multiple ratios (1:4 and 1:2) and we also tested the reliability of the measures obtained with this paradigm. In line with previous studies, our results provided evidence that infants can discriminate both ratios, confirming that infants in the first year of life develop an ANS acuity that allows them to discriminate numerosities when the ratio is 1:4 and 1:2. In the 1:4 ratio we observed longer looking times to the changing image stream than in the 1:2 ratio. However, contrary to the literature, we didn't find a significant reliability between the two levels of difficulty. This discrepancy with the previous study could be due to differences in the method that we used compared to previous studies (e.g. Libertus et al., 2010), to the choice of the ratios or to the low variability across subjects in one of the two condition (1:4 ratio).

In parallel, we have also assessed the infants' face perception ability as control task of the longitudinal study. We decided to test face perception to be sure that in case of significant positive correlation at T2, this could be liable to differences in discrimination of quantities and not to more general perceptual abilities. 12-month-old infants were tested with the same paradigm used in the numerical part except that infants observed face images. Our results showed that infants can perceive not only *featural* differences (sensitivity to the shape of eyes, nose and mouth) but also *second-order* differences (sensitivity to the distance among these features). Moreover, we demonstrated the significant positive correlation between these levels of difficulty, indicating that our stimuli/design provide a stable and sensitive estimates on inter-individual variability in face perception skills.

At the same study we have also explored, and here for the first time, the link between parents' and infants' abilities in these two domains: number and face perception. Regarding the numerical acuity, parents were administered an ANS task, where they had to choose which of two arrays contained more dots.

We found no significant correlations with the infant's preference scores, neither in the 1:4 ratio nor in the 1:2 ratio. Given previous findings demonstrating the association between parents and children of 5-8 years old in ANS acuity, it is plausible to support the idea that environmental factors influence children performances later in development. Future studies could systematically extend the present investigation regarding the relation between parents and children in ANS acuity. Indeed, only one recent study has already explored this line of research (Braham & Libertus, 2016) and many questions remain open. One project could test this link at different ages, observing when this link appears and which variables influence the children's performances at each age.

Regarding face processing, we have assessed parents in a face memory test (CFMT; Duchaine & Nakayama, 2006), where participants were instructed to memorize faces and then tested with a three-alternative forced choice task, where one of them was the right face. Findings revealed a significant relation between fathers (and not mothers) and infants when considering infant's preference score in the *featural* change. This very interesting result needs to be further replicated to be confirmed before we could speculate on its potential significance.

4.2 The role of dynamic information in tracking small sets of objects

In chapter 2, I reported a study that investigated the OTS and in particular the process that allows tracking and locating small sets through space and time. We focused our attention on the individuation process, the ability to define how many objects are present in a scene, assessing the weight of dynamic and non-dynamic perceptual information in 10-month-old infants and adults. Participants observed one object appearing from behind one side of a screen and moving autonomously; then at the opposite side an identical object was grasped by a hand, dropped on the floor and pushed again behind the screen. The screen was removed revealing either one or two objects. For the first time we provided evidence for a relevant role of dynamic information in individuation process. Indeed, the most important finding was that infants before the end of the first year of life can individuate different objects only considering the autonomous and passive motion.

We then replicated these results in another experiment where we controlled the objects' trajectories and the presence of the hand in both sides of the screen. We obtained similar results to the first experiment.

These findings provide further evidence for the hypothesis that infants at very early age can individuate small sets of number based on the sortals concept AGENT and INERT OBJECT. They are also consistent with previous studies of Bonatti and colleagues. These authors demonstrated that infants as young as 10-months could individuate two objects not only when they compared humanlike faces/artifacts and human/animal faces (Bonatti et al., 2002), but also when puppets showed different face orientation (Bonatti et al., 2005). These findings led to the proposal of the *human first hypothesis*, according to which before the first year of life infants can use specific properties of human being to success in complex individuation tasks. In support of the *human first hypothesis*, 10-month-olds were shown pairs of objects alternately emerging from behind a screen and returning behind it (Surian & Caldi, 2010). One object showed an autonomous movement (e.g., a green caterpillar) while the other one had a passive motion and was grasped and dropped by a hand (e.g., a red cup). At the end of this familiarization, the screen was raised, revealing one-object or two-objects outcome. Participants looked longer at the one-object outcome, showing the violation of expectation.

Our study posits some considerations for the neuropsychological models postulated for the individuation process. Considering the model of Leslie and colleagues (1998), infants can assign a mental index to an object, and this process is supported first by spatiotemporal information ('where' route) and only later in the development by featural cues ('what' route); the two pathways would be completely connected at the end of the first year of life. However, our results demonstrated that infants before 12 months can assign two different indexes when dynamic information is available.

One explanation could be found in the idea of a major contribution of the where system in infants object individuation. It could bind not only spatio-temporal information to an object but also other information such as the type of motion.

Our results also lead to some considerations about the infants' reasoning of physical events. Indeed, some authors focused their studies on the concept of inert/self-propelled objects (Luo et al., 2009; Saxe et al., 2007). In a series of experiments (Luo et al., 2009), the authors found that infants of 5-6.5 months old can have expectations about physical events involving inert and self-propelled objects, for example infants are surprised when an inert box changes direction autonomously. Baillargeon and colleagues (2012) proposed a model supporting the idea that infants are equipped with a system that allows them to reason about objects' physical events. When infants observe an event, a physical representation of it is created with one structural layer, that contains spatiotemporal and general/categorical information (such as self-propelled and inert object), and one variable layer, that contains more specific information about the event (such as shape, size, color etc.). The individuation process fails when the two layers include diverging information. The model postulates that both layers can be already used by infants at 10 months and in case of discrepancies between the two layers, infants should be unable to create precise numerical expectations. Thus, considering this model, infants in our study should not have specific numerical expectations. Indeed, two objects' expectation is created in the structural layer, due to different categorical descriptors (self-propelled ball and inert ball), but only one object expectation in the variable layer, due to the identical perceptual information. By contrast, infants correctly individuate two objects.

Interestingly, infants and adults presented different pattern in object individuation. Infants' expectation was consistent with the structural layer, while adults' expectation was more based on the variable layer.

In sum, our results indicate that infants of 10 months can individuate separately animate and inanimate objects, supporting the assumption that animacy plays a relevant role in individuation process in the first steps of development. Future studies should deepen this aspect by testing with the same paradigm other motion cues, such as semi-rigid against rigid motion cues, creating representations of biological against mechanical objects.

4.3 Are the ANS and the OTS impaired in developmental dyscalculia?

In the third chapter, I reported a study that aims to clarify the role of ANS and OTS in dyscalculia and to compare different hypotheses that have tried to explain this neurodevelopmental disorder. As we have seen in the General Introduction, it is unclear the influence of each system on dyscalculia and findings in the literature reported contradictory results. We compared performances of dyscalculics and typically developing children in multiple tasks. In particular, they were tested in non-symbolic comparison task (to estimate the ANS acuity), enumeration task (to estimate the OTS capacity), symbolic comparison task, STM and WM abilities (that reflect domain-general abilities).

Firstly, we found a defective ANS in dyscalculic children and we replicated some previous results showing an impaired capacity to discriminate the larger of non-symbolic numerical arrays (Piazza et al., 2010; Mazzocco et al., 2011; Mussolin et al., 2010). Children without DD showed better performances in comparing non-symbolic numerosities and presented more precise estimates. We provided evidence for a defective ANS in dyscalculics and for a distinct trajectory of development of this ability in the two groups. Indeed, controls presented a lower w fraction compared to dyscalculic children. However, there are no differences in RTs from typically developing children. Thus, dyscalculics seem to have different internal representations of quantities, rather than different strategies to identify the greater numerosity.

With respect to the assessment of the OTS, we administered an enumeration task where children were asked to name aloud the exact number of dots presented. Overall, we found differences between the two groups in accuracy and RTs. However, further analyses revealed impairments in the counting range (4-7) and not in the subitzing range (1-3), even if we explicitely used several measures to try and be sensitive to even small potential across groups difference. Contrary to previous studies (Andersson & Östergren, 2012; Schleifer & Landerl, 2011) our findings did not support the idea of a specific deficit in the precise estimation within the subitizing range in DD. Indeed, children with DD present no problems in tracking up to three elements at time, whereas they exhibit severe difficulties to identify larger quantities. Therefore, these findings are not in line with the OTS hypothesis and with studies that support a specific deficit in manipulating exact small quantity representations.

In addition, we found partially evidence for the access deficit hypothesis. According to some authors dyscalculic children would not show impairments "in processing numerosity per se but rather in accessing to the numerical meaning from symbols" (Rousselle & Noel, 2007). Convergent with this hypothesis, our data displayed a significant deficit in the symbolic comparison task, but contrary to it these deficits are not limited to symbolic quantities. As we have already seen children with dyscalculia presented impairments in the non-symbolic comparison task.

Interestingly, dyscalculics showed worse performances when the distances between two symbols were very low (i.e. 1,2 and 3), suggesting a major overlap between symbols in dyscalculia than in typically development. These findings can be taken as evidence that the deficit in accessing to the numerical meaning of symbols cannot be considered the unique and more severe core deficit of DD.

Finally, we took into account more domain-general hypotheses, comparing the two groups in a STM task and in a WM task (Corsi block test). Dyscalculics were less accurate and slower in RTs than controls when they had to compare two images with colored dots and when we asked them to tap a sequence of blocks previously touched by the experimenter. We argued that they probably present general cognitive deficits that involve storage and manipulation of visual and spatial information. These results give further support to the hypothesis of a defective STM and WM in DD (Andersson & Lyxell, 2007; Kyttälä, Aunio, & Hautamäki, 2010; Passolunghi & Cornoldi, 2008; Wilson & Swanson, 2001). Deficits in this domain could also create difficulties in many aspects of mathematical domains. Indeed, some studies have demonstrated the fundamental role of this cognitive function in math, in particular in calculation and problem solving (e.g. Bull & Sherif, 2001; Furst & Hitch, 2000).

In conclusion, the present study provides evidence for a defective ANS but not for a specific deficit in OTS. We also found a severe impairments in STM and WM. We argued that, considering our data, DD should be linked to multiple deficits rather then a single core deficit. (Wilson & Dehaene, 2007; Dowker, 2005; Rubinsten & Henik, 2009; Andersson & Östergren, 2012).

Future research should focus their attention on the multiple diagnosis of dyscalculia, considering not only different tasks but also different profiles. Indeed, little is known about domain-general and domain-specific hypotheses in different groups of dyscalculics.

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