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# **Precursors of mathematics learning: identification and intervention**

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# Chapter 1

## General Introduction

The number of students with mathematical difficulties has greatly increased over the last 20 years (Swanson, 2000). Several studies found that between 5% and 10% of children and adolescents experience a substantive learning deficit in at least one area of mathematics (Barbarese, Katusic, Colligan, Weaver, & Jacobsen, 2005; Shalev, Manor, & Gross-Tsur, 2005; Shalev, 2007). Students who find mathematics difficult choose not to study mathematics in secondary school or further education (Brown, Askew, Millett, & Rhodes, 2003). This choice must be considered a risk factor as several studies found that mathematical abilities predict financial and educational success, particularly for women (Bynner & Parsons, 2006; Geary, Hoard, Nugent, & Bailey, 2013). Given these findings, the identification of children at risk of mathematical disability as early as possible is crucial, because early intervention could help reduce the problem.

An increasing number of studies have investigated the cognitive components that contribute to the development of mathematical skills, confirming that some abilities in kindergartners can predict mathematical achievement outcomes in later life (De Smedt et al., 2009; Krajewski & Schneider, 2009b; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Mazzocco & Thompson, 2005; Passolunghi, Vercelloni, & Schadee, 2007; Passolunghi & Lanfranchi, 2012). Competencies that specifically predict mathematical abilities may be considered specific precursors, whereas general cognitive abilities (i.e. domain-general precursors) may predict performance not only in mathematics but also in other school subjects.

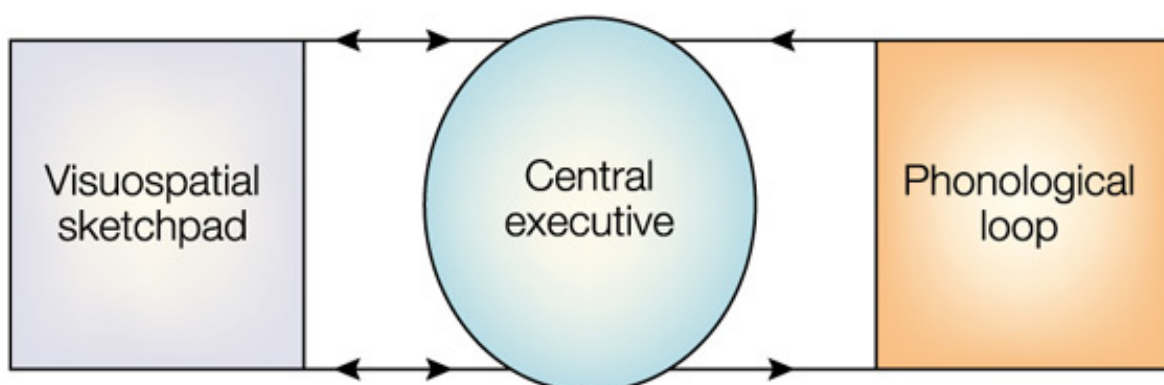
### **Working Memory Ability and Mathematics**

With regard to domain-general precursors, some general cognitive abilities, such as working memory (WM), processing speed and intelligence level, predict performance in mathematics (De Smedt et al., 2009; Espy et al., 2004; Passolunghi & Lanfranchi, 2012; Passolunghi, Mammarella, & Altoè, 2008; Passolunghi et al., 2007). The role of the domain-general precursors of learning is particularly important during the preschool years, but their involvement seems to decrease in the following years as a consequence of a greater influence of the domain-specific abilities (Passolunghi & Lanfranchi, 2012). Of all these general cognitive skills, several studies demonstrated that working memory is a key predictor of mathematical competence (De Smedt et al., 2009; Gathercole & Pickering, 2000; Gersten, Jordan, & Flojo, 2005; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Krajewski & Schneider, 2009b; Passolunghi & Lanfranchi, 2012). The term “working memory” refers to a temporary memory system that plays an important role in supporting learning during the childhood years because its key feature is the capacity to both store and manipulate information (Bull & Scerif, 2001; Gathercole & Alloway, 2006; Miyake & Shah, 1999). Indeed, different mathematical tasks, such as performing mental arithmetic and understanding mathematical word problems, require the storage of information while it is being

processed or integrated with information retrieved from long-term memory (Swanson, 2004; Tronsky, 2005). Furthermore, WM skills are necessary even when very young children need to mentally represent and manipulate quantitative information (Alibali & DiRusso, 1999).

Further evidence of the importance of working memory in children's mathematical skills has been provided by longitudinal studies that demonstrated that the working memory performance in preschoolers predicts mathematical achievements several years after kindergarten (Gathercole, Brown, & Pickering, 2003; Mazzocco & Thompson, 2005; Passolunghi & Lanfranchi, 2012). Specifically, several studies showed a direct influence of working memory on mathematical achievements in first and second graders (De Smedt et al., 2009; Passolunghi et al., 2008, 2007).

Various models of the structure and function of working memory exist, but the present study applied the multi-component model of working memory proposed by Baddeley and Hitch in 1974 and revised in succeeding years (Baddeley, 1986, 2000). This model consists of three main parts (Figure 1). The two "slave" systems of working memory (i.e., the phonological loop and visuo-spatial sketchpad) are specialized to process language-based and visuo-spatial information, respectively. The central executive, which is not modality-specific, coordinates the two slave systems and is responsible for a range of functions, such as the attentional control of actions. The distinction between the central executive system and specific memory storage systems (i.e., the phonological loop and visuo-spatial sketchpad) in some way parallels the distinction between the working memory, involving storage, processing and effortful mental activity, and the Short-Term Memory (STM), typically involving situations in which the individual passively holds small amounts of information (Swanson & Beebe-Frankenberger, 2004).



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**Figure 1.** (from Baddeley, 2003) The WM model initially proposed by Baddeley and Hitch (1974) comprises a control system, the central executive, and two storage systems, the visuospatial sketchpad and the phonological loop.

With regard to the contribution of the three core components of working memory to the development of mathematical skills, many studies showed a direct association between executive function and children's early emergence and development of mathematical abilities across a wide age range (Bull, Espy, & Wibe, 2008; Bull & Scerif, 2001; Gathercole, Pickering, Knight, & Stegmann, 2004; Gathercole & Pickering, 2000; McLean & Hitch, 1999). For example, dual task studies suggest that central executive resources are implicated in children's arithmetic performance (e.g. Imbo & Vandierendonck, 2007) and longitudinal data found that inhibitory control predicted later mathematical outcomes (Blair & Razza, 2007; Mazzocco & Kover, 2007). On the other hand, children who are poor in mathematics also have a poor performance in central executive tasks, especially in tasks that require the inhibition of irrelevant information and updating (Espy et al., 2004; Passolunghi, Cornoldi, & De Liberto, 1999; Passolunghi & Siegel, 2001; St Clair-Thompson & Gathercole, 2006).

Spatial skills and visuo-spatial working memory were also found to be related to children's early counting ability (Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003) and general mathematical competence (Jarvis & Gathercole, 2003; Passolunghi & Mammarella, 2011). Indeed, the visuo-spatial sketchpad appears to support the representation of numbers in counting, arithmetic calculations, and especially in mental calculation (D'Amico & Guarnera, 2005; Heathcote, 1994; McKenzie, Bull, & Gray, 2003; McLean & Hitch, 1999). This component is also fundamental in the process of problem solving, because it allows the individual to build a visual mental representation of the problem (Holmes & Adams, 2006). Moreover, visuo-spatial WM abilities assessed in the preschool years predict complex arithmetic, number sequencing and graphical representation of data in primary school (Bull et al., 2008).

The results of studies that considered the role of the phonological loop in children's mathematical processing have been unclear. Dual-task studies showed that 8-9 year old children (but not younger children) use a verbal approach supplemented by visual-spatial resources during on-line arithmetic performance (McKenzie et al., 2003). In the field of learning disabilities, some studies found no differences in phonological loop abilities between children with and without mathematical difficulties, especially when differences in reading ability were controlled (McLean & Hitch, 1999; Passolunghi & Siegel, 2001, 2004). Other authors suggest that the phonological loop is involved in basic fact retrieval (Holmes & Adams, 2006). The role of each working memory component in mathematical cognition must be considered to vary with expertise and development (Meyer, Salimpoor, Wu, Geary, & Menon, 2010), with an increasing involvement of the phonological loop in mathematical cognition from the age of seven onward (Hitch, Halliday, Schaafstal, & Schraagen, 1988; Raghubar, Barnes, & Hecht, 2010; Rasmussen & Bisanz, 2005).



## **Domain-Specific Precursors of Mathematics**

Another important aspect of the acquisition of mathematical skills is represented by domain-specific components. Foundational-specific skills necessarily underlie the development of arithmetic skills. Two abilities were identified that could be considered fundamental domain-specific precursors of mathematical learning: the “number sense” or the ability to represent and manipulate numbers nonverbally (Dehaene, Molko, Cohen, & Wilson, 2004; Dehaene, 1997; Gilmore, McCarthy, & Spelke, 2007), and early symbolic numeracy (Geary, Hoard, & Hamson, 1999; Passolunghi & Lanfranchi, 2012). Although researchers agree that children develop number sense and early symbolic numeracy abilities prior to the development of formal mathematical skills, they disagree about the precise definition of early symbolic numeracy and number sense (Berch, 2005; Gersten et al., 2005). With the presented work, based on previous findings, we tried to propose a general framework for the classification of domain-specific precursors of mathematical learning

### **Number sense.**

No unique definition of number sense exists (Gersten et al., 2005), but it generally includes subitizing (i.e., the rapid and accurate enumeration of small sets of objects), making quantity comparisons, estimating, and forming representations of numerical magnitudes in the form of a mental number line (Berch, 2005; Dehaene, 1997; Jordan et al., 2006). Such skills develop before formal instruction and it has been suggested that they are innate (Butterworth, 2005; Dehaene, 1997; Jordan et al., 2006), but refinements have also been observed as a consequence of teaching and training procedures (Ramani & Siegler, 2008; Van Herwegen, Costa, & Passolunghi, under review; Whyte & Bull, 2008).

In particular, there are two core cognitive systems responsible for the non-verbal representation of numbers. Indeed, large and small numerosities seem to activate different systems (Feigenson, Dehaene, & Spelke, 2004). The Approximate Number System (ANS) is used for representing large, approximate numerical magnitudes, while the Object Tracking System (OTS) is used for the precise representation of small numbers. Both can be observed in adults, infants and other animal species (Feigenson et al., 2004).

***The approximate number system.*** The ANS is a cognitive system that underlies the preverbal ability to perceive and discriminate approximate large numerosities. This ability is robust across multiple modalities of input (e.g. visual or sound stimuli), increases in precision throughout development and is ratio dependent according to Weber’s law (Barth, Kanwisher, & Spelke, 2003; Halberda & Feigenson, 2008a; Lipton & Spelke, 2003). Within the ANS, numerosities seem to be ordered spatially in a sort of mental number-line with increasing acuity throughout development

(Feigenson et al., 2004; C. Gallistel & Gelman, 2000; Halberda & Feigenson, 2008b). On this mental number-line, each numerosity has a specific position with smaller numerosities placed at the left and bigger numerosities placed on the right (Dehaene, Bossini, & Giraux, 1993). Number-line representations of numerical magnitude are logarithmically compressed (Dehaene, 2007; Siegler & Opfer, 2003), in that the perceived distance between small quantities is larger than the perceived distance between big quantities (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007). As a consequence small quantities are over-represented on the mental number-line.

The approximate number representations can be mentally combined to perform comparison, addition and subtraction across sets. The ANS can be assessed using tasks which involve viewing, comparing, adding or subtracting non-symbolic quantities, such as arrays of dots (C. Gilmore, Attridge, & Inglis, 2011; Halberda & Feigenson, 2008a; Piazza, Pinel, Le Bihan, & Dehaene, 2007).

The ANS seems to be active from the first few months of life. Indeed, it has been shown that 6-9 month old infants exhibit the capacity to create abstract representations of numerosity that support the ability to discriminate numerosities, recognize the ordinal relationship between numerosities and form expectations of the outcomes of simple arithmetic problems (Lipton & Spelke, 2003; McCrink & Wynn, 2004; Xu & Spelke, 2000). The ANS system remains active also in older children and adults (Barth et al., 2003; Cordes, Gelman, Gallistel, & Whalen, 2001). Moreover, this system has been found to correlate with mathematical achievements (Bonny & Lourenco, 2013; Halberda, Mazocco, Feigenson, & Halberda, 2008; Libertus, Feigenson, & Halberda, 2011) and is severely impaired in children with developmental dyscalculia (e.g. Mazocco, Feigenson, & Halberda, 2011).

It remains unclear when the noisy ANS representations integrate with more formal mathematical abilities. It has been suggested that the acquisition of the meaning of symbolic numerals is done by mapping symbolic numerals (number words or Arabic digits) onto the pre-existing approximate number representation. As a consequence, ANS provides semantic representations of numbers and the precision of the ANS plays a crucial role in the early foundation of symbolic number knowledge (Dehaene, 1997; Holloway & Ansari, 2009; Wynn, 1992).

***The object tracking system.*** The OTS is a cognitive system that allows precise representation of distinct individuals. This system is involved in keep tracking of small numbers of objects (up to three-four items) and in representing information about continuous quantitative properties of objects. Similar to the ANS, the OTS varies across individuals (Halberda et al., 2008; Revkin, Piazza, Izard, Cohen, & Dehaene, 2008) and is subject to maturation (Oakes, Ross-Sheehy, & Luck, 2006; Rose, Feldman, & Jankowski, 2001). It is a non-numerical mechanism that supports

the quick, accurate and effortless perception of the numerosity of small sets of objects, a phenomenon known as subitizing. This ability to discriminate between small quantities does not depend on numerical ratio but on the absolute number of items presented (Feigenson, Carey, & Hauser, 2002; Feigenson & Carey, 2003) and is robust across modalities (Wynn, 1996). Moreover, the OTS also seems to be fundamental to compute information about the continuous quantitative properties of stimuli (Clearfield & Mix, 1999; Feigenson et al., 2002; Xu & Spelke, 2000). For example, when 10-12 months old infants were asked to choose between two quantities of crackers, they chose the larger quantity by comparing 1 versus 2 and 2 versus 3 (but failed with comparisons of 3 versus 4, 2 versus 4, and 3 versus 6). However, when the crackers were different sizes, the total surface area or volume determined the choice. Infants only succeeded in this task when 3 or fewer objects were shown in either location (Feigenson et al., 2002).

The OTS supports visual enumeration of small sets of objects, but its role in performing symbolic number tasks is not yet clear (Piazza, 2010). Information about the importance of the OTS in numerical development comes from studies in the field of learning disabilities. Indeed, children with developmental dyscalculia have a deficit in subitizing and tend to use serial counting to determine the numerosity of small sets of objects (Landerl, Bevan, & Butterworth, 2004; Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009; Schleifer & Landerl, 2011); a finding which suggests the importance of the OTS for the development of numerical abilities (Carey, 2001; Le Corre & Carey, 2007). Moreover, an exact small number representation seems to be involved even in adult's symbolic number processing. Adults show an immediate and accurate recognition of numerosities 1-4, after which the error rate and response time increase significantly. These results suggest that small numbers are processed via subitizing, differently from large numbers (Mandler & Shebo, 1982; Pylyshyn, 2001; Trick & Pylyshyn, 1994). In conclusion, small arrays of objects activate the OTS responsible for representing and tracking numerically distinct individual objects. The activation of this system allows the process of either continuous quantitative properties of objects, or the number of individual objects in the array (Feigenson et al., 2004).

### **From Number Sense to Early Symbolic Numeracy**

The acquisition of early symbolic numeracy, which includes the ability to identify number symbols as well as counting skills, allows children to progress beyond the pre-verbal number processing systems. The development of early symbolic numeracy is grounded on number sense skills, which provide semantic representations of numbers (Piazza, 2010). Therefore, during development we can observe the creation of a connection between quantities and symbolic numbers, providing the number symbols with a non-symbolic magnitude meaning (Dehaene, 2001; Hannula & Lehtinen, 2005). Some studies found that in this process the ANS plays a fundamental

role (Dehaene & Changeux, 1993; Gallistel & Gelman, 1992; Lipton & Spelke, 2003) while others stressed the importance of the OTS (Carey, 2001, 2009; Le Corre & Carey, 2007); other studies considered the combination of the two systems as crucial (Feigenson et al., 2004; Spelke & Kinzler, 2007). The link between the symbolic and non-symbolic representation of numbers has been called *number sense access* (Rousselle & Noël, 2007; Wilson, Dehaene, Dubois, & Fayol, 2009) and is an important skill for mathematical learning (Kolkman, Kroesbergen, & Leseman, 2013). Indeed, the integration of the ANS and the OTS through verbal counting seems to pave the way for the understanding of exact numbers (Carey, 2001; Le Corre & Carey, 2007; Lipton & Spelke, 2003).

At 2-3 years old children learn to count and thereby already acquire precise number words. This early counting list is numerically meaningless as they do not yet use number words to describe quantities (Fuson, 1988; Krajewski & Schneider, 2009a; Le Corre, Van de Walle, Brannon, & Carey, 2006; Wynn, 1990, 1992). The numerals in the list function as placeholders that can be mapped onto core representations of numbers to support the acquisition of counting principles (Le Corre & Carey, 2007). Then, children gradually learn that “4” matches an array of four objects and that the number “20” is bigger than the number “7”.

Adults and young children access non-symbolic representations of numbers when solving problems presented in Arabic numerals or verbal form (Gilmore, McCarthy, & Spelke, 2007). However, the automaticity of the connection between symbols and quantities is not yet established in early childhood (Girelli, Lucangeli, & Butterworth, 2000; Rousselle & Noël, 2007) but becomes gradually automatic with development (Naccache & Dehaene, 2001; Rusconi, Priftis, Rusconi, & Umiltà, 2006). Thus, children quickly learn to map symbolic numbers onto their pre-existing number-line representation of numerical magnitude. This mapping, initially logarithmic, becomes linear during development as people learn to compensate for the logarithmic compression of the mental number line.

In the development of mathematical abilities, non-symbolic quantity skills, symbolic skills, as well as the development of an accurate number sense access are important for the learning of more advanced mathematical operations such as addition or subtraction (Booth & Siegler, 2006; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Kolkman et al., 2013). However, recent studies highlighted the fundamental role played by the number sense access for mathematical achievement and arithmetic strategy use during development, (De Smedt & Gilmore, 2011; Rousselle & Noël, 2007; Vanbinst, Ghesquière, & De Smedt, 2012) suggesting that number sense access could be an alternative core deficit in dyscalculia (Rousselle & Noël, 2007; Rubinsten & Henik, 2005).

## **Outline of this Dissertation**

The theoretical background described above generates important questions, which highlight the necessity for further research in the field of precursors of mathematical learning. The studies presented in this thesis contribute to the growing body of knowledge regarding the relationships between domain-general precursors, domain-specific precursors and mathematical learning.

Given the previous inconsistent results about the link between ANS acuity and mathematical abilities (i.e. Kolkman et al., 2013) we were interested in the investigation of the relationship between the ANS and early mathematics abilities in preschool years. This relationship was explored by using two different approaches: in Chapter 2 the relationship between ANS and different mathematical measures, measured concurrently, were investigated; Chapter 3 examined the possibility to improve the ANS abilities in preschool children by using intensive adaptive training over a relatively short period. Moreover, the transfer effects of the training on early mathematical abilities were also examined.

The second aim of this dissertation concerned the potential role played by STM and WM skills in supporting domain-specific precursors of mathematics. The few studies that considered the role of WM in simple quantity comparison abilities did not provide a strong basis for any firm conclusions on such a relationship (Mussolin, Nys, Leybaert, & Content, 2012; Soltész, Szűcs, & Szűcs, 2010) since they didn't assess all of the WM components. Chapter 2 focuses on uncovering which specific WM component is involved in non-symbolic approximate quantity comparison processing in the preschool age. Moreover, in order to further explore the relationship between WM abilities and ANS, Chapter 3 investigated whether training focusing on the improvement of ANS abilities produced a far-transfer effect on WM abilities. Several studies found that WM abilities are related to overall mathematical skills (Gersten et al., 2005; Jordan et al., 2006; Passolunghi & Lanfranchi, 2012), therefore Chapter 4 investigated a possible causal relationship between domain-general working memory abilities and domain-specific numerical competence through a training study during the preschool years.

The third aim of this dissertation was to explore the malleability of cognitive precursors of mathematical learning. In Chapter 3, the possibility to improve ANS abilities was investigated, whereas Chapter 4 aimed to verify and compare the effects on early mathematical competence of two types of training. One type of training focused on the enhancement of domain-general precursors, working memory abilities; while the other focused on the enhancement of domain-specific precursors, early numeracy abilities. In the field of intellectual disabilities, some studies suggested that WM skills of children with neurodevelopmental disorders (like Down's syndrome) tend to be impaired and very poor compared to typically developing children of a similar mental

age (Gathercole & Alloway, 2006). In Chapter 5, the efficacy of a school-based visuo-spatial WM training on STM and WM skills for two individuals with DS was examined.

In summary, the studies presented in this dissertation address three general aims:

1. To investigate the relationship between the ANS and early mathematical abilities during the preschool years.
2. To specify the potential role played by STM and WM skills in supporting domain-specific precursors of mathematics.
3. To explore the malleability of cognitive precursors of mathematical learning (ANS, WM, early numeracy).

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# Chapter 2

## Approximate Number System in Preschool Children: Relationship with Mathematics and Working Memory

Costa, H. M. & Passolunghi, M. C. (Manuscript in preparation). Approximate Number System in preschool children: relationship with mathematical ability and working memory.

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## **Abstract**

Previous studies investigating the relationship between the Approximate Number System (ANS) and mathematics provided mixed results. Moreover, it remains unknown whether the possible link between ANS and mathematical ability could be mediated by general cognitive factors such as memory skills. The present study addressed two main questions. Firstly, the relationship between the performance in ANS and mathematical abilities was investigated. Secondly, the potential role played by Short-Term Memory (STM) and Working Memory (WM) abilities in supporting the ANS performance was examined. The participants were 67 3 to 5 year-old preschool children.

When correlation analyses were conducted, the results indicated that performance in ANS was associated with mathematical abilities and visuo-spatial STM, even when verbal and non-verbal IQ were controlled. By examining the differences between children with a higher ANS performance and children with a lower ANS performance it was found that children in the high-performance group showed better mathematical abilities and visuo-spatial STM abilities than their peers. The implications of these findings are discussed.

An increasing number of studies have investigated the cognitive components that contribute to the development of mathematical skills. Several studies investigated the role of precursors of mathematical learning, showing that some abilities assessed in preschool years can predict later mathematical achievement outcomes (De Smedt et al., 2009; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Mazzocco & Thompson, 2005; Passolunghi & Lanfranchi, 2012; Passolunghi, Vercelloni, & Schadee, 2007). Competencies that specifically predict mathematical abilities may be considered specific precursors: these are foundational-specific skills that underlie the development of arithmetic abilities. Such a core skills that predict children's performance in mathematics have been referred to under the general term "number sense" or the ability to represent and manipulate numbers non-verbally. Although no unique definition of number sense exists (Gersten, Jordan, & Flojo, 2005), it generally includes the ability to quickly represent and manipulate numerical quantities (Dehaene, 1997, 2001). One central component of number sense is the Approximate Number System (ANS), defined as a mental system of magnitude representation (Mazzocco, Feigenson, & Halberda, 2011a). The ANS is active in both children and adults, is widespread across cultures and shared with nonhuman animals (Dehaene, 2009). The ANS produce imperfect "noisy" estimates of numbers and the acuity of this system improves from infancy to adulthood (Halberda & Feigenson, 2008; Libertus & Brannon, 2009; Lipton & Spelke, 2003). The accuracy of numerical estimates and the ability to compare ANS representations, accords to Weber's Laws, with larger numerical estimates being increasing imprecise. Thus, the ability to discriminate between large sets of objects is a function of the ratio between them. It remains unclear when the noisy ANS representations integrate with more formal mathematical abilities. It has been suggest that the acquisition of the meaning of symbolic numerals is done by mapping symbolic numerals (number words or Arabic digits) onto the pre-existing approximate number representation. As a consequence, the ANS provides semantic representations of numbers and the precision of the ANS would play a crucial role in the early foundation of symbolic number knowledge (Dehaene, 1997; Holloway & Ansari, 2009; Wynn, 1992).

Several studies investigating the specific role of ANS representations in the development of more formal mathematical abilities, suggested that individual differences in ANS acuity may be linked to mathematical achievement since the preschool years, prior to the large amount of formal instruction children receive in primary school (Bonny & Lourenco, 2013; Libertus, Feigenson, & Halberda, 2011; Mazzocco, Feigenson, & Halberda, 2011b; Mussolin, Nys, Leybaert, & Content, 2012). In 2011 Libertus et al. assessed ANS acuity as well as mathematical abilities and verbal abilities in preschool children. They found that children's ANS acuity correlated with their mathematical ability, even when age and verbal skills were controlled for. Their result supports the

idea that the relationship between quantity discrimination and mathematical ability starts early in life. Another study showed similar results, suggesting that performance in numerosity comparison is associated with mastery of symbolic numbers between the ages of 3 and 6 (Mussolin et al., 2012). Further evidence of a relationship between numerosity comparison and mathematical performance comes from a longitudinal study showing that ANS acuity measured at preschool age predicted performance on school mathematical achievement two years later (Mazzocco et al., 2011b). However, the direction of such a developmental association between these two abilities is currently a matter of debate. For example, the results of a second longitudinal study showed a reverse link, suggesting that the symbolic number abilities predict later accuracy in numerosity comparison (Mussolin, Nys, Content, & Leybaert, 2014). One possible explanation for these inconsistencies might be the possibility that symbolic and non-symbolic numerical abilities enhance one another over the course of development (Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2013; Piazza, Pica, Izard, Spelke, & Dehaene, 2013). Moreover, other studies have failed to find a significant relationship between ANS performance, assessed by a non-symbolic magnitude comparison task, and mathematical achievement in the preschool years (Sasanguie, De Smedt, Defever, & Reynvoet, 2012a; Sasanguie, Van den Bussche, & Reynvoet, 2012; Soltész, Szűcs, & Szűcs, 2010).

### **ANS and Working Memory**

Very little is known about the cognitive mechanisms underlying the ANS acuity and it remains unknown whether the link between ANS acuity and mathematical ability is mediated by general cognitive factors. One domain-general ability shown to be predictive of mathematical abilities in preschool years is working memory (Gathercole & Pickering, 2000; Gersten et al., 2005; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Krajewski & Schneider, 2009; Passolunghi & Lanfranchi, 2012). The term working memory (WM) refers to a temporary memory system that plays an important role in supporting mathematical learning during the childhood years, because its key feature is the capacity of short-term storage and manipulation of information. According to Baddeley's model (Baddeley & Hitch, 1974; Baddeley, 1986) WM consists of three main parts: two passive modality-specific systems (i.e., the phonological loop and the visual-spatial sketchpad) specialized in retaining language-based and visuo-spatial information; and the central executive that coordinates the two slave systems and is responsible for a range of functions, such as the attentional control of actions (e.g., inhibiting irrelevant information, shifting attention, updating information). Thus, the phonological loop and visual-spatial sketchpad subsystems involve simple representation and maintenance. The central executive system is involved whenever information stored in the slave systems needs to be manipulated (Repovs & Baddeley, 2006). The distinction between the active central executive system and the specific memory storage systems (i.e., the phonological

loop and the visual-spatial sketchpad) in some ways parallel the distinction between working memory (WM) and short-term memory (STM). Indeed, the WM is considered an active system that involves both storage and information processing, while the STM typically involves situations in which the individual passively holds small amounts of information (Cornoldi & Vecchi, 2003; Swanson & Beebe-Frankenberger, 2004).

Several studies found that mathematical tasks, such as performing mental arithmetic and understanding mathematical word problems, require the information to be stored while it is processed or integrated with information retrieved from the long-term memory (Bull, Espy, & Wibe, 2008; De Smedt et al., 2009; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013; Passolunghi et al., 2007). In particular, the visuo-spatial component of the WM seems to play a central role in the development of early mathematical abilities in younger children (Kyttälä, Aunio, Lehto, Van Luit, & Hautamäki, 2003; McKenzie, Bull, & Gray, 2003; Rasmussen & Bisanz, 2005).

The extent to which the WM plays a role in the tasks involving the Approximate Number System remain at present an open issue. Some recent studies have demonstrated that WM abilities underlie non-symbolic approximate calculation processing (Barth et al., 2006; Xenidou-Dervou, De Smedt, van der Schoot, & van Lieshout, 2013; Xenidou-Dervou, van Lieshout, & van der Schoot, 2014). During a non-symbolic approximation arithmetic task, the child needs to perform an approximate addition of two arrays of dots and then compare the sum to a third dot array. In this kind of task, the involvement of WM abilities is fundamental in order to maintain in memory and, more importantly, to manipulate the dot sets. Individual differences in non-symbolic approximate calculation processing could therefore be explained by individual differences in WM capacity with particular involvement of the central executive component of WM in storing and manipulating non-symbolic approximate numerosities during early arithmetic (Xenidou-Dervou et al., 2013, 2014). Another measure frequently used to assess ANS acuity is the numerosity comparison task that requires children to maintain in memory a visual representation of multiple arrays in order to compare them. This kind of task seems to involve short-term maintenance of visual information rather than both storage and manipulation of the visual information. Soltész et al. in 2010 found that magnitude discrimination correlated with short-term memory in 4- to 7-year-old children. Moreover, other authors found that the visuo-spatial STM was associated with accuracy in numerosity discrimination (Mussolin et al., 2012). These results suggest that more general cognitive abilities like STM may play a role in the performance of magnitude comparison acuity. However, to our knowledge, no study has examined in detail the role of WM and STM in non-symbolic approximate comparison and this inter-relationship needs to be investigated further.

## **The Current Study**

Previous studies have produced some inconsistent results about the link between ANS and mathematical abilities. Specifically the association between ANS and mathematics in preschool children was evidenced in some studies (e.g. Bonny & Lourenco, 2013; Halberda, Mazocco, Feigenson, & Halberda, 2008; Mazocco et al., 2011b), but not in others (e.g. Sasanguie, De Smedt, Defever, & Reynvoet, 2012b; Sasanguie, Van den Bussche, et al., 2012; Soltész et al., 2010). Moreover, only few studies considered the role of WM in simple quantity comparison (Mussolin et al., 2012; Soltész et al., 2010) and they do not yet have a strong basis for any firm conclusions on such a relationship as they didn't examine in detail the role played by all WM and STM components.

Given previous inconsistent results about the link between ANS and mathematical abilities, in the present study we investigated the relationship between the performance in numerosity comparison and early mathematical abilities in preschool children. Moreover, we were interested in the identification of the role of WM and STM skills in non-symbolic approximate numerosity comparison skills. Specifically, we focused on uncovering which specific WM component is involved in this kind of ANS processing at preschool age. The quantity comparison task requires to maintain in memory visual representations without an active elaboration (storage and manipulation) of the information held in memory, as happens during a non-symbolic approximation addition task. Therefore, an involvement of the STM skills but not of the active WM skills in the ANS acuity assessed by the numerosity comparison task was expected.

## **Method**

### **Participants**

The participants were 67 preschool children ( $M_{\text{age-in-months}} = 51.94$ ,  $SD = 5.08$ , 30 girls), recruited through three preschools located in an urban area of northern Italy. After consent was provided by the schools, letters were given to the parents/guardians of each child for individual consent. Socio-economic status (SES) was measured using mothers' highest level of education: 28% of mothers have a secondary school qualification, 33% were educated to A level, 33% of mothers held a degree and 3% a PhD. All children were fluent Italian speakers and none of the children had a diagnosis for a developmental disorder or had vision or hearing problems.

## **Assessments**

### **Working memory tasks.**

*Visuo-spatial working memory.* The visuo-spatial working memory task required a visuo-spatial dual task (Lanfranchi, Cornoldi, & Vianello, 2004). The child had to remember the frog's starting position on a path on a  $4 \times 4$  chessboard, in which one of the 16 cells was colored red. The child also had to tap on the table when the frog jumped onto the red square. The task had four different levels of difficulty, depending on the number of steps in the path (i.e., two, three, four, and five steps, respectively). The score of 1 was given for every trial performed correctly, with the child both remembering the first position of the pathway and performing the tapping task. Otherwise, a score of 0 was given. The minimum score was 0 and the maximum score was 8.

*Verbal working memory.* During the verbal dual task (Lanfranchi et al., 2004) the child was presented with a list of two to five two-syllable words and was asked to remember the first word on the list and tap on the table when the word "palla" (ball) was presented. A score of 1 was given when the initial word of the series was remembered correctly at the same time the dual task was performed. The minimum score was 0 and the maximum score was 8.

### **Short-term memory tasks.**

*Visuo-spatial short-term memory.* During pathway recall (Lanfranchi et al., 2004), the child was shown a path taken by a small frog on a  $3 \times 3$  or  $4 \times 4$  chessboard. Then, the child had to recall the pathway immediately after presentation by moving the frog from square to square, reproducing the experimenter's moves. The task had four levels of difficulty, depending on the number of steps in the frog's path and dimensions of the chessboard ( $3 \times 3$  in the first level with two steps and  $4 \times 4$  in the other levels, with two, three, and four steps, respectively). A score of 1 was given for every trial performed correctly. The minimum score was 0 and the maximum was 8.

*Verbal short-term memory.* The word recall forward task (Lanfranchi et al., 2004) was used to tap children's verbal STM capacity. In this task the child was presented with lists of two to five words and was required to repeat the list immediately and in the same order as presented. The span was considered to be correct if the child recalled all of the items in the correct order. A score of 1 was given for every list recalled correctly. The minimum score was 0 and the maximum was 8.

### **Numerosity comparison.**

Children's numerosity comparison abilities were assessed with the ANS task used by Van Herwegen, Costa, and Passolunghi (under review). This task was based upon the materials used in Halberda and Feigenson (2008). Children sat at a computer with a touch screen and they heard "let's play a game". First, the child was introduced to Big Bird's items for 2000 msec and a voice

said “here are big bird’s dots”. Next, the child saw Grover’s items for 2000 msec with a voice saying “these are Grover’s dots”. Then, the pictures appeared side by side and the child was asked “who has more dots?”. The pictures appeared at the same time as the label onset. In contrast to the original task by Halberda and Feigenson (2008) children responded by touching a screen in order to reduce eye-hand coordination difficulties. Children received feedback for each trial to maintain motivation. For a correct answer, a green smiley face appeared with a sheering sound. For incorrect responses, a red sad face appeared with the sound “oh”. Following four practice trials, 60 test items trials were presented in random order using the software program E-prime. The trails included 2 pictures displaying different ratios of 1-16 dots (see Table 1). Each ratio was presented six times using 6 different overall contour lengths (2.9981, 4.1012, 5.0912, 5.9397, 6.2225, 6.7034 cm total diameter length). The dots were scattered randomly on the screen, avoiding any dice-like presentations. The number of correct trials was recorded. Before children started the game, they were administrated 4 practice trials.

**Table 1.** The 10 pairs of numerosities used across the different ratio in the Numerosity Comparison Task

Ratio	Set size	
	1	2
1:2	1 vs. 2	8 vs. 16
2:3	2 vs. 3	8 vs. 12
3:4	3 vs.4	6 vs. 8
4:5	4 vs. 5	8 vs. 10
5:6	5 vs. 6	10 vs. 12

**Mathematical abilities.**

To asses mathematical abilities we administered the battery of test used by Van Herwegen et al. (under review)

**Early Number Concepts.** The Early Number Concepts sub-test from the British Ability Scales (BAS3; Eliot & Smith, 2011) was carried out to assess early numeracy abilities. This sub-test consist of 30 items and evaluates different aspects of young children’s numerical competence, such as counting abilities, number concepts, quantitative understanding and simple arithmetic. The items are scored, with 0 for a wrong answer and 1 for a right answer.



**Counting.** To measure children's counting abilities, children were asked to recite the number word list upto "sixty". The highest number counted correctly was recorded as a measure of the counting range.

**Cardinality principle.** To measure children's cardinality understanding, children were shown flash cards that depicted 1-16 coloured objects and asked to count the objects shown. Once they had counted the objects children were asked how many objects there were. If children started to recount the objects the trial was recorded as incorrect. The items are scored, with 0 for a wrong answer and 1 for a right answer.

**Number recognition.** For number recognition, children were shown digits 1 to 16 on black and white flash cards. The items are scored, with 0 for a wrong answer and 1 for digits named correctly.

### **Intelligence.**

Intellectual capacities were evaluated using two subtest of the Wechsler Preschool and Primary Scale of Intelligence (WPPSI-3; Wechsler, 2002).

**Verbal IQ.** The Receptive Vocabulary subtest of the WPPSI-3 is a measure of verbal knowledge and was considered as an indicator of verbal intelligence. In general, vocabulary subtests are considered relatively good estimates of general intelligence (Sattler, 2001).

**Non-verbal IQ.** The Block Design subtest is a measures of perceptual organization and spatial reasoning abilities and was considered as an indicator of non-verbal Intelligence (Sattler, 1992).

### **Procedure**

The experimenters were three female Italian masters' students trained and supervised by the authors. Each child was tested individually in a quiet room at school on three different occasions lasting 20-30 minutes each. The tests were administered in a fixed sequence designed to vary task demands across successive tests. The first session included the Intelligence tasks and the Early Number Concepts task; the second session included the WM and STM tasks and the Numerosity comparison task; the third session included the Counting task, the Cardinality principle task and the Number recognition task. In order to encourage children and keep them motivated, they received stickers at the end of each session.

## Results

### Outline of the Result Session

The results are divided into two subsections. In the first section, correlational analyses are reported to examine cognitive correlates of ANS performance. In the second section, the profiles of subgroups of children with above- and below-median ANS abilities are compared.

### Correlations

#### Simple correlations.

Simple correlational analyses were conducted to explore the relationships ANS abilities and age, mathematical abilities, working memory and short-term memory measures. In line with previous research, children's age significantly correlated to their ANS acuity performance ( $r(67) = .26, p = .03$ ), such that older children performed better than young children. Moderate-to-large correlations were found between all mathematical measures and ANS task (Cardinality:  $r(67) = .58, p < .001$ ; Counting:  $r(67) = .48, p < .001$ ; Number recognition:  $r(67) = .48, p < .001$ ; Early Number Concepts;  $r(67) = .71, p < .001$ ). We also found a small correlation between ANS abilities and Verbal ( $r(67) = .28, p = .02$ ) and Visuo-spatial ( $r(67) = .27, p = .02$ ) WM abilities. Moreover, the ANS abilities were related to the visuo-spatial STM abilities ( $r(67) = .51, p < .001$ ) but not to verbal STM abilities ( $r(67) = .07, p = .59$ ). As can be seen in Table 2 the mathematical measures were all significantly intercorrelated .

**Table 2.** Correlation between ANS abilities, mathematical abilities, working memory and short-term memory measures.

	1	2	3	4	5	6	7	8	9	10
1. ANS	1									
2. Early Number Concepts	.71**	1								
3. Verbal STM	.07	.21	1							
4. Verbal WM	.28*	.30*	.18	1						
5. Visuo-spatial STM	.51**	.49**	.25*	.39**	1					
6. Visuo-spatial WM	.27*	.36**	.11	.39**	.29	1				
7. Cardinality	.58**	.69**	.06	.15	.42**	.37**	1			
8. Counting	.55**	.57**	.33**	.21	.37**	.35**	.48**	1		
9. Number recognition	.50**	.60**	.24*	.22	.41**	.41**	.65**	.57**	1	
10. Age	.30*	.44**	.17	.30*	.38**	.27*	.43**	.45**	.51**	1

\* $p < .05$

\*\* $p < .01$

### Partial Correlations.

To check for the possibility that the link between ANS abilities and the other measures was mediated by general intelligence we calculated partial correlations with verbal intelligence and non-verbal intelligence controlled for (see Table 3).

Again children showed positive correlation between ANS abilities and Age ( $r(63) = .27, p = .03$ ), Cardinality ( $r(63) = .51, p = <.001$ ), Counting ( $r(63) = .51, p = <.001$ ), Number recognition ( $r(63) = .43, p = <.001$ ), and Early Number Concepts ( $r(63) = .61, p = <.001$ ). Moreover, the results showed a positive correlation between ANS and Visuo-spatial STM ( $r(63) = .43, p = <.001$ ). The correlations between ANS abilities and WM abilities failed to reach significance when general intelligence was controlled for (verbal WM:  $r(63) = .14, p = .22$ ; Visuo-spatial WM:  $r(63) = .10, p = .42$ ). The correlation between ANS abilities and Verbal STM abilities remained non significant ( $r(63) = .12, p = .33$ ). This means that higher mathematical and visuo-spatial STM scores are associated with higher ANS acuity. These findings indicate that preschool children who had more precise approximate number representation tend to perform better on mathematical and visuo-spatial STM measures.

**Table 3.** Partial Correlations between ANS abilities, mathematical abilities, working memory and short-term memory measures controlling for verbal and non-verbal IQ.

	1	2	3	4	5	6	7	8	9	10
1. ANS	1									
2. Early Number Concepts	.62**	1								
3. Verbal STM	.12	.27*	1							
4. Verbal WM	.15	.18	.21	1						
5. Visuo-spatial STM	.43**	.40**	.24*	.33**	1					
6. Visuo-spatial WM	.10	.21	.15	.32**	.20	1				
7. Cardinality	.51**	.62**	.05	.05	.30*	.27*	1			
8. Counting	.51**	.53**	.35**	.15	.30*	.29*	.42**	1		
9. Number recognition	.43**	.56**	.23	.16	.30*	.37**	.60**	.53**	1	
10. Age	.27*	.47**	.15	.09	.36**	.27*	.43**	.44**	.49**	1

\* $p < .05$

\*\* $p < .01$

## Regression

A regression analysis was conducted to examine the extent to which the cognitive measures considered in this study explained unique variance in ANS performance (We were interested in which cognitive measures predicted performance in the ANS task). We did not have specific hypothesis with respect to the order of importance of the predictors. Therefore, a stepwise multiple linear regression analysis was conducted for the ANS variable with WM tasks, STM tasks, mathematical abilities and IQ measures as predictors. Table 4 show the regression analyses results. The prediction model contained four of the ten predictors and was reached in seven steps. The model Results showed that the variable Early Number Concepts was the best predictor of ANS in the multiple regression model,  $t(66) = 3.73, p < .001$ . The second best predictor was the verbal IQ ( $t(66) = 2.51, p = .01$ ) followed by counting ( $t(66) = 2.04, p = .046$ ) and visuo-spatial STM ( $t(66) = 2.11, p = .038$ ).

**Table 4.** Multiple regression coefficients

Model	<i>B</i>	<i>SE B</i>	$\beta$	<i>t</i>	<i>p</i>
Constant	18.46	3.50		5.28	.000
Verbal IQ	.75	.30	.22	2.52	.014
Early Number Concepts	.68	.18	.42	3.73	.000
Visuo-spatial STM	1.15	.54	.20	2.12	.038
Counting	.16	.08	.20	2.04	.046

**Note.** The dependent variable was ANS.  $R^2 = .604$ , Adjusted  $R^2 = .578$

## Group Comparisons

To further examine the ANS variable, a median split was introduced to identify a group of children with relatively high ANS performance ( $M_{\text{age-in-months}} = 52.83, SD = 5.14$ ; 14 girls, 18 boys) and a group of children with lower ANS performance ( $M_{\text{age-in-months}} = 50.97, SD = 4.94$ ; 16 girls, 19 boys). Means and standard deviations for the ANS abilities, Age, Mathematical abilities, working memory and short-term memory measures, and Intelligence measures by groups, are presented in Table 5.

Children performed significantly above chance (score of 30) on the ANS task both in the high performance group,  $t(34) = 29.92, p < .001$ , and in the ANS low performance group,  $t(31) = 5.37, p < .001$ . A series of analyses of variance (ANOVAs) established no significant age

differences between groups  $F(1,65) = 2,28, p = .14, \eta_p^2 = .03$ ). There is a significant difference between low-ANS group and high-ANS group in Verbal IQ ( $F(1,65) = 4.93, p = .03, \eta_p^2 = .07$ ) and non-verbal IQ ( $F(1,65) = 7,63, p = .007, \eta_p^2 = .105$ ). However, the difference on the ANS remained significant when these scores were covaried ( $F(1,63) = 111,70, p = .007, \eta_p^2 = .105$ ).

**Table 5.** Descriptive statistics of ANS precision, mathematical abilities, working memory and short-term memory measures, and univariate test results for high-ANS group and low-ANS groups.

	High-ANS N=32		Low-ANS N=35		F
	Mean	SD	Mean	SD	
ANS	36.06	6.38	51.26	4.20	111.70 **
Early Number Concepts	11.41	4.48	17.43	5.33	14.36 **
Verbal STM	3.97	.90	4.14	.94	.88
Verbal WM	1.50	1.52	2.37	1.86	1.74
Visuo-spatial STM	4.25	1.68	5.23	1.35	5.70
Visuo-spatial WM	2.19	2.02	2,89	2.23	.09
Cardinality	4.97	4.57	9.20	3.95	9.63 **
Counting	10.63	6.45	19.51	14.18	6.83 *
Number recognition	9.40	5.09	5.13	4.46	8.88 **

\*\*<.01

\*<.05

Analyses of covariance (ANCOVAs) were computed to compare the groups on measures of mathematical abilities, working memory and short-term memory abilities with verbal intelligence and non-verbal intelligence controlled for. For the comparisons of the difference between groups,  $\eta_p^2$  was used as a measure of effect size. The criteria of Cohen (1988) were used to classify the effect sizes: small effect:  $\eta_p^2 = .01$ ; medium effect:  $\eta_p^2 = .06$ ; and large effect:  $\eta_p^2 = .14$ .

A significant difference was observed between high/low ANS performance groups in Early Number Concepts ( $F(1, 63) = 14.36, p < .001, \eta_p^2 = .19$ ), Cardinality ( $F(1, 63) = 9.63, p = .003, \eta_p^2 = .13$ ), Counting ( $F(1, 63) = 6.83, p = .01, \eta_p^2 = .10$ ), and Number Recognition ( $F(1, 63) = 8.88, p = .004, \eta_p^2 = .12$ ). No significant difference was observed between low/high performance groups in Verbal STM ( $F(1, 63) = .88, p = .35, \eta_p^2 = .01$ ), Verbal WM ( $F(1, 63) = 1.74, p = .19, \eta_p^2 = .03$ ), Visuo-spatial STM ( $F(1, 63) = 2.82, p = .09, \eta_p^2 = .04$ ), Visuo-spatial WM ( $F(1, 63) = .09, p = .77, \eta_p^2 = .001$ ). If only verbal intelligence was entered as a covariate the children in the high-ANS group show significantly better score in the visuo-spatial STM task than children in the low-ANS

group ( $p = .02$ ).

This analysis appears to show that participants with high ANS scores perform better than children with low ANS scores in all mathematical tasks. Differently, there isn't difference between groups in any WM and STM tasks if verbal and non-verbal intelligence are controlled for.

## Discussion

The present study addressed two main questions. Firstly, given previous inconsistent results about the link between ANS acuity and mathematical abilities, we were interested in the investigation of the relationship between the performance in numerosity comparison and early mathematical abilities in preschool children. Secondly, the potential role played by STM and WM abilities in supporting the ANS performance was examined.

Our findings revealed a positive correlation between ANS performance and all the mathematical measures considered in this study: cardinality, counting, number recognition and early number concepts. Therefore, the children who showed a good performance in the numerosity comparison task also had higher abilities in manipulating numerical symbols than the children who were less accurate in the numerosity comparison task. Importantly, this link held even when IQ measures were taken into account. These findings are consistent with previous studies which found a relationship between ANS abilities and general mathematical competence in preschool children (Bonny & Lourenco, 2013; Halberda et al., 2008; Libertus et al., 2011; Mazzocco et al., 2011b)

We also found a small positive correlation between ANS performance and verbal WM, visuo-spatial WM and visuo-spatial STM. However, only the link with visuo-spatial STM held when IQ measures were taken into account. This indicates that the visuo-spatial STM may play an important role in children's performance in numerosity comparison, which requires children to retain in memory a visual representation of multiple arrays for comparison. Active WM skills, involving the central executive functions, do not seem to be involved in this task, probably because an active manipulation of information held in memory isn't required. These results show that ANS performance is related to both mathematical abilities and short-term memory skills in the preschool years. Amongst the different skills considered in this study, general early numeracy abilities, verbal IQ, counting abilities and visuo-spatial STM skills are particularly linked to accuracy in numerosity comparison.

By examining the differences between the children with a higher ANS performance and children with a lower ANS performance it was found that children in the high-performance group showed better mathematical abilities than their peers in the low-performance group. Indeed, the high-ANS group had significantly higher scores in early number concepts, cardinality, counting and

number recognition. These findings provide further evidence for a link between ANS acuity and mathematical ability early in life (Halberda et al., 2008; Libertus et al., 2011; Mazzocco et al., 2011b; Mussolin et al., 2012) and suggest that noisier ANS representations may cause difficulties in the development of mathematical concepts (Gilmore, McCarthy, & Spelke, 2007, 2010; Mazzocco et al., 2011a). On the other hand, no differences between the groups in WM or STM measures were found, when verbal and non-verbal IQ were controlled for. However, the group differences in visuo-spatial STM are approaching significance. Given that visuo-spatial ability is related to Block Design performance (Mervis, Robinson, & Pani, 1999) we repeated analysis removing non-verbal IQ as covariate. If we controlled the comparison just for verbal IQ, which is considered a relatively good estimates of general intelligence (Sattler, 2001), the high-ANS group performed significantly better on the visuo-spatial STM task than the low-ANS group. These additional results about the relationship between visuo-spatial memory and quantity comparison abilities are interesting and support the idea that visuo-spatial STM abilities may have a role to play in determining ANS abilities in preschool children. Further evidence about the nature of the relationship between ANS, mathematics, and memory could come from studies investigating this link in children who are considered to be at risk for developing mathematical learning disability. Moreover, longitudinal and training studies are needed to identify the direction of the link between ANS and mathematical ability and to better understand the relationship between ANS, mathematical abilities and more general cognitive abilities like visuo-spatial STM skills.

Although the present study provides evidence for a relationship between ANS and mathematical abilities, and between ANS and visuo-spatial STM, some limitations should be acknowledged. A first limitation is the relatively small sample size, especially when analyzed by higher versus lower ANS performers. Future studies should increase the number of participants and investigate the relationship between ANS, mathematics, and memory abilities in different age groups. Second, in line with some previous studies of preschool children (Fuhs & McNeil, 2013; Halberda & Feigenson, 2008; Mazzocco et al., 2011b), the ANS task used in this study includes both small and large quantities. However, some authors argue that the representation of large numbers ( $>4$ ) is carried out by the ANS, while smaller numbers ( $<4$ ) invoke subitizing (rapid, quick, and accurate enumeration of small numbers) (e.g. Feigenson, Dehaene, & Spelke, 2004; Lipton & Spelke, 2003; Revkin, Piazza, Izard, Cohen, & Dehaene, 2008; Xu, 2003). Other studies, however suggested that small numerosities ( $<4$ ) could be represented with both the Object Tracking System (subitizing) and the approximate number systemres (Burr et al., 2010, 2011; Hyde and Wood, 2011; Piazza et al., 2011). In particular it appears that “General constraints on visual

processing, attention, and working memory determine if a given set of items is represented as individual object files or as an approximate numerical magnitude” (Hyde, 2011, p. 5).

In summary, the results described above provide further evidence about the relationship between ANS abilities and mathematical abilities and provide evidence for a link between ANS acuity and visuo-spatial STM in preschool years. The present study have several practical implications for the identification of children at risk to develop a mathematical learning disability and for intervention. Indeed, these findings may contribute toward efforts to identify core deficits that underlie difficulties in mathematics and suggest the possibility for early screening of risk for mathematical learning difficulty.

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# Chapter 3

## Training Approximate Number System in Preschool Children

Costa, H. M., Van Herwegen, J., & Passolunghi, M. C. (Manuscript in preparation). Training Approximate Number System in preschool children.

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## **Abstract**

This study was an attempt to replicate an earlier investigation in which preschool children were trained to improve their Approximate Number System (ANS) abilities. We investigated whether playing Preschool Number Learning Scheme (PLUS) that target the ANS system on a daily basis would improve Italian preschool children's ANS abilities, in comparison to an active control group of children who were involved in interactive book reading sessions.

The participants were 50 preschool children. Children in the training group followed the PLUS for 10 minutes each day for a time period of five weeks. Children in the active control group took part in interactive or shared picture book readings for 10 minutes per day for five weeks. The results showed that, playing PLUS games that target ANS abilities each day for five weeks improved the children's ANS abilities. No transfer effect was found on mathematical abilities or working memory neither immediately post-training nor five weeks later at follow-up. The current study provides a demonstration that ANS can be effectively trained in preschool years.

Children form non-verbal approximate representations of numerosities and are capable of using these representations to discriminate visual arrays (Feigenson, Dehaene, & Spelke, 2004; Libertus & Brannon, 2009). This ability to non-verbally represent numbers is shared across species and across development (Dehaene, 1997; Feigenson et al., 2004). The approximate number system (ANS) is the primitive cognitive system that allows individuals to represent and process numerical magnitude information, which underlies the ability to make quantitative judgments and decisions (Barth, Kanwisher, & Spelke, 2003; Brannon, 2002; Feigenson et al., 2004; Xu, Spelke, & Goddard, 2005; Xu, 2003). Representations within the ANS become increasingly imprecise with increasing magnitudes and the ability to nonverbally discriminate between two quantities depends on their ratio. The precision of the ANS increases substantially during human development.

Several authors suggest that ANS plays an important role in the development of the symbolic number system acquired in early childhood (Dehaene, 2005; Hubbard et al., 2008). Specifically, individual differences in ANS acuity correlate with mathematical achievement at different ages (Bugden & Ansari, 2011; Dewind & Brannon, 2012; C. K. Gilmore, McCarthy, & Spelke, 2010; Halberda, Mazocco, Feigenson, & Halberda, 2008; Libertus, Feigenson, & Halberda, 2011; Lourenco, Bonny, Fernandez, & Rao, 2012). In support of this view studies investigating ANS in children with atypical mathematical development found that those children were impaired in their ability to process numerical magnitudes (Bonny & Lourenco, 2013; Mazocco, Feigenson, & Halberda, 2011a).

These findings suggest that numerical magnitude processing is an important foundation for higher level numerical and mathematical skills. However, most of the evidence suggesting a link between ANS and mathematics is indirect (Bonny & Lourenco, 2013; Halberda et al., 2008; Libertus et al., 2011; Mazocco, Feigenson, & Halberda, 2011b; Mussolin, Nys, Leybaert, & Content, 2012) as these studies usually examined the association in only one direction, showing that ANS predicts symbolic number processing. Therefore, it remains unclear whether the differences in ANS play a causal role in creating differences in mathematical development (Piazza, Pica, Izard, Spelke, & Dehaene, 2013), or whether symbolic number knowledge causes changes in ANS acuity (Mussolin, Nys, Content, & Leybaert, 2014).

Moreover, the relationship between ANS and mathematics could be mediated by other general cognitive factors, such as executive function or memory (e.g. Fuhs & McNeil, 2013; Smedt, Noël, Gilmore, & Ansari, 2013). Indeed, general abilities like memory may play an important role in children's performances in non-symbolic number comparison, helping them to maintain in memory multiple arrays and to keep the task-relevant dimension in their minds, so that they can ignore the task-irrelevant features more easily (Soltész, Szűcs, & Szűcs, 2010).

It also remains unclear when the noisy ANS representation would integrate with more formal mathematical abilities. It has been suggested that the acquisition of the meaning of symbolic numerals is done by mapping symbolic numerals (number words or Arabic digits) onto the pre-existing approximate number representation. As a consequence, ANS provides semantic representations of numbers and the precision of the ANS plays a crucial role in the early mathematical development (Dehaene, 1997; Holloway & Ansari, 2009; Wynn, 1992).

Past research provided mixed results concerning the association between performance in non-symbolic number processing and mathematical skills. More information about the functional association between ANS and symbolic mathematics could be provided by longitudinal studies and training studies in both children and adults.

### **ANS Training**

A number of programs currently seek to target the emergent mathematical skills in preschoolers (Arnold, Fisher, Doctoroff, & Dobbs, 2002; Greenes, Ginsburg, & Balfanz, 2004; Starkey, Klein, & Wakeley, 2004; Young-Loveridge, 2004). These training programs include different activities designed to promote a range of skills, which the literature suggests are important precursors of mathematical learning, including counting, recognizing and writing numbers, one-to-one correspondence, comparisons, change operations, and understanding numbers and quantities. Most of the training studies that targeted very specific aspects of numerical magnitude processing, using both symbolic and non-symbolic stimuli, didn't consider the effects of the training on non-symbolic measures of numerical magnitude processing (Ramani & Siegler, 2008; Siegler & Ramani, 2008; Whyte & Bull, 2008). The only two studies investigating the effects of an adaptive game designed to improve basic number skills (numerical comparison, links between numbers and space, links between non-symbolic and symbolic representations of numbers; and understanding and fluency of access to basic addition and subtraction facts) on a non-symbolic comparison task provided mixed results. Wilson, Dehaene, Dubois, and Fayol (2009) found improvements in tasks traditionally used to assess number sense (numerical comparison of digits and words) but no improvement in non-symbolic measures of number sense. By contrast, a recent study found a significant effect of the training on non-symbolic comparison skills in first graders (Obersteiner, Reiss, & Ufer, 2013).

Moreover, one study investigated whether the activation of the ANS enhanced children's performance of symbolic arithmetic (Hyde, Khanum, & Spelke, 2014). Authors found that school-age children who briefly practiced tasks that engaged primitive approximate numerical quantities performed better on subsequent exact symbolic arithmetic problems than did children who were given other tasks involving comparison and manipulation of non-numerical magnitudes (brightness



and length). However, they didn't consider the effects of the training on non-symbolic measures of numerical magnitude processing.

A Training study with adults found that ANS acuity improved after only one training session in adults who completed an ANS task during which they received trial-by-trial feedback and that performance on the ANS task remained stable even when feedback was removed (Dewind & Brannon, 2012). In another study, several days of training on a non-symbolic approximate numerical addition and subtraction task led to improvements in ANS acuity and symbolic mathematics (Park & Brannon, 2013).

These studies show that training on tasks that tap into ANS abilities could be possible even if it is yet unclear whether early intervention focused on exercising the ANS would be effective in preschool children, and if improved ANS acuity would lead to better mathematical abilities.

### **PLUS Training Programme**

Given that the ANS is thought to play an important role in mathematical learning (Bonny & Lourenco, 2013; Booth & Siegler, 2006; Halberda et al., 2008; Jordan, Kaplan, Locuniak, & Ramineni, 2007; Libertus et al., 2011; Mazzocco et al., 2011b), in a previous pilot study we explored the possibility to improve ANS acuity using a specific training procedure in preschool children (Van Herwegen, Costa, & Passolunghi, under review). The training used, called *Preschool number learning scheme (PLUS)*, included different daily games involving guessing and matching of numerosities. The results showed that children in the training group improved their ANS abilities. Moreover, improved ANS seems to have a positive impact on children's counting and overall mathematical abilities, but not on WM abilities. However, further work is needed in order to validate the PLUS programme.

### **The Present Study**

With the present study we intend to replicate and extend our previous study about the effectiveness of the PLUS programme in improving ANS skills and mathematical abilities in a different cultural and school environment. The preschool education in Italy includes free play as well as more structured activities, and children must attend preschool activities every day. Differently in the UK context the preschool system is mainly based on free play, and usually children are not obliged to attend preschool every day, which increases the risk of drop-out of participants.

The current study explored whether typically developing 3- to 5-year-old preschoolers who played specially designed estimation and guessing games, called PLUS, on a daily basis would show improved ANS abilities, in comparison to an active control group. The improvement of

emergent mathematical skills in preschool children has been demonstrated by using both formal and informal instruction, even before the children entered primary school (Ramani, Siegler, & Hitti, 2012; Ramani & Siegler, 2008; Siegler & Ramani, 2008; Van Herwegen et al., under review; Whyte & Bull, 2008). In line with previous findings we expected an improvement of ANS abilities in the children participating in the PLUS program specifically targeting ANS abilities.

In addition, since ANS abilities seems to be correlated to mathematical development (Bonny & Lourenco, 2013; Halberda et al., 2008; Libertus et al., 2011; Mazzocco et al., 2011b; Mussolin et al., 2012), it was examined whether improved ANS abilities impacted on children's symbolic numerical knowledge as well as on their general mathematical abilities immediately after the training and at follow-up. Finally, since previous studies have suggested that memory may play an important role in children's ANS performance (Barth et al., 2006; Soltész et al., 2010; Xenidou-Dervou, De Smedt, van der Schoot, & van Lieshout, 2013; Xenidou-Dervou, van Lieshout, & van der Schoot, 2014) it was also investigated whether our training focusing on the improvement of ANS abilities also produced a far-transfer effect on Short-Term Memory (STM) and Working Memory (WM) abilities.

## **Method**

### **Participants**

The participants were 50 preschool children recruited through 3 preschools located in an urban area of northern Italy. The data for one child were excluded, because he couldn't complete the post-test assessment due to illness. The results presented are based on the remaining 49 (28 boys) children. After consent was provided by the schools, a letter was given to the parents/guardians of each child for individual consent. Children with significant developmental delays (as identified by the local education services) were excluded. The socioeconomic status (SES) of the sample was established using mothers' and fathers' highest level of education, as parental education is considered to be one of the most stable aspects of SES (Sirin, 2005). The information about parental education was obtained through a survey. The highest level of mothers' education was: secondary school (30%), High school (30%), Degree (35%), and PhD (5%). The highest level of fathers' education was: secondary school (25%) High school (45%), Degree (20%), and PhD (7%).

Children were randomly allocated to either the training group (N = 26 children,  $M_{\text{age}} = 52.35$  months, SD 4.32, nine girls) or the active control group (N=23  $M_{\text{age}} = 53.74$  months, SD = 4.59, 13 girls).

## **Procedure**

Before and after the training each child was tested individually in a quiet room at school in three different sessions lasting 15-20 minutes each. In the first session ANS abilities and IQ were assessed; in the second session mathematical skills were assessed; in the third session the memory (WM and STM) skills of the children were measured. The experimenters who conducted the assessments were blind to the group the children belonged to.

Over 5 successive weeks the training group followed the PLUS program, while the active control group took part in interactive picture book reading. These activities took place every day for 10 minutes in small groups of two children with a researcher.

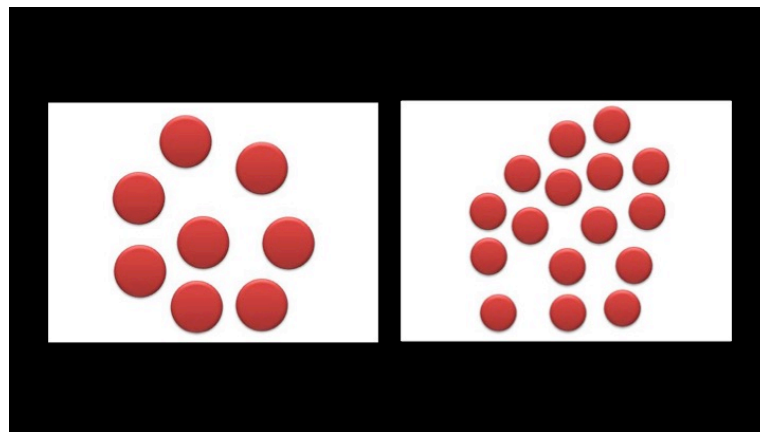
## **Assessments**

### **ANS abilities.**

The approximate number representations can be mentally combined to perform comparison, addition and subtraction across sets. The ANS can be assessed using tasks which involve the viewing, comparing, adding, or subtracting non-symbolic quantities, such as arrays of dots (Gilmore, Attridge, & Inglis, 2011; Halberda & Feigenson, 2008a; Piazza, Pinel, Le Bihan, & Dehaene, 2007; Xenidou-Dervou, Lieshout, & Menno Schoot, 2014). To assess ANS abilities we selected two tasks previously used with preschool children: the numerosity comparison task and the approximate addition task (which assess more complex aspects of the Approximate Number System).

***Numerosity comparison task.*** Children's numerosity comparison abilities were assessed with the ANS task used by Van Herwegen, Costa, and Passolunghi (under review). This task was based upon the materials used in Halberda and Feigenson (2008). Children sat at a computer with a touch screen and were presented with arrays of spatially separated dots. When the task started children heard "let's play a game". First, the child was introduced to Big Bird's items for 2000 msec and a voice said "here are big bird's dots". Next, the child saw Grover's items for 2000 msec with a voice saying "these are Grover's dots". Then, the pictures appeared side by side and the child was asked "who has more dots?". The pictures appeared at the same time as the label onset, and children had to indicate which is the array with more dots by touching the screen. Children received feedback for each trial to maintain motivation. For a correct answer, a green smiley face appeared with a cheering sound. For incorrect responses, a red sad face appeared with

the sound “oh”. Children were instructed to respond as correctly and as fast as possible. Following four practice trials, 60 test items trials were presented in random order using the software program E-prime 2.0. The trials included 2 pictures displaying different ratios of 1-16 dots (see Table 1). Each ratio was presented six times using 6 different overall contour lengths (2.9981, 4.1012, 5.0912, 5.9397, 6.2225, 6.7034 cm total diameter length). The dots were scattered randomly on the screen, avoiding any dice-like presentations. The number of correct trials was recorded. Before children started the game, they were administered 4 practice trials.

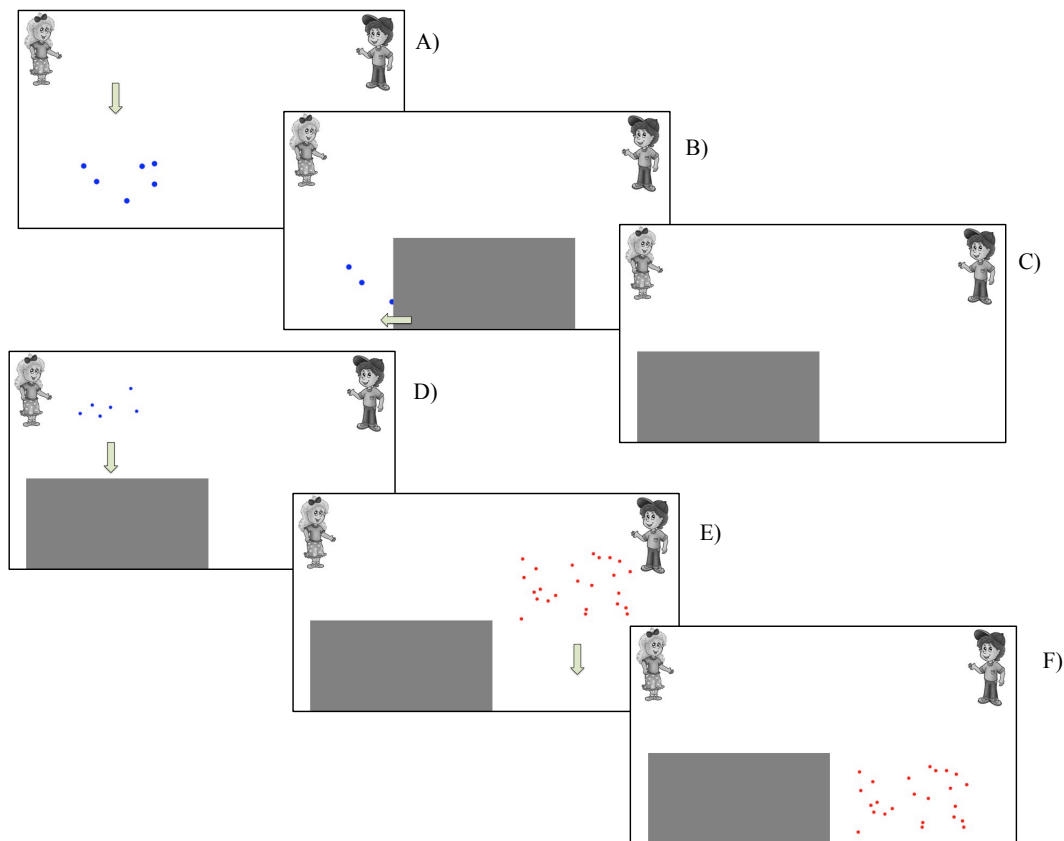


**Figure 1** The Numerosity Comparison task: illustration of a trial (Van Herwegen et al., under review)

**Table 1.** The 10 pairs of numerosities used across the different ratio in the Numerosity Comparison task

Ratio	Set size	
	1	2
1:2	1 vs. 2	8 vs. 16
2:3	2 vs. 3	8 vs. 12
3:4	3 vs. 4	6 vs. 8
4:5	4 vs. 5	8 vs. 10
5:6	5 vs. 6	10 vs. 12

**Approximate addition task.** We used the approximate addition task used by Xenidou-Dervou et al. (2013) (adapted from Xenidou-Dervou et al., 2014). In each trial, the child was presented with four sequential steps: 1) a set of blue dots dropped down on the left side of the screen, 2) these dots were covered up by a grey box, 3) another set of blue dots dropped into the box, 4) on the right top side of the screen, a set of red dots popped out and then dropped down. At the end the child must indicate whether there were more blue or more red dots. Following six practice trials, 24 testing trials were presented in random order using the software program E-prime 2.0. The duration of each of these animated steps was 1300 ms and between each step there was an interval of 1200 ms. Children could respond from the moment the red dots popped up on the right upper side of the screen. Then, they had a maximum of 7000 ms to respond. Numerosities in this task ranged from 6 to 70. The sum of the blue arrays differed from the comparison red set by three ratios 4:7, 4:6, 4:5 (see Table 2).



**Figure 2** The Approximate Addition task task: illustration of a trial (Xenidou-Dervou et al., 2013, 2014)

In half of the trials the sum of the blue sets was larger than the red comparison set. In the other half, the comparison target was larger. The task was designed in order to control for dot size, total surface area, total contour length and density (Barth et al., 2006; C. K. Gilmore et al., 2010).

Children were asked to respond as correctly and as fast as possible. They responded by pressing the corresponding response button in front of them (blue or red). Instructions were given verbally during practice. No feedback was provided during the testing trials except for verbal encouragement to sustain engagement with the task. Before initiating the task, the experimenter would ask the child to point out on the screen the set of blue and the set of red dots in order to identify possible difficulties related to color blindness.

**Table 2.** Ratios and Testing trials of the non-symbolic approximate addition tasks (from Xenidou-Dervou et al. 2013)

Set	Testing trails		
	Ratio 4:7	Ratio 4:6	Ratio 4:5
1	12 vs. 21	16 vs. 24	16 vs. 20
2	20 vs. 35	24 vs. 36	24 vs. 30
3	28 vs.49	32 vs. 48	32 vs. 40
4	36 vs. 63	40 vs. 60	40 vs. 50
5	28 vs. 16	18 vs. 12	20 vs. 16
6	42 vs.24	42 vs. 28	65 vs. 52
7	56 vs. 32	60 vs. 40	40 vs. 32
8	70 vs. 40	36 vs. 24	50 vs. 40

### **Mathematical abilities.**

For the assessment of mathematical abilities we used different tasks in order to measure overall early numeracy abilities as well as specific skills like counting, Number recognition, and understanding of cardinality principle.

**Early Number Concepts.** The Early Number Concepts sub-test from the British Ability Scales (BAS3; Eliot & Smith, 2011) was carried out to assess early numeracy abilities. This sub-test consist of 30 items and evaluates different aspects of young children’s numerical competence, such as counting abilities, number concepts, quantitative understanding and simple arithmetic. The items are scored, with 0 for a wrong answer and 1 for a right answer.

**Counting.** To measure children's counting abilities, children were asked to recite the number word list up to "sixty". The highest number counted correctly was recorded as a measure of the counting range.

**Cardinality principle.** (Van Herwegen et al., under review) To measure children's cardinality understanding, children were shown flash cards that depicted 1-16 coloured objects and asked to count the objects shown. Once they had counted the objects children were asked how many objects there were. If children started to recount the objects the trial was recorded as incorrect. The items are scored, with 0 for a wrong answer and 1 for a right answer.

**Number recognition.** For number recognition, children were shown digits 1 to 16 on black and white flash cards. The items are scored, with 0 for a wrong answer and 1 for digits named correctly.

#### **Working memory measures.**

**Visuo-spatial working memory.** The visuo-spatial working memory task (Lanfranchi, Cornoldi, & Vianello, 2004) required a visuo-spatial dual task. The child had to remember the frog's starting position on a path on a  $4 \times 4$  chessboard, in which one of the 16 cells was red. The child also had to tap on the table when the frog jumped onto the red square. The task had four different levels of difficulty, depending on the number of steps in the path (i.e., two, three, four, and five steps, respectively). The score of 1 was given for every trial performed correctly, with the child both remembering the first position of the pathway and performing the tapping task. Otherwise, a score of 0 was given. In each task, the minimum score was 0 and the maximum score was 8.

**Verbal working memory.** During the verbal dual task (Lanfranchi et al., 2004) the child was presented with a list of two to five two-syllable words and was asked to remember the first word on the list and tap on the table when the word "palla" (ball) was presented. A score of 1 was given when the initial word of the series was remembered correctly at the same time the dual task was performed.

**Visuo-spatial short-term memory.** During pathway recall (Lanfranchi et al., 2004), the child was shown a path taken by a small frog on a  $3 \times 3$  or  $4 \times 4$  chessboard. Then, the child had to recall the pathway immediately after presentation by moving the frog from square to square, reproducing the experimenter's moves. The task had four levels of difficulty, depending on the number of steps in the frog's path and dimensions of the chessboard ( $3 \times 3$  in the first level with two steps and  $4 \times 4$  in the other levels, with two, three, and four steps, respectively). A score of 1 was given for every trial performed correctly. The minimum score was 0 and the maximum was 8.

**Verbal short-term memory.** The word recall forward task (Lanfranchi et al., 2004) was used to tap children's verbal STM capacity. In this task the child was presented with lists of two to five words and was required to repeat the list immediately and in the same order as presented. The span was considered to be correct if the child recalled all of the items in the correct order. A score of 1 was given for every list recalled correctly. The minimum score was 0 and the maximum was 8.

### **Intelligence.**

Intellectual capacities were evaluated using two subtest of the Wechsler Preschool and Primary Scale of Intelligence (WPPSI-3; Wechsler, 2002).

**Verbal IQ.** The Receptive Vocabulary subtest of the WPPSI-3 is a measure of verbal knowledge and was considered as an indicator of verbal intelligence. In general, vocabulary subtests are considered relatively good estimates of general intelligence (Sattler, 2001).

**Non-verbal IQ.** The Block Design subtest is a measures of perceptual organization and spatial reasoning abilities and was considered as an indicator of non-verbal intelligence (Sattler, 1992).

### **PLUS Training Programme**

Children in the training group followed the *Preschool number learning scheme* (PLUS; developed by Jo Van Herwegen) for ten minutes each day for a time period of 5 weeks in small groups of two children and a researcher. The PLUS games include two types of games, each type tapping into either comparing of quantities of various ratios (matching games) or estimating (guessing games). The PLUS programme include activities that are familiar to preschoolers and the stimuli of the games related to a variety of senses, including touch, sounds, and visual stimuli. Each session, the child played one guessing and one matching game. To prevent counting, we required children to respond within a short delay (i.e., by asking the children to compete with each other and completing the game as quickly as they could) or by showing the stimuli only for a very short time. All of the games started with large ratios (i.e., 1/2), with a clear differences between the number of items presented in the different sets. The ratios became smaller as the weeks of training progressed. A description of each game can be found in the Appendix 1. For all games, corrective feedback was provided by the researcher, i.e. “that is right, there are a lot of dots here and a lot of dots there so those two go together”. In addition, The order of presentation of the games was the same in each group.

Children in the control group participated in interactive picture book reading in small groups of two children with a researcher for 10 minutes per day for five weeks. The active control group was included to control unspecific effects of the PLUS training (e.g. Hawthorne effect).



## Results

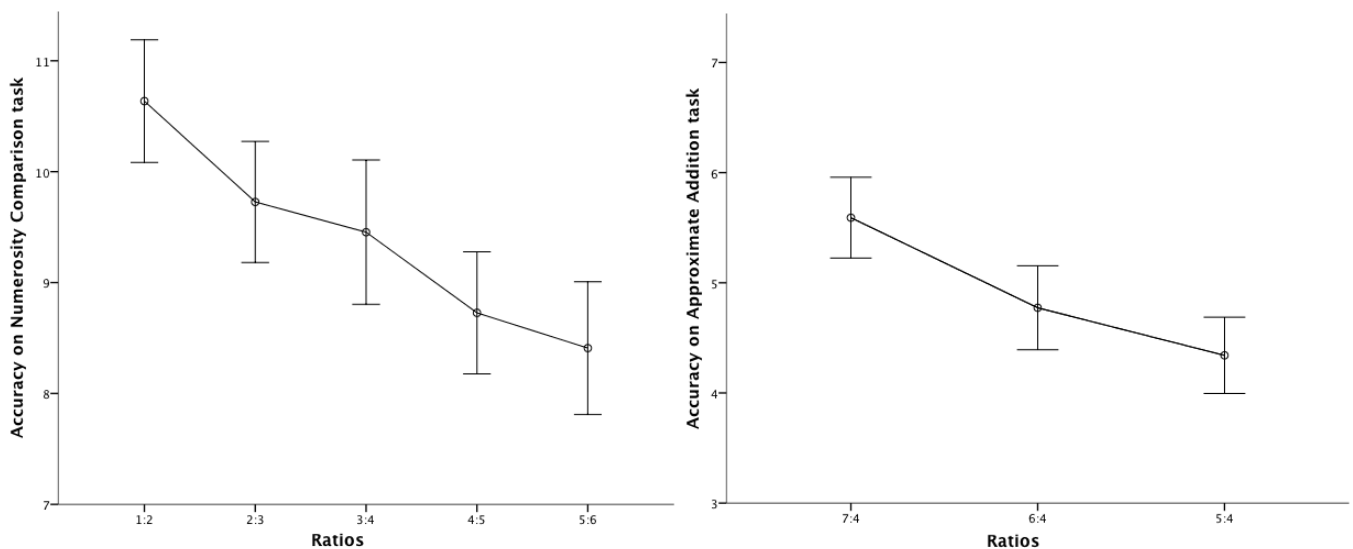
### Preliminary Analyses

In line with previous research on ANS (Lyons, Price, Vaessen, Blomert, & Ansari, 2014; Van Herwegen et al., under review) and to make sure that all children understood the instructions of the task, we excluded all children ( $N=5$ ) scoring at chance level on the Numerosity Comparison pre-training (i.e. they had scores lower than 30 out of 60 on the ANS task).

To verify that the ANS tasks did, in fact, engage children's ANS abilities, we examined whether or not children showed evidence of the standard ratio effect<sup>1</sup> in both tasks. We tested the effect of ratio difficulty on performance using a repeated measures ANOVA with mean accuracy in each ratio as dependent variable (Figure 3).

In the Numerosity Comparison task there was a significant main effect of ratio  $F(4,40) = 17.40, p < .001, \eta_p^2 = .29$ . As predicted by Weber's Law, children's average accuracy decreased with ratio difficulty  $F_{linear}(1, 43) = 64.78, p < .001, \eta_p^2 = .60$ .

Also in the Approximate Addition task we found a significant main effect of ratio,  $F(2,42) = 15.91, p < .001, \eta_p^2 = .27$  and children's average accuracy decreased with ratio difficulty  $F_{linear}(1, 43) = 29.49, p < .001, \eta_p^2 = .41$ .



**Figure 3.** Group means for preschoolers' performance in ANS tasks as a function of the size of the numerical ratio between item arrays. Group mean values correspond to number of correct trials for different levels of ratio size. Error bars are 95% confidence intervals.

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<sup>1</sup> Young children's performance on ANS tasks accords to Weber's law (Barth et al., 2003; Halberda & Feigenson, 2008; Lipton & Spelke, 2003). Therefore, the ability to discriminate large sets of objects is a function of the ratio between them and the large numerical distance makes their comparison much easier.

### Primary Analyses

Mean and standard deviation of pre-test and post-test scores of the three groups are presented in Table 4. A series of MANOVAs established that there were no significant differences between the training and the control groups at pre-test for Chronological age  $F(1,42) = 2.30, p = .14, \eta_p^2 = .05$ ; Verbal IQ  $F(1,42) = .19, p = .66, \eta_p^2 = .005$ ; Non-verbal IQ  $F(1,42) = .54, p = .47, \eta_p^2 = .01$ ; Numerosity Comparison  $F(1,42) = .08, p = .77, \eta_p^2 = .002$ . In addition, there was no significant difference for the amount of intervention sessions received between the two groups  $F(1,42) = .22, p = .63, \eta_p^2 = .005$  (see table 3). Therefore, these factors were not further included as covariates in the analyses.

**Table 3.** Overview of chronological age (CA), Verbal and non-verbal IQ and number of training sessions per group

	Training group		Control group	
	N=23		N=21	
	Mean	SD	Mean	SD
CA in months	52.04	4.40	54.10	4.56
Verbal IQ	10.65	2.83	10.29	2.70
Non-verbal IQ	11.35	3.23	12.10	3.53
Training sessions	19.30	2.96	18.95	1.69

To examine performance gains between the pre-test and post-test sessions for all of the tasks, we conducted analyses of covariance (ANCOVA) with the Group (PLUS training and control) used as the factor, Pre-test Scores used as the covariate, and Gain Scores (post-test score minus pre-test score) examined as the dependent variable. For the comparisons of the gain difference between groups,  $\eta_p^2$  was used as a measure of effect size. The criteria of Cohen (1988) were used to classify the effect sizes: small effect:  $\eta_p^2 = .01$ ; medium effect:  $\eta_p^2 = .06$ ; and large effect:  $\eta_p^2 = .14$ .

**Table 4.** Impact of training on cognitive measures.

	Training group						Control group					
	Pre- training		Post-training		Follow-p		Pre-training		Post-training		Follow-up	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
<b>ANS</b>												
Numerosity Comparison	46.65	7.18	50.17	5.52	---	---	47.29	7.48	47.57	8.19	---	---
Approximate Addition	15.04	2.67	13.35	1.50	---	---	14.33	2.33	13.67	2.24	---	---
<b>Mathematical measures</b>												
Cardinality	8.39	3.90	8.78	4.25	9.96	3.66	9.67	3.72	10.90	3.66	10.58	3.73
Early Number Concepts	16.61	4.90	17.35	5.18	18.91	4.59	15.43	5.71	17.24	5.33	18.00	5.57
Number recognition	7.87	5.38	7.83	5.1	8.26	4.96	9.57	5.27	10.10	5.73	10.89	5.57
Counting	16.38	14.60	20.48	14.69	22.04	14.44	18.14	11.89	19.52	11.06	23.37	14.15
<b>Memory measures</b>												
Visuo-spatial WM	2.22	2.07	3.70	2.34	---	---	3.10	2.09	3.24	2.30	---	---
Visuo-spatial STM	5.30	.76	5.52	1.20	---	---	5.05	1.60	5.48	1.08	---	---
Verbal WM	2.35	1.97	3.22	1.83	---	---	1.67	1.68	2.62	1.32	---	---
Verbal STM	3.96	.77	4.43	.90	---	---	4.10	1.04	4.48	.87	---	---

The ANCOVA on Numerosity Comparison gain scores revealed a significant difference between groups after controlling for the effect of pre-test scores,  $F(1,41) = 5.04, p = .03, \eta_p^2 = .11$ , with training gains significantly greater for the training than the control group. Moreover, we found a significant negative correlation in the training group between Numerosity Comparison scores in the pre-test and Numerosity Comparison gains ( $r(23) = -.64, p = .001$ ). Thus, children in the training group displayed larger improvement in numerosity comparison compared to the control group and within the training group, children with lower Numerosity Comparison abilities in the pre-test displayed greater Numerosity Comparison gains following the training.

The interaction term was not significant for the Approximate Addition,  $F(1,41) = 1.05, p = .31, \eta_p^2 = .02$ , and for any Mathematical measure considered in this study (BAS,  $F(1,41) = .59, p = .45, \eta_p^2 = .01$ , Counting  $F(1,41) = 1.16, p = .29, \eta_p^2 = .03$ , Number recognition  $F(1,41) = 1.07, p = .31, \eta_p^2 = .02$ , Cardinality  $F(1,41) = 1.80, p = .19, \eta_p^2 = .04$ ). The group differences remained non significant at follow-up. Moreover, The ANCOVA on the WM and STM results revealed no interactions for Visuo-spatial WM  $F(1,41) = 1.41, p = .24, \eta_p^2 = .03$ , visuo-spatial STM,  $F(1,41) = .008, p = .93, \eta_p^2 = <.001$ , Verbal STM  $F(1,41) = .002, p = .96, \eta_p^2 = <.001$ , and Verbal WM  $F(1,41) = .86, p = .36, \eta_p^2 = .02$

## Discussion

The present study examined the possibility to improve ANS abilities in Italian preschool children by using intensive adaptive training over a relatively short period. Moreover, the transfer effects of the training on mathematical abilities and working memory skills were also investigated. The findings showed that the group of children who had received the ANS training exhibited a significant enhancement of ANS abilities assessed with the Numerosity Comparison task, compared to the control group. This result, in line with our previous findings (Van Herwegen et al., under review.), provides further evidence that the ability to make quantitative judgments based on the ANS can be ameliorated by intensive adaptive training over a relatively short period and confirms previous results about the malleability of ANS skills in both adults and children (Dewind & Brannon, 2012; Obersteiner et al., 2013; Park & Brannon, 2013). Moreover, the PLUS training programme seemed to be particularly effective for the children with lower ANS abilities in the pre-test. Previous studies suggest that acuity of the ANS contributes to the risk of mathematical learning disability (Mazzocco et al., 2011a), and that the correlation between ANS precision and mathematical competence is stronger for children with lower maths' scores than for children with higher maths' scores (Bonny & Lourenco, 2013). Therefore, it should be important in future studies to investigate the possibility to implement the PLUS program with children at risk to develop a

mathematical learning disability. Indeed, the improvement of ANS skills could facilitate the number sense access, or the link between symbolic and non-symbolic representations of number, and possibly reduce their deficit.

Despite improved ANS after the training sessions, no transfer effect of the training on mathematical measures either immediately after training or five weeks later at the follow-up session was found. We also didn't find a transfer effect on the Approximate Addition task based on more complex ANS skills. In previous studies, the improvement or simply the activation of the ANS led to improved symbolic arithmetic skills in primary school children (Hyde et al., 2014) and in adults (Park & Brannon, 2013). It seems that the present results do not support the causal link between ANS and symbolic arithmetic performance previously suggested (Hyde et al., 2014; Mazzocco et al., 2011b; Park & Brannon, 2013). In contrast, in our previous study (Van Herwegen et al., under review) we found increased ANS abilities as well as increased counting skills in preschool children. The different school context may have played a role in these contrasting results. The UK preschool system is mainly based on free play and doesn't usually involve school-based structured activities. Differently, preschool education in Italy includes free play as well as more structured activities for the development of precursors of literacy and numeracy. In the UK context, where children did not receive mathematical education ANS improvement led to better counting skills in the training group. However, in the Italian context, where all children (even those in the control group) benefitted from early mathematical instruction, the PLUS training may not have been sufficient to create a difference between the training group and the control group in mathematical abilities.

Even though no direct transfer effect of the ANS training on symbolic mathematical abilities was found, we can not exclude the possibility that the increased ANS acuity promotes the development of number sense access (or links between symbolic and non-symbolic representations of number) leading to better mathematical outcomes later in life, maybe at the start of formal education in primary school. Indeed, performing training activities such as those presented in the this study could promote the mapping between the symbolic number system and non-symbolic numerical magnitudes, promoting the acquisition of symbolic arithmetic skills. Future studies should further investigate the long term effects of ANS training on the acquisition of complex mathematical skills. Moreover, it would be important to examine whether, increasing the training time (duration in weeks as well as minutes per session), might lead to more positive improvements.

In line with our previous study (Van Herwegen et al., under review) no transfer effects of the training on WM or STM skills were found. Even though it has been demonstrated that WM and STM abilities play a role in tasks involving the Approximate Number System (Mussolin et al.,

2012; Soltész et al., 2010; Xenidou-Dervou et al., 2013, 2014), exercising ANS acuity for a short period of time does not seem sufficient to affect memory skills.

The results described above constitute an important initial step toward understanding the malleability of ANS acuity and the design of effective ANS training programs for children. The ANS resulted to be malleable and trainable in preschool years. No effect of the PLUS training used in this study on mathematical and WM abilities were found either immediately after the training or at the follow-up. These findings stress the specificity of the effect of the ANS training used on numerosity comparison skills. More research is needed to confirm the possibility that mathematical abilities can be enhanced using ANS training procedures, and thereby to investigate the causal mechanism of this pattern of results.

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## **Appendix 1** (from Van Herwegen et al., under review)

### **Guessing games:**

1. **Guessing game:** In this game children were asked questions about how many items they thought were presented. For example, how many sweets are in this box, how many keys on the keypad, how many leaves on this tree, how many people are in this room etc. Regardless of the answer children received a sticker for their guess and then correct feedback was given, i.e. “I think there are ...”. This game promotes guessing and allows children to learn new number words that are introduced by the researcher via the feedback that is provided. Again children were asked to answer as fast as they could.
2. **In a line:** children were presented with a card on the table with 1 to 16 coloured objects of different sizes on them in a random order. Next, they were shown a new card and asked whether the new card had more or less objects on it. Children were asked to respond as fast as they could and the card was only presented for a very short time to prevent counting strategies.
3. **Grab and guess:** in this game children were asked to grab some uncooked pasta from a box. The box contained different sizes and shapes of pasta. After each child had grabbed some pasta and put it in front of them, they were asked who had more or who had less pasta. Again, children were asked to respond as fast as possible.
4. **In the sock:** In this game the researcher hid two quantities of different sized beads in two different socks. Each child was then asked to feel both of the socks with each hand and to guess which sock contained either more or fewer beads. The socks were only presented for a short time to prevent counting.

### **Matching games:**

5. **Play that number:** in this game the child and experimenter sat back to back from each other. The experimenter played a number of sounds on an instrument and then the child was asked to play the same amount of sounds on a different instrument.
6. **Dominoes:** in this game children used special cards that displayed a scattered number of dots on the left and right side of the card. Children were asked to identify which side of the card contained more dots and to match the correct side (large or small number) of their card with the card presented by the researcher on the table.

7. Matching game: using cards with 1 to 16 coloured objects of different sizes on them, children were asked to sort the card in their hand to cards presented on the table, putting large number s of objects with large number and small number of objects with small. Again the researcher manipulated the ratios of the amount of objects presented starting with easy ratios and then increasing to harder ratios as the weeks progressed. Again children were asked to perform this task as quickly as possible.
8. Action game: in this game the experimenter performed a number of actions (e.g., clapped her hands a lot or only a few times) and the child was asked to repeat this action. Actions were carried out very quickly to prevent counting.

# Chapter 4

## Working Memory and Early Numeracy Training in Preschool Children

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## **Abstract**

Many factors influence children's performance in mathematical achievement, including both domain-specific and domain-general factors. This study aimed to verify and compare the effects of two types of training on early numerical skills. One type of training focused on the enhancement of working memory, a domain-general precursor, while the other focused on the enhancement of early numeracy, a domain-specific precursor. The participants were 48 five-year-old preschool children. Both the working memory and early numeracy training programs were implemented for 5 weeks. The results showed that the early numeracy intervention specifically improved early numeracy abilities in preschool children, whereas working memory intervention improved not only working memory abilities but also early numeracy abilities. These findings stress the importance of performing activities designed to train working memory abilities, in addition to activities aimed to enhance more specific skills, in the early prevention of learning difficulties during preschool years.

Several recent studies investigated precursors of mathematical learning in preschool children. Competencies that specifically predict mathematical abilities may be considered domain-specific precursors, such as early numeracy, whereas general cognitive abilities, such as working memory, that may predict performance not only in mathematics but also in other school subjects may be considered domain-general precursors (Gathercole, Brown, & Pickering, 2003; Gathercole, Pickering, Knight, & Stegmann, 2004; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Passolunghi & Lanfranchi, 2012; Träff, 2013). The key role of both domain-specific and domain-general precursors in the development of mathematical abilities has led researchers to design studies to investigate the possibility of developing training programs to improve these abilities in children. These training programs may be crucial in the prevention of mathematical learning difficulties during preschool years.

The number of students with mathematical difficulties has greatly increased over the last 20 years (Swanson, 2000). It seems that the estimated prevalence of children that experience a substantive learning deficit in at least one area of mathematics is between 5% and 10% (Barbarese, Katusic, Colligan, Weaver, & Jacobsen, 2005; Shalev, Manor, & Gross-Tsur, 2005; Shalev, 2007). These students that find mathematics difficult choose not study maths in secondary or further education (Brown, Askew, Millett, & Rhodes, 2003). This choice must be considered a risk factor as several studies found that mathematical abilities predict financial and educational success, particularly for women (Geary, Hoard, Nugent, & Bailey, 2013; Parsons & Bynner, 2005). Given these finding it should be considered the importance to intervene as soon as possible in order to improve basic academic skills and reduce future learning difficulty.

Although some efforts have been made to improve precursors of mathematical learning, is still unclear what the influence and the different effects of training focused on the enhancement of either domain-general or domain-specific precursors would be. In this study, our aim was to verify and to compare the effects on early numerical competence of two types of training in a sample of 5-year-old preschool children. One type of training focused on the enhancement of domain-general precursors, working memory abilities, and the other focused on the enhancement of domain-specific precursors, early numeracy abilities.

### **Domain-General Precursors: The Role of Working Memory**

Working memory (WM) refers to a mental workspace, which enables a person to hold information in mind while simultaneously performing other complex cognitive tasks (e.g., mathematical processing) (Holmes & Adams, 2006).

Various models of the structure and function of working memory exist, but the present study considered the multi-component model of working memory initially proposed by Baddeley and

Hitch (1974; see also Baddeley, 1986, 2000). This model consists of three main parts. The two passive modality-specific systems (i.e., the phonological loop and visual-spatial sketchpad) are specialized for processing language-based and visuo-spatial information, respectively. The central executive, which is not modality-specific, coordinates the two slave systems and is responsible for a range of functions, such as the attentional control of actions (e.g., inhibiting irrelevant information, shifting attention, updating information). The distinction between the central executive system and specific memory storage systems (i.e., the phonological loop and visuo-spatial sketchpad) in some ways parallel the distinction between working memory and Short-Term Memory (STM). The WM is considered an active system that involves both storage and processing of information, while STM typically involves situations in which the individual passively holds small amounts of information, as required in span forward tasks (Cornoldi & Vecchi, 2003; Swanson & Beebe-Frankenberger, 2004).

Several studies demonstrated that WM is a key domain-general predictor of mathematical competence. WM abilities seem to be related both to early numeracy skills and to later mathematical skills (Alloway & Alloway, 2010; Alloway & Passolunghi, 2011; De Smedt et al., 2009; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013; Gathercole & Pickering, 2000; Gersten, Jordan, & Flojo, 2005; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Passolunghi & Lanfranchi, 2012). Indeed, even the simplest mathematics calculations require WM processes: temporary storage of problem information, retrieval of relevant procedures, and processing operations to convert the information into numerical output (Brainerd, 1983). These same processes are needed even for simple number comparison tasks: the child need to map the different number symbols onto the corresponding quantities, store them into memory and then integrate this with the incoming information to performing the task (Kroesbergen, van't Noordende, & Kolkman, 2014).

Further evidence in favor of the importance of working memory in children's mathematical skills has been provided by longitudinal studies that demonstrated that working memory performance in preschoolers predicts mathematical achievement several years after preschool (Bull, Espy, & Wibe, 2008; Gathercole et al., 2003; Mazzocco & Thompson, 2005; Passolunghi & Lanfranchi, 2012). Specifically, several studies showed a direct influence of working memory on mathematical achievement in first and second graders (De Smedt et al., 2009; Passolunghi, Mammarella, & Altoè, 2008; Passolunghi, Vercelloni, & Schadee, 2007). Moreover, several studies in the field of mathematical learning disability demonstrated that poor WM ability in children is related to poor math performance (Alloway, 2009; Gathercole & Pickering, 2000; Kroesbergen,



Van Luit, & Naglieri, 2003; Passolunghi & Siegel, 2004; Raghobar, Barnes, & Hecht, 2010; van der Sluis, van der Leij, & de Jong, 2005).

### **Domain-Specific Precursors: Early Numeracy Abilities**

Another important aspect of the acquisition of mathematical competence is represented by domain-specific components: foundational specific skills that necessarily underlie the development of arithmetic skills. Such core skills that predict children's performance in mathematics have been referred to under the general term "early numeracy abilities" and include skills such as counting ability, one-to-one correspondence, making quantity comparison, and forming representation of numerical magnitudes in the form of a mental number line (Gersten et al., 2005; Griffin, 2004; Jordan et al., 2006; Van De Rijt & Van Luit, 1999). Among these abilities counting ability, in particular verbal counting, seems to be one of the most discriminating and efficient precursor of early mathematics learning (Mazzocco & Thompson, 2005; Passolunghi et al., 2007). Counting ability implies being able to understand the one-to-one relation between objects in a set and their numerical representations and some studies show individual differences in the level of counting ability in subjects with different scores in arithmetic tasks (see Geary, Hoard, & Hamson, 1999). In addition, research demonstrated that accurate mental number line representations and quantity discrimination are strong predictors of arithmetic and mathematics skills when children enter school (Booth & Siegler, 2006; Gersten et al., 2005; Jordan et al., 2006; Siegler & Booth, 2004).

Therefore, early numeracy abilities are considered strong predictors of mathematics skills when children enter school (Booth & Siegler, 2006; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013; Siegler & Booth, 2004). In particular, these abilities assessed in preschool years have been shown to predict mathematical performance in the first grade (Aunio & Niemivirta, 2010; Jordan, Kaplan, Locuniak, & Ramineni, 2007; Passolunghi & Lanfranchi, 2012) and second grade (Locuniak & Jordan, 2008). On the other hand, weak early numeracy abilities and less accuracy in spatially map numbers have been shown to contribute to lower calculation skills and mathematical learning disabilities (Geary, Hoard, Nugent, & Byrd-Craven, 2008; Gersten et al., 2005; Landerl, Fussenegger, Moll, & Willburger, 2009; Mazzocco & Thompson, 2005; Rousselle & Noël, 2007).

### **Early Numeracy Training**

Improving early numeracy abilities in preschool children has been demonstrated using both formal and informal instruction, even before the children's entrance into primary school (Ramani, Siegler, & Hitti, 2012; Ramani & Siegler, 2008; Siegler & Ramani, 2008; Whyte & Bull, 2008). Low numeracy can be caused by a lack of experience with numbers and number-related activities, and different types of interventions could be used to build early numeracy abilities. It has been

shown that using numerical board games and activities at the preschool level improves children's numerical estimation skills and number comprehension (Ramani & Siegler, 2008; Siegler & Ramani, 2008; Whyte & Bull, 2008). Indeed, these numerical games provide multiple cues to both the order of numbers and numerical magnitudes (Siegler & Booth, 2004). Number-line estimation, counting, numerical magnitude comparison, and numerical identification all improved through the use of linear numerical board games (Ramani & Siegler, 2008), whereas only number comprehension and counting skills improved using non-linear numerical games (Whyte & Bull, 2008). Moreover, various programs seek to specifically target emergent mathematics skills through activities that are designed to promote skills that the literature suggests are important, including counting, recognizing and writing numbers, one-to-one correspondence, comparisons, change operations, and understanding numbers and quantities (Arnold, Fisher, Doctoroff, & Dobbs, 2002; Greenes, Ginsburg, & Balfanz, 2004; Starkey, Klein, & Wakeley, 2004; Young-Loveridge, 2004). In conclusion, intervening in preschool children years to enhance early numeracy skills is possible and could be an important strategy to prevent subsequent underachievement in mathematics learning.

### **Working Memory Training**

Other studies investigated whether mathematical learning problems can be overcome by training designed to enhance working memory abilities. The debate regarding the effects of WM training is still open: some studies show a positive effects of WM training on arithmetic abilities in primary school children using computerized or school-based training procedures (Alloway, Bibile, & Lau, 2013; Holmes, Gathercole, & Dunning, 2009; Holmes & Gathercole, 2013; St Clair - Thompson, Stevens, Hunt, & Bolder, 2010; Witt, 2011). Other authors questioned the effectiveness of WM training concluding that there is no convincing evidence of the generalization of working memory training to other skills (Melby-Lervåg & Hulme, 2013). However, it should be considered the possibility that cognitive training applied to younger individuals tends to lead to significantly more widespread transfer of training effects (Wass, Scerif, & Johnson, 2012).

Holmes et al. (2009) provided the first evidence of the efficacy of the computerized "Cogmed" training in overcoming common impairments in working memory and associated learning difficulties in 10-year-old children. They proposed different training tasks that involve the temporary storage and manipulation of either sequential visuo-spatial information, verbal information, or both for a period of 5 to 7 weeks. The majority of the children who completed the program improved their working memory substantially, and a significant increase in mathematics performance was also found 6 months after training. St. Clair-Thompson et al. (2010) also showed that a computerized working memory training strategy resulted in significant improvements in tasks

that assess the phonological loop, the central executive, mental arithmetic, and following instructions in the classroom. Enhancing mathematical abilities in 9- to 10-year-old children is also possible using individual school-based working memory training (Witt, 2011). This study suggested that children who underwent working memory training made significantly greater gains in the trained working memory tasks, as well as on an untrained visuo-spatial working task, than a matched control group. Moreover, the training group also made significant improvements in mathematics performance.

Only a few studies have explored the possibility of enhancing working memory abilities in kindergartners using specific working memory training (Dowsett & Livesey, 2000; Röthlisberger, Neuenschwander, Cimeli, Michel, & Roebbers, 2012; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009). A study by Kroesbergen et al. (2014) systematically investigated the transfer effect of WM training on early numeracy. This study demonstrated that low performing children who participated in working memory intervention significantly improved their working memory skills. Furthermore, their early numeracy skills also improved.

### **The Present Study**

The findings described above show promising effects of both working memory training and early numeracy training on children's mathematical performance, but also a lack of any comparisons of the effects of the two types of training on early numerical abilities in mainstream preschool settings. In the present study, our aim was to investigate the effects on early numeracy of two specific training programs that focus on either working memory or early numeracy in a sample of mainstream preschool children. For this purpose, we compared performance of a domain-specific early numeracy training group, a domain-general WM training group and an untrained control group.

Previous longitudinal correlational studies showed that working memory is a precursor of early numeracy abilities and mathematics achievement (Alloway & Alloway, 2010; De Smedt et al., 2009; Passolunghi & Lanfranchi, 2012; Passolunghi et al., 2007). Accordingly, we expected that our training focused on the improvement of working memory abilities should improve not only working memory but will also produce a transfer effect on early numeracy. This hypothesis is in line with previous studies dealing with WM training and transfer effects on math abilities in primary school children and kindergarten (Holmes et al., 2009; Kroesbergen et al., 2014; St Clair - Thompson et al., 2010; Witt, 2011).

Regarding early numeracy abilities, it has been proved that this domain-specific precursor predicts later mathematical achievement (De Smedt et al., 2009; Gersten et al., 2005; Jordan et al., 2006; Passolunghi & Lanfranchi, 2012; Passolunghi et al., 2007). Moreover, several studies proved

that preschool training and intervention on early numeracy lead to enhancement of emergent mathematic skills (Arnold et al., 2002; Greenes et al., 2004; Ramani & Siegler, 2008; Siegler & Ramani, 2008; Starkey et al., 2004; Whyte & Bull, 2008; Young-Loveridge, 2004). However, there are no evidences proving that early numeracy abilities can predict the performance in a more general domain as working memory, and one study demonstrated no transfer effects of early math training on working memory abilities of low performing children (Kroesbergen, Van't Noordende, & Kolkman, 2012). Therefore, we expect that our early numeracy training will have a more specific and limited effect on early numeracy abilities compared to the WM training.

## **Method**

### **Participants**

The participants were 5-year-old preschool children attending their final year of preschool. After consent was provided by the schools, letters were given to parents/guardians of each child for individual consent. Children with significant developmental delays (as identified by local educational services) were excluded. Of the children from whom consent was received, 48 were randomly selected. The socioeconomic status of the sample was primarily middle class, established on the basis of school records. The children were recruited through six preschools located in an urban area of northern Italy and were randomly allocated to one of three groups: 15 children ( $M_{\text{age-in-months}} = 65.8$ ,  $SD = 2.1$ , seven girls) underwent working memory training; 15 children ( $M_{\text{age-in-months}} = 64.67$ ,  $SD = 2.9$  six girls), underwent early numeracy training; and a control group of 18 children ( $M_{\text{age-in-months}} = 64.4$ ,  $SD = 3.2$ , nine girls) performed their usual school activities in the classroom.

### **Procedure**

The experimenters were three female Italian master students trained by the authors. Two experimenters carried out pre- and post-assessments, while the third experimenter carried out both of the training programs. The experimenters who conducted the assessments were blind to the group the children belonged to. The authors monitored the training implementation once a week and The interrater agreement on the reliability of treatment implementation was 92 %.

The working memory training included different paper-and-pencil tasks that were designed to enhance all three components of Baddeley's working memory model (Baddeley, 1986). The early numeracy training included different paper-and-pencil tasks that were designed to enhance early numerical abilities such as counting, number-line representation, one-to-one correspondence between quantities and numerals and quantity comparison. Over five successive weeks the children

under experimental conditions participated in ten training session (twice weekly) implemented in small groups of five children. Training duration was 1 hour per session.

Before and after training, children's working memory ability and early numeracy ability were assessed. Both at the pre-test and at the post-test stage, the children were individually tested in two sessions. In the first session, the memory (WM and STM) skills of the children were measured and in the second session, early numeracy skills were measured. The assessments took place in a quiet room inside the schools and each session lasted about 20 minutes.

### **Pre- and Post-Training Assessments**

#### **Visuo-spatial short-term memory.**

During pathway recall (Lanfranchi, Cornoldi, & Vianello, 2004), the child was shown a path taken by a small frog on a  $3 \times 3$  or  $4 \times 4$  chessboard. Then, the child had to recall the pathway immediately after presentation by moving the frog from square to square, reproducing the experimenter's moves. The task had four levels of difficulty, depending on the number of steps in the frog's path and dimensions of the chessboard ( $3 \times 3$  in the first level with two steps and  $4 \times 4$  in the other levels, with two, three, and four steps, respectively). A self-terminating procedure was employed: participants performed the tasks until they were able to solve at least one item out of two at a specific level. A score of 1 was given for every trial performed correctly. The minimum score was 0 and the maximum was 8. Cronbach's alpha<sup>2</sup> for pathway recall is .70.

#### **Visuo-spatial working memory.**

The visuo-spatial working memory task required a visuo-spatial dual task (Lanfranchi et al., 2004). The child had to remember the frog's starting position on a path on a  $4 \times 4$  chessboard, in which one of the 16 cells was colored red. The child also had to tap on the table when the frog jumped onto the red square. The task had four different levels of difficulty, depending on the number of steps in the path (i.e., two, three, four, and five steps, respectively). A self-terminating procedure was employed: participants performed the tasks until they were able to solve at least one item out of two at a specific level. The score of 1 was given for every trial performed correctly, with the child both remembering the first position of the pathway and performing the tapping task. Otherwise, a score of 0 was given. In each task, the minimum score was 0 and the maximum score was 8. Cronbach's alpha for for visuo-spatial dual task is .81.

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<sup>2</sup> Cronbach's alpha for all tasks was reported according to the manual of the test or from published papers describing the task.

### **Verbal short-term memory.**

The word recall forward task (Passolunghi & Siegel, 2001) was used to tap children's verbal STM capacity. In this task the child was presented with lists of two to six words and was required to repeat the list immediately and in the same order as presented. A self-terminating procedure was employed: participants performed the tasks until they were able to solve at least one item out of two at a specific level. The span was considered to be correct if the child recalled all of the items in the correct order. Cronbach's alpha for word recall is .88.

### **Verbal working memory.**

During the verbal dual task (Lanfranchi et al., 2004) the child was presented with a list of two to five two-syllable words and was asked to remember the first word on the list and tap on the table when the word "palla" (ball) was presented. A self-terminating procedure was employed: participants performed the tasks until they were able to solve at least one item out of two at a specific level. A score of 1 was given when the initial word of the series was remembered correctly at the same time the dual task was performed. Cronbach's alpha for the verbal dual task is .84.

### **Early numeracy abilities.**

We assessed numerical competence using the Early Numeracy Test (ENT; Van Luit, Van de Rijt, & Pennings, 1994). The ENT consists of 40 items and has two analogous versions, version A and version B. In this study, only version A was used. The test evaluates different aspects of young children's numerical competence, such as concepts of comparison, classification, correspondence, seriation, use of number words, structured counting, resultative counting, and general knowledge of numbers. The items are scored, with zero for a wrong answer and one for a right answer. The maximum number of points is 40. The ENT was developed as a one-dimensional test (Van De Rijt, van Luit, & Pennings, 1999). Cronbach's alpha for ENT is .84.

## **Training Programs**

### **Working memory training.**

The WM training was conducted in groups of five children for 1 hour, two times a week. The full training program consisted of eight different games grouped into four different categories (see Table 1): verbal WM games, verbal STM games, visuo-spatial WM games and visuo-spatial STM games. In each session, two games were played. The games for each session were selected in such a way that within one week all children were exposed to one game from each of the categories. The order of presentation of the games was the same in each group. The children participated in the activity one after the other. The training was adaptive with the instructor adapting the tasks to the

child's performance (e.g., if the child failed to remember three items, on the next occasion the instructor asked for two items, and after a successful repetition of two items, asked for three again).

**Verbal WM games.** The first category of games tapped verbal WM abilities. The game "Animals' home," required the temporary storage and manipulation of sequences of spoken verbal items. Children were presented with lists of words. When they heard the name of an animal, they together had to make its noise and keep in mind the first word of the list. For each presentation, a child was asked to recall the first word of the list. The game "Mysterious objects back" was designed to enhance backward span ability. Children were presented with lists of words orally and had to recall the list in the reverse order.

**Visuo-spatial WM games.** The second category of games tapped visuo-spatial WM abilities. The game "Jellyfishes" required a visuo-spatial dual task. A matrix was positioned on the floor. Children were presented with a path and had to recall the first step of the path with the noise given by an interference task. In the "Game of cards back", some cards with pictures were presented, one at a time, and the children had to recall the list in the reverse order.

**Verbal STM games.** The third category tapped verbal STM abilities. These games ("Mysterious objects" and "Line of words") were designed to enhance forward span ability. Children were presented with lists of words and had to recall the lists in the correct order.

**Visuo-spatial STM games.** The fourth category tapped visuo-spatial STM abilities. These games required the immediate serial recall of visuo-spatial information. For the game "Farmers" a matrix positioned on the floor was used and children had to remember paths of different lengths. In the "Game of cards", some cards with pictures were presented, one at a time, and the children had to recall the list in the correct order.

**Table 1.** WM training games

<b>Games</b>	<b>Objective</b>	<b>Category</b>
1. Animals' Home	- Temporary storage and manipulation of sequences of spoken verbal items.	Verbal WM Games
2. Mysterious Objects Back	- Recall lists of spoken words forward and backward	
3. Jellyfishes	- Remember the starting position of the path while performing a secondary task.	Visuo-spatial WM Games
4. Game of Cards Back	- Recall list of pictures in the reverse order.	
5. Mysterious Objects	- Recall lists of spoken words forward	Verbal STM Games
6. Line of Words	- Recall lists of spoken words forward	
7. Farmers	- Recall of pathways within a matrix	Visuo-spatial STM Games
8. Game of Cards	- Recall lists of pictures forward	

### **Early numeracy training.**

The early numeracy training was conducted in groups of five children for 1 hour, two times a week. The full training program consisted of eight different games grouped into four different categories (see Table2): counting, linear representation of numbers, relationships between numbers and quantities, and comparison of quantities. In each session, two games were played. The games for each session were selected in such a way that within one week all children were exposed to one game from each of the categories. The order of presentation of the games was the same in each group. The children participated in the activity one after the other. The training was adaptive with the instructor adapting the tasks to the child's performance (e.g., if the child failed to perform the task, on the next occasion the instructor presented an easier one. After a successful performance, the instructor increased the difficulty level of the task again). The first and the second week children played games that focused on the numbers 1 to 10. From the third week numbers 11 to 20 were introduced.

**Counting games.** The first category of games tapped counting abilities. The game "Fingers" required the verbalization of counting sequences through finger-counting. The other game ("Numbers rhyme") consists in the teaching of a rhyme that made use of the number. The numbers rhyme was presented with a series of cards that illustrated the numbers.

**Linear number board games.** The second category of games tapped the linear representation of numbers. The first was a linear-number board game ("Number path"), in which



the children had to complete a path. Each child alternatively threw dice. According to the number shown on the dice, the child should move on a number-line. On every square of the path were instructions to perform a numerical task. In the second game (“Number-line game”) the children had to extract from a box some cards that showed numbers and place them in the correct position on a line, with or without the references given by the vertical bars, to build the line of numbers.

**Number – quantity linkage games.** The third category of games tapped the identification of relationships between numbers and quantities. In the first game (“Tombola”), the children had to connect the quantities represented on their cards with the corresponding numbers extracted. Another game (“Pairs”), challenged the children to remember the locations of cards placed on a grid, with the goal of pairing cards that represented numbers with cards that represented the corresponding quantity.

**Quantity comparison games.** The fourth category tapped the comparison of quantities (“more than” and “less than”). In the game “Cats and mice” children engaged in an activity in which pictures of two cats were shown. Each cat was given a quantity of mice. The goal of the game was to identify how many mice were given to each cat and decide which of the two cats had more mice. The game “Tokens” required children to compare quantities of coins scattered on the table.

**Table 2.** Early Numeracy Training games

<b>Games</b>	<b>Objective</b>	<b>Category</b>
1. Fingers	- Verbalization of counting sequences through finger counting.	Counting Games
2. Numbers Rhyme	- Learning of a rhyme that made use of the number words.	
3. Number Path	- According to the number shown on a dice, the child should move on a number line.	Linear Number Board Games
4. Number-Line game	- Place number cards in the correct position on a line, with or without the references given by the vertical bars.	
5. Tombola	- Connect the quantities represented on cards with the corresponding numbers extracted.	Number-Quantity Linkage Games
6. Pairs	- Pairing cards that represented numbers with cards that represented the corresponding quantity.	
7. Cats and mice	- Identify the quantity of mice given to each cat and decide which of the two cats had more mice.	Quantity Comparison Games
8. Tokens	- Compare quantities of coins scattered on the table.	

## Results

Mean and standard deviation of pre-test and post-test scores of the three groups are presented in Table 3. A series of analyses of variance tests (ANOVAs) established no significant differences at pre-test between the three groups in any measure: early numeracy,  $F(2,45) = 1.21, p = .31, \eta_p^2 = .05$ , visuo-spatial short-term memory,  $F(2,45) = .05, p = .95, \eta_p^2 = .002$ , visuo-spatial working memory,  $F(2,45) = 1.30, p = .28, \eta_p^2 = .05$ , verbal short-term memory,  $F(2,45) = 1.18, p = .32, \eta_p^2 = .05$ , verbal working memory,  $F(2,45) = .23, p = .79, \eta_p^2 = .01$ .

There was no difference between the three groups for chronological age,  $F(2,45) = 1.06, p = .35, \eta_p^2 = .04$ , and there was no significant difference for the amount of intervention sessions received between the two training groups;  $F(1,34) = .70, p = .41, \eta_p^2 = .02$ . Therefore, these factors were not further included as covariates in the analyses.

To examine performance gains between the pre-test and post-test sessions for all of the tasks, we conducted analyses of covariance (ANCOVA) with the group (working memory training, early numeracy training, and control) used as the factor, pre-test scores used as the covariate, and difference scores (post-test minus pre-test) examined as the dependent variable. Bonferroni-adjusted post hoc pairwise comparisons were also conducted difference scores (post-test minus pre-test) between groups.

For the comparisons of the gain difference between groups,  $\eta_p^2$  was used as a measure of effect size. The criteria of Cohen (1988) were used to classify the effect sizes; small effect:  $\eta_p^2 = .01$ ; medium effect:  $\eta_p^2 = .06$ ; and large effect:  $\eta_p^2 = .14$ . Effect sizes (Cohen's  $d$ ) for post hoc pairwise comparisons are also reported; small effect  $d = 0 - 0.2$ ; medium effect  $d = 0.3 - 0.5$ ; large effect  $d = 0.6$ .

The ANCOVA on early numeracy gain scores revealed a significant difference between groups after controlling for the effect of pre-test scores,  $F(2,44) = 17.96, p < .001, \eta_p^2 = .45$ , reflecting the differential effect of treatments. Bonferroni-adjusted post hoc pairwise comparisons indicated that the working memory group displayed larger improvement compared to the control group ( $Mdiff = 3.82, p = .005, d = .80$ ). Also the early numeracy group displayed larger improvement compared to the control group ( $Mdiff = 6.65, p < .001, d = 1.63$ ). The gain difference between the two intervention groups did not reach statistical significance ( $Mdiff = 2.83, p = .06, d = .95$ ).

**Table 3.** Pre- and post-test scores and univariate test results for gain differences between the conditions.

	Working memory training				Early Numeracy training				Control				
	Pre-training		Post-training		Pre-training		Post-training		Pre-training		Post-training		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Verbal STM	4.73	.80	4.93	.88	5.00	1.36	5.40	1.30	5.28	.82	5.28	.75	.69
Verbal WM	3.60	1.63	5.73	1.67	3.40	1.96	3.87	2.03	3.17	1.85	3.56	1.65	7.62*
Visuo-spatial STM	5.47	1.55	6.27	1.39	5.33	.72	5.60	1.24	5.39	1.14	5.56	1.25	1.42
Visuo-spatial WM	4.93	2.05	6.73	1.16	3.93	2.63	4.60	2.67	3.72	2.05	3.44	2.12	10.46*
Early Numeracy	23.53	6.75	28.00	6.91	20.07	8.07	28.33	5.39	19.89	7.21	21.56	6.13	17.96*

The ANCOVA on the visuo-spatial working memory gain scores revealed a significant difference between groups,  $F(2,44) = 10.46, p < .001, \eta_p^2 = .32$ , reflecting differential effects of training. Bonferroni-adjusted post hoc pairwise comparisons of performance gain differences indicated that children in the working memory group had a significant greater gain compared with the control group ( $Mdiff = 2.52, p < .001, d = 1.16$ ), whereas no significant difference was found between the early numeracy group and control group ( $Mdiff = 1.02, p = .19, d = .58$ ). The gains produced in the working memory group were significantly higher than those in the early numeracy group ( $Mdiff = 1.50, p = .03, d = .90$ ).

The ANCOVA of the verbal working memory gain scores results revealed a significant difference between groups,  $F(2,44) = 7.62, p = .001, \eta_p^2 = .25$ , reflecting the differential effects of training. Bonferroni-adjusted post hoc pairwise comparisons revealed that the improvement in performance from pre- to post-test was significantly greater in the working memory group than in the control group ( $Mdiff = 1.96, p = .002, d = .97$ ), whereas no significant difference was found between the early numeracy group and control group ( $Mdiff = .19, p = 1, d = .04$ ). The gains produced in the working memory group were significantly higher than those in the early numeracy group ( $Mdiff = 1.76, p = .009, d = .96$ ).

The ANCOVA of the short-term memory results revealed no interactions for verbal STM,  $F(2,44) = .69, p = .51, \eta_p^2 = .03$ , or visuo-spatial STM,  $F(2,44) = 1.42, p = .25, \text{partial } \eta^2 = .06$ .

## Discussion

The present study examined the effects of working memory training and early numeracy training on early numerical abilities in preschoolers, and the effects of these two types of training on the different components of working memory. As expected, our findings showed that only the children in the WM training group increased their working memory skills. More interestingly, not only the children in the early numeracy training group, but also the children in the WM training group showed substantial gains in early numeracy abilities.

Regarding the early numeracy training, the group of children that received this type of training exhibited a significant enhancement of early numeracy abilities compared to the control group. This result confirms previous findings about the possibility of improving early numeracy skills in preschool children using numerical games and activities, even before their entrance into primary school (e.g., Ramani & Siegler, 2008; Whyte & Bull, 2008). However, children in the early numeracy training group did not significantly improve working memory abilities or short-term memory abilities when compared with the control group and the working memory training group.

The improvement was not significant with regard to the verbal component of short-term memory and working memory, or for the visuo-spatial component of short-term memory and working memory. These findings stressed the specificity of the effect of the early numeracy training on early numerical skills, given that no working memory or short-term memory measures improved in this group.

More importantly, this study showed that the group that received working memory training exhibited a significant enhancement of both working memory abilities and early numeracy abilities. Significant increases in verbal and visuo-spatial working memory abilities were observed in the working memory training group compared with the control group and early numeracy training group. This encouraging result is consistent with previous studies of working memory training in school-aged children and preschoolers (Dowsett & Livesey, 2000; Kroesbergen et al., 2014; Röthlisberger et al., 2012; Thorell et al., 2009). The WM training used effectively improved memory skills that are supported by the central executive component of Baddeley's model that is the most strongly predictive of a broad range of learning achievement including mathematics (Alloway & Passolunghi, 2011; De Smedt et al., 2009; Gathercole et al., 2003; Passolunghi et al., 2007).

Regarding the transfer effects of the WM training on school learning, children in the WM training group significantly enhanced their early numeracy abilities. The gain obtained in the working memory training group did not differ significantly from the gain obtained in the early numeracy training group. This result shows that working memory training effect can be transferred to untrained and specific early numeracy abilities in mainstream preschool children. Moreover, this finding suggests the possibility of going beyond the correlational approach used in previous studies (De Smedt et al., 2009; Passolunghi & Lanfranchi, 2012; Passolunghi et al., 2007), and supports the idea of a possible causal relationship between domain-general working memory abilities and domain-specific numerical competence in preschoolers (Kroesbergen et al., 2014). Our results about the transfer effects of WM training are consistent with previous studies dealing with the effects of working memory training on mathematical achievement or early numeracy skills with older children and low-performing kindergarteners (Holmes et al., 2009; Kuhn & Holling, 2014). However, a recent meta-analysis (Melby-Lervåg & Hulme, 2013) stated that there was no convincing evidence of the generalization of working memory training to other skills. However, the possibility that the role of working memory training could vary with development should be considered. Most of the studies investigating the effects of WM training focused on school-aged children, while only a few studies have explored the possibility of enhancing working memory (and related early numeracy abilities) in younger children, as were examined in the present study. It is

entirely possible that the effects of WM training might be stronger in younger children, when neural system is more malleable to experience (Wass et al., 2012).

Working memory training, similar to early numeracy training, had no significant impact on verbal or visuo-spatial short-term memory abilities. This finding may be attributable to the structure of the short-term memory tasks that involved situations in which small amounts of material are passively held, without any manipulation of the to-be-recalled information, and then reproduced in the same order of presentation (e.g., forward digit or word span tasks). The passive recall of information may be considered a measure that is stable and more difficult to improve by training procedures, whereas working memory skills can be improved through the acquisition of appropriate strategies to improve information-processing skills.

The findings of the present study have several practical implications for intervention. Some previous studies used computerized training procedures to examine the possibility to improve WM abilities and early numeracy abilities (Alloway et al., 2013; Holmes et al., 2009; Kuhn & Holling, 2014; St Clair - Thompson et al., 2010). In this study, we decided to develop group-based intervention programs because we consider this modality easy to integrate into preschool activities and because it promotes motivation and peer-based learning (Ramani et al., 2012). The present results regarding the positive effects of the early numeracy training and the WM training used may contribute to plan interventions in preschool. Performing training activities such as those presented in the this study, as well as computerized training, may help children to improve cognitive precursors fundamental in future school learning encouraging the prevention of learning difficulties at preschool level. In particular, different studies highlighted the great importance of WM in a range of cognitive skills including mathematics (see Cowan & Alloway, 2008). Thus, the development of different types of WM training programs may be crucial in planning interventions for the early prevention of learning difficulties in different school subjects.

The present study has some limitations. The first of these regards the lack of information about the durability of any gains made by training. It is important to examine whether beneficial effects of preschool training on early numerical competence and working memory are maintained when children entered primary school (Melby-Lervåg & Hulme, 2013). Moreover, it should also be noted that our positive effects should be interpreted with caution because the size of the sample was relatively small, which made the results sensitive to random effect.

A final consideration for future research regards the investigation of the effects of WM training in preschoolers who are considered to be at risk for developing learning disabilities. In fact, WM training could be particularly appropriate for low performing preschool-children, in order to minimize the future learning difficulties that result from WM deficits. Moreover, future studies may

consider introducing more tasks to assess working memory abilities and numerical competence to better investigate the transfer effect of working memory training.

In summary, we found that early numeracy training proved to be effective in improving early numerical skills, and working memory training had a significant effect not only on memory but also on early numeracy abilities. These results stress the importance of performing activities designed to train working memory abilities, in addition to activities aimed to enhance more specific skills in preschool years. More research is needed to investigate the possibility that early numerical abilities can be enhanced using different training procedures and thus to investigate the causal mechanism of this pattern of results.

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# Chapter 5

## Improving WM Abilities in Individuals with DS: a Treatment Case Study

Costa H. M., Purser H.R.M., and Passolunghi M. C. (submitted). Improving working memory abilities in individuals with Down syndrome: a treatment case study.

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## **Abstract**

Working Memory (WM) skills of individuals with Down's syndrome DS tend to be very poor compared to typically developing children of similar mental age. Particularly, research has found that in individuals with DS visuo-spatial WM is better preserved than verbal WM. This study investigated whether is possible to train Short-Term Memory (STM) and WM abilities in individuals with DS. The cases of two teenage children are reported: E.H., 17 years and 3 months, and A.S., 15 years and 11 months. A school-based treatment targeting visuo-spatial WM was given to E.H. and A.S. for six weeks. Both prior to and after the treatment, they completed a set of assessments to measure WM abilities and their performance was compared with younger typically developing nonverbal mental age controls. The results showed that the trained participants improved their performance in some of the trained and non-trained WM tasks proposed, especially with regard to the tasks assessing visuo-spatial WM abilities. These findings are discussed on the basis of their theoretical, educational and clinical implications.

DS is a pervasive developmental disorder caused by abnormalities of chromosome 21. It is one of the most common causes of intellectual disability, affecting about 1 in 700/1000 live births (Parker et al., 2010; Sherman, Allen, Bean, & Freeman, 2007; Steele, 1996). IQ generally ranges between 25 and 70 and the cognitive development of individuals with DS is characterized by significant delays and difficulties in WM and STM abilities. WM plays a key role in everyday life (e.g., reading, writing, arithmetic, learning, language-processing, orientation, imagination) for TD children as much as for individuals with cognitive disabilities. Given this link between WM performance and classroom and daily life functioning, it is of substantial interest to investigate the effectiveness of interventions designed to reduce WM and STM difficulties in order to provide effective evidence-based training programs for young people with DS. Indeed, the enhancement of memory skills would be expected to promote skill development (e.g., Gathercole & Alloway, 2006) and independence of individuals with DS, minimizing the impact of the WM deficit on their lives.

### **DS and WM Abilities**

WM has been defined as a mental workspace, which enables a person to hold information in mind while simultaneously performing other complex cognitive tasks (e.g. Holmes & Adams, 2006). Various models of the structure and function of WM exist, but the investigation of WM abilities in DS has been largely conducted within the framework of the multi-component model of WM initially proposed by Baddeley and Hitch(1974; see also Baddeley, 1986, 2000). This model consists of three main parts. The two modality-specific systems (i.e., the phonological loop and visual-spatial sketchpad) are specialized for processing language-based and visuo-spatial information, respectively. The central executive, which is not modality-specific, coordinates the two slave systems and is responsible for a range of functions, such as the attentional control of actions (e.g., inhibiting irrelevant information, shifting attention, updating information). The distinction between the central executive system and specific memory storage systems (i.e., the phonological loop and visuo-spatial sketchpad) in some ways parallel the distinction between WM and STM. WM is considered an active system that involves both storage and processing of information, while STM typically involves situations in which the individual passively holds small amounts of information, as required in forward span tasks (Cornoldi & Vecchi, 2003; Swanson & Beebe-Frankenberger, 2004).

A number of studies have examined WM processes in individuals with DS, providing substantial evidence of a dissociation between verbal and visuo-spatial abilities (Brock & Jarrold, 2005; Jarrold & Baddeley, 1997; Laws, 2002). Compared with children with intellectual disability or younger typically developing children matched for mental age, it has been found that there is a large deficit for those with DS in several verbal STM measures (Buckley, Broadley, & MacDonald,

1995; Jarrold, Baddeley, & Hewes, 1999; Kay-Raining Bird & Chapman, 1994; Laws, 1998). The current best explanation for the deficit in phonological loop component of WM in individuals with DS is that they have a problem that originates in storage rather than either encoding or rehearsal (Baddeley & Jarrold, 2007; Jarrold, Baddeley, & Phillips, 2002; Purser & Jarrold, 2005). Within Baddeley's (1986) WM framework, DS seems to be associated with a reduction in phonological store capacity (Baddeley & Jarrold, 2007).

On the other hand, the visuo-spatial sketchpad abilities of individuals with DS are found to be in line with what one would expect given individuals' general level of ability (Baddeley & Jarrold, 2007; Jarrold & Baddeley, 1997; Lanfranchi, Baddeley, Gathercole, & Vianello, 2012). Compared to TD children of the same mental age, DS children obtain largely equivalent scores (Lanfranchi, Cornoldi, & Vianello, 2004). However, some studies showed that even if visuo-spatial STM is less impaired in DS than verbal STM, some differences emerged when the visuo-spatial component of WM is broken down into separate spatial and visual components (Ellis, Woodley-Zanthos, & Dulaney, 1989; Laws, 2002). Indeed, individuals with DS appear to show an unimpaired spatial memory (e.g. memory of spatial positions), but an impaired visual memory (memory of objects and their visual properties, such as colours, surfaces, etc.). Although visuo-spatial STM abilities seem to be better preserved if compared with phonological STM abilities, is important to remember that both verbal and visuo-spatial WM skills are usually impaired if compared to chronological age-matched individuals (Kay-Raining Bird & Chapman, 1994).

The studies that examined the central executive component of WM suggested that there is a central executive limitation in DS. Children with DS have difficulties with executive load WM on both verbal and visuo-spatial measures, compared to mental age matched TD children (e.g. Silvia Lanfranchi et al., 2004). In particular, the results of a recent study of Lanfranchi et al. (2011) suggests that individuals with DS have a general executive deficit resulting in disproportionate deficits when two tasks are coordinated. These results are in agreement with previous studies that showed a deficit in performing executive tasks in DS individuals (e.g., Lanfranchi, Jerman, Pont, Alberti, & Vianello, 2010; Rowe, Lavender, & Turk, 2006) as well as a broad impairment in performing all kinds of dual tasks (Lanfranchi et al., 2004).

### **WM and Learning**

A variety of studies have found that both verbal and visuo-spatial WM are strongly associated with a range of measures of learning (Gathercole & Alloway, 2006; Gathercole & Baddeley, 1993; Jarvis & Gathercole, 2003). Moreover, WM deficits are characteristic of children with learning difficulties both in literacy and in mathematics (Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Passolunghi & Siegel, 2001; Pickering, 2006; Schuchardt, Maehler, & Hasselhorn,



2008). Compared to WM abilities, STM skills are much more weakly associated with general academic attainment (Gathercole & Alloway, 2006). However, verbal STM skills are linked to reading progress and an accurate phonological representation within STM is required for new word learning (e.g., S E Gathercole, Hitch, Service, & Martin, 1997; Jarrold, Thorn, & Stephens, 2009; Service & Kohonen, 1995).

In the field of ID, some studies have suggested that the WM and STM deficits associated with DS play a key role in causing the learning difficulties seen in the condition. DS is characterized by generalized difficulties in performing number and calculation tasks (Marotta, Viezzoli, & Vicari, 2006). In particular, individuals with DS exhibit several mathematical difficulties compared to typically developing (TD) individuals (Brigstocke, Hulme, & Nye, 2008). They obtain lower scores in a wide range of tests assessing basic mathematical knowledge, arithmetic abilities and counting skills (Buckley & Sacks, 1986; Carr, 1988; Porter, 1999). Recently it has been suggested that visual WM memory difficulties in DS could lead to deficits in some early numerical abilities that are thought to be foundational to mathematical learning (Sella, Lanfranchi, & Zorzi, 2013).

On the other hand, weak verbal WM and STM abilities make processing verbal information and learning from listening difficult for children with DS. Indeed, the marked phonological STM deficit seems to underlie the characteristic patterns of inefficient language skills in individuals with DS (e.g. deficits in phonology, speech intelligibility, language production, syntax, reading) (Byrne, MacDonald, & Buckley, 2002; Dodd & Thompson, 2001; Lanfranchi, Jerman, & Vianello, 2009).

### **WM Intervention**

The results described above provide evidence that DS is characterized by significant delays and difficulties in WM and STM abilities that are associated with general learning disabilities and language impairment. Therefore, it is clearly of some importance to investigate the effectiveness of interventions designed to reduce the WM and STM difficulties, in order to provide effective evidence-based training programs for DS children. However, WM has traditionally been considered a genetically fixed cognitive ability (Kremen et al., 2007). Therefore, it wasn't considered the possibility to enhance WM skills by acting on an individual's environmental experiences and opportunities. Recently, a growing set of studies with TD children and adults have shown that WM skills can be improved through training demonstrating that considerable cerebral plasticity exists and that WM capacity may potentially be improved (Olesen, Westerberg, & Klingberg, 2004; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009). Some studies have even shown a transfer effect of WM training on school-related skills (Alloway, Bibile, & Lau, 2013; Holmes, Gathercole, & Dunning, 2009; Passolunghi & Costa, 2014; St Clair-Thompson, Stevens, Hunt, &

Bolder, 2010). However, the debate is still open; in fact, a recent meta-analysis questioned the effectiveness of WM training, concluding that there is no convincing evidence of the generalization of WM training to other cognitive skills (Melby-Lervåg & Hulme, 2013).

Given that the WM system is important for language learning, intervention studies designed to target the memory difficulties associated with DS have typically focused on improving verbal STM skills, generally by training children to use rehearsal strategies (Broadley & MacDonald, 1993; Laws, MacDonald, & Buckley, 1996). These studies have focused on improving the ability to repeat items in the correct order. Groups with DS have been shown to benefit from training of an overt cumulative rehearsal strategy, in which participants are required to rehearse aloud increasing amounts of material in the course of an STM task (Broadley & MacDonald, 1993; Comblain, 1994; Laws et al., 1996). Some of the studies dealing with rehearsal training used picture supports (children used visual processing to aid their memory span) and found significant improvements for visual span measures but mixed outcomes for auditory span measures (Broadley & MacDonald, 1993; Laws et al., 1996). A third study (Comblain, 1994) phased out picture supports ending in auditory-only training and found a clear improvement in auditory memory span. Using a somewhat different approach Connors, Rosenquist, Arnett, Moore, and Hume (2008) used purely auditory rehearsal training auditory and the results showed verbal span improvements.

To our knowledge, Bennett, Holmes, and Buckley (2013) is the only study to have investigated the effects of a visuo-spatial training in DS children. This training consisted of seven computerized STM and WM games: four of them involved only the storage of visual information, two of them involved both manipulating and storing visual information, and one incorporated the storage of information in both modalities. Results showed that performance on trained and non-trained visuo-spatial STM tasks was significantly enhanced for children in the intervention group and this improvement was sustained four months later. However, they failed to find any transfer effect of the training either to visuo-spatial WM or verbal STM and WM skills. Despite this lack of transfer, these results suggest that training the visuo-spatial component of WM in a school setting may be possible for children with DS.

### **The Present Study**

The aim of the current study was to evaluate the efficacy of a school-based visuo-spatial WM training on STM and WM skills for two individuals with DS. Previous studies of memory training for individuals with DS have focused on the enhancement of verbal STM abilities by teaching rehearsal strategies, with positive results (Broadley & MacDonald, 1993; Comblain, 1994; Laws et al., 1996). Only one study has used WM training that taps both STM and WM skills (Bennett et al., 2013), in which a positive effect was found of training on visuo-spatial STM

abilities (passive recall of information) but not on visuo-spatial WM abilities. However, several studies have demonstrated the effectiveness of WM training in both TD children and children with intellectual disabilities (St Clair-Thompson et al., 2010; Thorell et al., 2009; Van der Molen, Van Luit, Van der Molen, Klugkist, & Jongmans, 2010). Therefore, it was expected that the training, targeting visuo-spatial STM abilities (simple recall of information) and visuo-spatial WM abilities (ability to both simultaneously process and store information) would improve visuo-spatial WM and STM abilities. Moreover, it was expected that our training should improve not only the visuo-spatial component of WM, but also produce a transfer effect on the verbal component of WM. This hypothesis is in line with previous studies dealing with WM training in TD children and individuals with intellectual disability (Thorell et al., 2009; Van der Molen et al., 2010).

## **Method**

### **Participants**

#### **AS Case report.**

AS is a boy with DS aged 15;11 at the time of the investigation. AS was selected from a database of participants, following on-going consent after recruitment for previous research studies by one of the authors (HP). After consent was provided by the schools, and prior to testing, parental consent was obtained. AS lives with his parents and attends a special secondary school for children with severe or moderate learning disabilities. AS was not on any medication at the time of the investigation. He received a diagnosis of DS two hours after birth (confirmed trisomy 21, without mosaicism). He was born by caesarean section and his birth weight was 1.81 kg. AS has salivary gland malfunction and was hospitalized at 3 years old in order to receive surgical operation for the correction of umbilical hernia. Developmentally, sitting was normal at 0;7, though walking was late at 2;5. AS spoke his first words at 0;8 and did not start putting 2–3 words together until around 4–5 years. He received a diagnosis of dyspraxia at 5 years old and currently has some speech problems: he speaks in short, simplified sentences. AS attended a mainstream school from 2;6 to 12;0 when he moved to a school for children with learning disabilities. Before entering primary school, he never received any type of special education service or preschool support. AS was reported to enjoy school. He has problems with writing, but his general academic achievement is in line with what would be expected given his intellectual level. He was reported to be well behaved at school, and to have good relationships with both adults and peers. AS was also reported to enjoy sports, in particular swimming. Additionally, he enjoyed 2 years work experience in a garden center.

Non-verbal Intelligence was assessed at time of testing using Raven's Coloured Progressive Matrices (RCPM; Raven, Raven, & Court, 1998). AS's RCPM raw score was 16, and his non-verbal mental age was 7. AS was also assessed on the British Picture Vocabulary Scale III (BPVS; Dunn, Dunn, Styles, & Sewell, 2009), a measure of receptive vocabulary. AS BPVS raw score was 96, his vocabulary mental age was 6 years and 5 months.

### **EH Case report.**

EH is a girl with DS aged 17;3 at the time of the investigation. Selection and consent were via the procedures described for AS. EH lives with her parents and attends a special secondary school for children with severe or moderate learning disabilities. EH was not on any medication at the time of the investigation except for hayfever tablets. She received a diagnosis of DS immediately after birth (confirmed trisomy 21, without mosaicism). She was born naturally and birth weight was 2.72 kg.

Developmental milestones were reportedly delayed: she started sitting at 0;10 and walking at 2;5. EH spoke her first words at 0;7 and did not start putting 2–3 words together until she was 3;0. Currently EH was not reported to have any speech problem. EH attended a mainstream school until 11;0 when she moved to a school for children with learning disabilities. Prior to entering primary school she never received any type of special education service or preschool support. She was reported to enjoy school with normal reading, spelling and arithmetic skills. EH was also reported to be well behaved at school, even if sometimes she does not want to do her homework. She gets on well both with both adults and peers. EH was reported to enjoy music and dance.

Non-verbal Intelligence was assessed at time of testing using RCPM (Raven et al., 1998). EH's RCPM raw score was 19, and her non-verbal mental age was 8. EH was also assessed on the BPVS III (Dunn et al., 2009), a measure of receptive vocabulary. AS BPVS raw score was 101, her vocabulary mental age was 7 years .

### **TD control group.**

The TD group was comprised of children randomly selected on the basis of date of birth from a mainstream primary school. Both school and parental consent were obtained prior to testing. The WM training used in this study targeted visuo-spatial WM, and AS and EH were therefore matched to TD controls on the basis nonverbal intelligence. This ensured that performance differences prior and after the training were not due to any general intelligence differences. Control children were administered RCPM. Children with a RCPM score below 15 and greater than 21 were excluded to ensure that AS and EH were compared to children with a comparable non verbal intelligence. Children with significant developmental delays (as identified by local educational

services) were excluded. There were 17 TD children (eight boys and nine girls) in the TD group. The mean age was 6 years, 1 (SD 0 years, 7 months), with a range of 5 years 7 months to 7 years 0 months.

## **Procedure**

Participants were individually tested at school in two sessions separated by approximately one week. Testing sessions lasted approximately 30 minutes. For matching purposes, the participants with DS completed their testing session first. Then, based on the score reached at the RCPM test, the 17 TD children were selected and they completed their testing sessions.

The WM training undertaken by the participants with DS included a number of paper-and-pencil tasks that were designed to improve visuo-spatial WM abilities. Over six successive weeks, AS and EH participated in 12 training sessions (twice weekly). Training duration was 40 minutes per session. After the training, AS and EH's WM abilities were assessed again.

## **Assessments**

### **Visuo-spatial STM.**

Pathway recall (Lanfranchi et al., 2004). The child was shown a path taken by a small frog on a 3 X 3 or 4 X 4 chessboard. Then, the child had to recall the pathway immediately after presentation by moving the frog from square to square, reproducing the experimenter's moves. The task had four levels of difficulty, depending on the number of steps in the frog's path and dimensions of the chessboard (3 X 3 in the first level with two steps and 4 X 4 in the other levels, with two, three, and four steps, respectively). A score of 1 was given for every trial performed correctly. The minimum score was 0 and the maximum was 8.

### **Visuo-spatial WM.**

Pathway recall backwards (Lanfranchi et al., 2004). The child was shown a frog's path on a 3 X 3 or 4 X 4 chessboard, in the same way as the pathway forwards task. The child had to remember the path in the reverse order. There were four levels of difficulty, depending on the number of steps in the frog's path and the size of the chess-board (3 X 3 in the first and second levels, and 4 X 4 in the other levels). A score of 1 was given for every trial performed correctly. The minimum score was 0 and the maximum was 8.

Selective pathways (Lanfranchi et al., 2004). the child was shown one or two paths taken by the frog on a 4 X 4 matrix, as in the pathways task. The task was to remember the frog's starting position(s). The task had four different levels of difficulty, depending on the number of pathways

and the number of steps in each pathway. At levels one and two, respectively, one pathway with two steps and one with three steps was performed. At levels three and four, two pathways of two and three steps, respectively, were presented. A score of 1 was given for every trial performed correctly. The minimum score was 0 and the maximum was 8.

Visuo-spatial dual task (Lanfranchi et al., 2004). The child had to remember the frog's starting position on a path on a 4 X 4 chessboard, in which one of the 16 cells was colored red. The child also had to tap on the table when the frog jumped onto the red square. The task had four different levels of difficulty, depending on the number of steps in the path (i.e., two, three, four, and five steps, respectively). The score of 1 was given for every trial performed correctly, with the child both remembering the first position of the pathway and performing the tapping task. Otherwise, a score of 0 was given. The minimum score was 0 and the maximum score was 8.

### **Verbal STM.**

Word span (Lanfranchi et al., 2004). In this task lists of two to five words were presented to the child, who was required to repeat the list immediately and in the same order as it was presented. A score of 1 was given for every trial performed correctly. The minimum score was 0 and the maximum was 8.

### **Verbal WM.**

Word span backward (Lanfranchi et al., 2004). Lists of two to five words were presented, but the child was asked to repeat each list in reverse order immediately after presentation. A score of 1 was given for every trial performed correctly. The minimum score was 0 and the maximum was 8.

Selective word recall (Lanfranchi et al., 2004). One or two lists were presented to the child, who was required to repeat the first word of each list after the presentation of the entire series. In the first trial, the child was presented with two 2-words lists; in the second trial, with two 3-words lists; and in the third trial, with three 2-words lists. ). A score of 1 was given for every trial performed correctly. The minimum score was 0 and the maximum was 8.

Verbal dual task (Lanfranchi et al., 2004). The child was presented with a list of two to five two-syllable words and was asked to remember the first word on the list and tap on the table when the word "ball" was presented. A score of 1 was given for every trial performed correctly, when the initial word of the series was remembered correctly at the same time the dual task was performed. Otherwise, a score of 0 was given. The minimum score was 0 and the maximum was 8.

## **Visuo-spatial WM Training**

The visuo-spatial WM training used was an adapted version of a WM training used in a previous study (Passolunghi & Costa, 2014) and it included different tasks that were designed to enhance visuo-spatial STM and WM abilities. The training was implemented for six weeks, twice weekly, with each session lasting 40 minutes. The full training program consisted of six different games grouped into two different categories: four visuo-spatial WM games, and four visuo-spatial STM games. In each session, two games were played: one mainly focused on the enhancement of visuo-spatial STM, one mainly focused on the enhancement of visuo-spatial WM.

The training was adaptive with the instructor adapting the tasks to the child's performance (e.g., if the child failed to remember three items, on the next occasion the instructor asked for two items and, after a successful repetition of two items, asked for three again). The children participated in the activity one after the other.

### **Visuo-spatial STM Games.**

The first category tapped visuo-spatial STM abilities. These games required the immediate serial recall of visuo-spatial information. For the game "Farmers," a matrix positioned on the floor was used and children had to remember paths of different lengths. In the game "Circles" some hula hoops are randomly positioned on the floor and children had to remember paths of different lengths. In the "Game of cards," some cards with pictures were presented, one at a time, and the children had to recall the list in the correct order using cards with pictures to respond. In the "Game of numbers" some cards with pictures were presented, one at a time, and the children had to recall the list in the correct order using cards with numbers to respond.

### **Visuo-spatial WM Games.**

The second category of games tapped visuo-spatial WM abilities. These games required a dual task procedure ("Colours" and "Pairs") or a backward recall ("The farmers backwards" and "Game of Cards Back").

For the game "Colours" A matrix was positioned on the floor. Children were presented with a path and had to recall the first step of the path with the noise given by an interference task. The game "Pairs" challenged the children to remember the locations of cards placed on a grid. On each turn, a player turns over two cards (one at a time) and keeps them if they match. For the game "Farmers backwards," a matrix positioned on the floor was used and children had to remember paths of different lengths in the reverse order after presentation. In the "Game of Cards Back," some cards with pictures were presented, one at a time, and the children had to recall the list in the reverse order using pictures to respond.

## **Analysis**

Performance was analysed using Crawford and Howell's (1998) modified *t*-test for comparison of an individual's score on a single test with the score of a normative or control sample. This method provides both significance tests and a point estimate of the percentage of the population that would obtain a more extreme score (or different score) and an interval estimate (i.e., confidence limits) on this percentage. Analyses were run using the computer program SINGLIMS\_ES.EXE, an upgraded version of the program Singlims.exe (Crawford & Garthwaite, 2002). It implements classical methods for comparison of a single case's score to scores obtained in a control sample.

In agreement with Perneger (1998), Bonferroni adjustments were not applied. If using Bonferroni adjustments for small sample sizes, the interpretation of a finding becomes dependent upon the number of analysis performed so they automatically increase the likelihood of Type II errors and important performance differences may be missed (Perneger, 1998).

The focus of the current study was of individuals with DS. It was expected that where performance differed to that of TD controls would be in the direction of impaired performance and one tailed *t*-test were used for the analysis (Crawford et al., 2003). However, literature shows how the WM memory deficit seems to be limited to the verbal rather than visuo-spatial domain (Jarrod & Baddeley, 1997; Laws, 2002). Indeed, the visuo-spatial sketchpad abilities of individuals with DS seems to be in line with what one would expect given individuals' general level of ability. (Baddeley & Jarrod, 2007; Jarrod & Baddeley, 1997; Lanfranchi et al., 2012). Therefore, for visuo-spatial STM measures two-tailed *t*-tests were used. For all *t*-tests, the .05 probability level for significance was used.

## **Results**

Performance prior and after training is reported for EH and AS, two teenagers with DS, in comparison to matched TD controls (see Table 1). In the first part of this section, results in visuo-spatial STM and WM abilities are reported. In the second part of the section, the results in verbal STM and WM are reported. Both parts are followed by a summary of the main findings (see Figure 1).



**Table 1** Scores for the WM and STM measures

Task	AS		EH		TD group (N= 17)	
	pre	post	pre	post	Mean	(SD)
Word span (STM)	0	4 *	4	4	5.18	1.38
Word span backwards	0	0	3	4	3.00	.87
Selective word recall	3	6 *	8	6	5.12	1.36
Verbal dual task	0	2 *	7	5	4.71	2.42
Cumulative verbal WM	3	8 *	18	15	12.82	3.34
Pathway recall (STM)	3	5 *	8	7	5.76	1.30
Pathway recall backwards	4	4	5	7	5.47	1.23
Selective pathways	3	6	1	8 *	5.06	1.75
Visuo-spatial dual task	0	4 *	3	7	5.47	1.70
Cumulative visuo-spatial WM	7	14 *	9	22 *	16.00	3.28

**Note** \* = improvement from a significantly impaired performance in the pre-test to a score that didn't differ significantly from the performance of TD group.

## Visuo-spatial STM

### Pathway recall.

EH's *Pathway recall* score did not differ significantly from the TD group either in the pre-test,  $t = 1.77$ ,  $p = .09$ , or in the post-test,  $t = .98$ ,  $p = .34$ . In both sessions her score was higher compared to the mean score of the control TD group and in the pre-test her performance was at ceiling. The estimated percentage of normal population falling below case's score was 95.21% (95% CI: 84.73%; 99.53%) before training and was 82.91% (95% CI: 65.90%; 94.36%) after the training.

Prior to training, AS recalled significantly fewer paths than the control group,  $t = 2.18$ ,  $p = .04$ . After training AS improved in performance on the *Pathway recall* and in the post-test session there was no longer a significant difference from the TD group,  $t = .60$ ,  $p = .56$ . The estimated percentage of the normal population falling below the case's score was 2.22% (95% CI: .08%; 9.19%) before training and increased up to 27.83% (95% CI: 12.91%; 46.44%) after the training.

## Visuo-Spatial WM

### Pathway recall backwards.

EH's score in *Pathway recall backwards* did not differ significantly from the TD group in the pre-test session,  $t = .37$ ,  $p = .36$ , or the post-test session,  $t = 1.2$ ,  $p = .12$ . However, the estimated percentage of the normal population falling below the case's score increased from 35.76% (95% CI: 19.22%; 54.64%) before training up to 87.79% (95% CI: 72.37%; 96.94%) after the training.

For AS, the score was the same prior and after the training and his performance did not differ significantly from the TD group,  $t = 1.16$ ,  $p = .13$ . The estimated percentage of the normal population falling below the case's score was 13.12% (95% CI: 3.49%; 28.90%).

### Selective pathways.

EH's *Selective pathways* performance in pre-test session was significantly impaired compared to the TD group,  $t = 2.25$ ,  $p = .02$ . Her performance improved after the training with a post-test score at ceiling and higher than the mean score of the TD group,  $t = 1.63$ ,  $p = .06$ . Strikingly, the estimated percentage of the normal population falling below the case's score was 1.92% in the pretest (95% CI: .06%; 8.3%) and 93.90% (95% CI: 82.17%; 99.22%) in the post-test.

AS's performance did not differ significantly from the TD group in the pre-test session,  $t = 1.14$ ,  $p = .13$ , or the post-test session,  $t = .52$ ,  $p = .30$ . The estimated percentage of the normal population falling below the case's score was 13.47% (95% CI: 3.67%; 29.38%) before training and was 65.56% (95% CI: 50.80%; 85.08%) after the training.

### Visuo-spatial dual task.

In the *visuo-spatial dual task*, EH's performance did not differ significantly from the TD group in the pre-test session,  $t = .99$ ,  $p = .16$ , or the post-test session,  $t = .61$ ,  $p = .27$ . However, the estimated percentage of the normal population falling below the case's score increased from 16.80% in the pretest (95% CI: 5.47%; 33.74%) to 72.62% (95% CI: 54.04%; 87.42%) in the post-test.

AS's *visuo-spatial dual task* performance in the pre-test session was significantly impaired compared to the TD group,  $t = 2.20$ ,  $p = .02$ , since he was not able to perform the double task. After training, AS's score did not differ significantly from the TD group,  $t = .59$ ,  $p = .28$ . The estimated percentage of the normal population falling below the case's score was 2.16% (95% CI: .08%; 9.00%) before training and increased up to 28.16% (95% CI: 13.16%; 46.80%) after the training.

### **Cumulative visuo-spatial WM score.**

In order to better understand the nature of EH and AS's WM improvements and for data reduction purposes, a *Cumulative visuo-spatial WM* score was created by summing the scores of the *visuo-spatial dual task*, the *Selective pathways*, and *Pathway recall backwards*.

EH's *visuo-spatial WM cumulative* score prior to training was significantly impaired compared to the TD group,  $t = 2.07$ ,  $p = .03$ . After training, EH's performance increased (EH = 22, control mean = 16, SD, 3.28) and she obtained a significantly higher score than the TD group,  $t = 1.77$ ,  $p = .047$ . The estimated percentage of the normal population falling below the case's score was 2.73% (95% CI: .014%; 10.55%) before training. After the training, the results showed that the estimated percentage of the normal population falling below EH's score was 95.28% (95% CI: 84.87%; 99.54%).

AS's *visuo-spatial WM cumulative* performance in the pre-test session was significantly impaired compared to the TD group,  $t = 2.67$ ,  $p = .008$ . After the training, there was no longer a significant difference from the TD group,  $t = .59$ ,  $p = .28$ . The estimated percentage of the normal population falling below the case's score was .84% (95% CI: .007%; 4.64%) before training and was 28.09% (95% CI: 13.11%; 46.71%) after the training.

### **Summary**

EH's performance in visuo-spatial STM, assessed with the pathway recall task was higher compared to the mean score of the control TD group both in the pre-test and post-test. The results did not show an improvement of EH's visuo-spatial STM abilities after training.

Considering the tasks assessing visuo-spatial WM abilities, in the *Pathway recall backwards* and in the *Visuo-spatial dual task* EH performance did not differ significantly from the TD group either in the pre-test or post-test sessions. However, in both tasks there was an improvement of performance after the training, as shown by the increased estimated percentage of the normal population falling below the case's score in the post-test session (from 35.76% to 87.78% for the *Pathway recall backwards*; from 16.80% to 72.62% in the *Visuo-spatial dual task*). The third task used in order to assess visuo-spatial WM abilities was the *Selective pathways*. EH's performance in the pre-test session was significantly impaired compared to the control TD group. The results showed that her performance improved after the training and her score did not differ from the TD group.

If one considers the *visuo-spatial WM cumulative score*, EH's performance prior to training was significantly impaired compared to the control group. The training led to an improvement of

overall visuo-spatial WM abilities given that after the training EH obtained a significant higher score in comparison to the TD group.

AS's performance in visuo-spatial STM, assessed with the pathway recall, was significantly impaired compared to the control TD group in the pre-test session. The results showed that his performance improved after the training when the score did not differ from the TD group.

Considering the tasks assessing visuo-spatial WM abilities, AS's *Pathway recall backwards* performance prior to training did not differ significantly from the TD group. Results showed no improvements in the post-test session. In the *Selective pathways* AS's performance did not differ significantly from the TD group either in the pre-test or post-test session. However, there was an improvement of performance after the training as shown by the increased estimated percentage of the normal population falling below the case's score in the post-test session (from 13.47% to 65.56%). Regarding the *Visuo-spatial dual task*, AS showed impaired performance in the pre-test session. The performance improved after the training, with no more significant difference from the average scores obtained by the TD group.

If one considers the *Visuo-spatial WM cumulative score*, AS's performance prior to training was significantly impaired compared to the control group. The training lead to an improvement of overall visuo-spatial WM abilities, given that after the training there was no longer a significant difference from the TD group.

## **Verbal STM**

### **Word span.**

For EH, *word span* score was the same prior and after the training and her performance did not differ significantly from the TD group,  $t = .83$ ,  $p = .21$ . The estimated percentage of normal population falling below case's score was 20.91% (95% CI: 8.01%; 38.72%).

AS's *word span* performance in pre-test session was significantly impaired compared to the TD group,  $t = 3.65$ ,  $p = .001$ , since it was not able to perform the task. After training, AS's score did not differ significantly from the TD group,  $t = .83$ ,  $p = .21$ . The estimated percentage of the normal population falling below the case's score was 0.11% (95% CI: 0%; .88%) before training and increased up to 20.21% (95% CI: 8.01%; 38.72%) after the training.

## Verbal WM

### Word span backwards.

EH's *Word span backwards* score in the pre-test was equal to the average score obtained from the control TD group,  $t = 0$ ,  $p = .50$ . In the post-test session again EH's performance did not differ significantly from the TD group,  $t = 1.17$ ,  $p = .14$ . The estimated percentage of the normal population falling below the case's score was 50.00% (95% CI: 31.73%; 68.27%) before training and was 85.98% (95% CI: 69.87%; 96.05%) after the training.

AS was not able to perform the *Word span backwards* either before or after the training. His performance was significantly poorer than the control group,  $t = 3.35$ ,  $p = .002$ , and the estimated percentage of the normal population falling below AS's score was 0.20% (95% CI: 0%; 1.51%).

### Selective word recall task.

EH's *Selective word recall* performance in the pre-test session was at ceiling and significantly higher than the TD group,  $t = 2.06$ ,  $p = .03$  while EH's post-test performance did not differ significantly from the TD group,  $t = .63$ ,  $p = .27$ . The estimated percentage of the normal population falling below the case's score was 85.98% (95% CI: 69.87%; 96.05%) in the pre-test and was 73.08% (95% CI: 54.53%; 87.77%) in the post-test.

The difference between AS's *Selective word recall* performance and the TD group in the pre-test session was found to be approaching significance,  $t = 1.51$ ,  $p = .07$ . After training, there was no longer a significant difference from the TD group,  $t = .63$ ,  $p = .26$ . The estimated percentage of the normal population falling below the case's score was 7.46% (95% CI: 1.18%; 20.27.77%) before training and increased up to 73.08% (95% CI: 54.54%; 87.77%) after the training.

### Verbal dual task.

EH's *Verbal dual task* score did not differ significantly from the mean score of the TD group either in the pre-test,  $t = .92$ ,  $p = .18$ , or post-test,  $t = .12$ ,  $p = .45$ . The estimated percentage of the normal population falling below EH's score was 81.43% (95% CI: 64.07%; 93.47%) in the pre-test and was 54.55% (95% CI: 35.97%; 72.41%) in the post-test.

AS's *Verbal dual task* performance in the pre-test session was significantly impaired compared to the TD group,  $t = 1.89$ ,  $p = .038$ , since he was not able to perform the double task. After training, AS's score did not differ significantly from the TD group,  $t = 1.09$ ,  $p = .15$ . The

estimated percentage of the normal population falling below the case's score was 3.84% (95% CI: .29%; 13.22%) before training and was 14.63% (95% CI: 4.26%; 30.93%) after the training.

### **Cumulative verbal WM .**

To better understand the nature of EH and AS's WM abilities and for data reduction purposes, a *Cumulative verbal WM* score was created by summing the scores of the *verbal dual task*, the *Selective word recall*, and *Word span backwards*.

EH's *Cumulative verbal* score in both sessions was higher compared to the mean score of the control TD group. Her score was higher compared to the TD group in the pre-test, but the difference only approached significance,  $t = 1.50$ ,  $p = .07$ . In the post-test, there was a decrease of performance but her score remained higher than the average score of the TD group. EH's post-test performance did not differ significantly from the TD group,  $t = .63$ ,  $p = .27$ . The estimated percentage of the normal population falling below the case's score was 92.44% (95% CI: 79.56%; 98.79%) before training and was 73.26% (95% CI: 54.72%; 87.90%) after the training.

AS's *Cumulative verbal WM* score in the pre-test session was significantly impaired compared to the TD group,  $t = 2.86$ ,  $p = .006$ . After the training, there was no longer a significant difference from the TD group,  $t = 1.40$ ,  $p = .09$ . The estimated percentage of the normal population falling below the case's score was .56% (95% CI: .0073%; 3.46%) before training and was 8.99% (95% CI: 1.70%; 22.80%) after the training.

### **Summary**

EH's performance in verbal STM, assessed with the *Word span*, did not differ significantly from the TD group prior to training. Results showed no improvements in the post-test session.

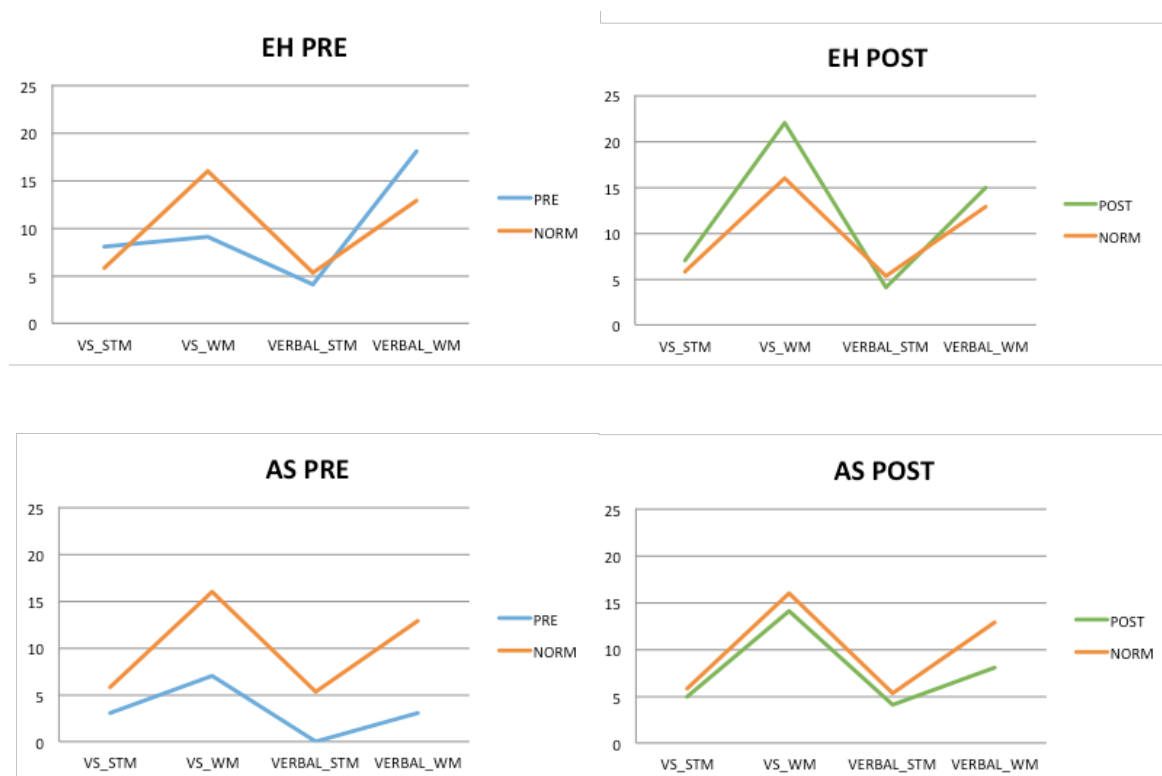
Considering the tasks assessing verbal WM abilities, the results showed no impairments in any verbal WM measure compared to the TD group in the pre-test session. After the training period the performance in all verbal WM tasks (*Word span backwards*, *Selective word recall*, and *Verbal dual task*) remained within the range of the TD group. In *Selective word recall* and in the *Verbal dual task* there was a decrease of performance, but her score remained higher than the average score of the TD group both in the pre- and post-test sessions. Only in the *Word span backwards task* was there an increased performance at post-test, as shown by the increased estimated percentage of the normal population falling below the case's score in the post-test session (from 50.00% in the pre-test to 85.98% in the post-test).

If one considers the *Verbal WM cumulative score*, EH's performance did not differ significantly from the TD group either in the pre-test or in the post-test. The results show a lower performance in the post-test but it should be noted that in both sessions her score was higher than the mean score of the control TD group.

AS's performance in all verbal STM and WM tasks was significantly impaired compared to the control TD group in the pre-test session, except for *Selective word recall* where the performance difference relative to the TD group was found to be only approaching significance. The results showed that AS's verbal STM performance improved after the training when his score did not differ from the TD group.

Considering the tasks assessing verbal WM abilities, the results showed an improvement in the post-test session in the *Selective word recall* and in the *Verbal dual task*, with no significant difference from the average scores obtained by the TD group. AS was not able to perform the *word span backwards* either before or after the training.

If one considers the *Verbal WM cumulative score*, AS's performance prior to training was significantly impaired compared to the control group. The training lead to an improvement of overall Verbal WM abilities, given that after the training there was no longer a significant difference from the TD group



**Figure 1** Visuo spatial STM and cumulative WM scores, and verbal STM and cumulative WM scores at pre-testing (for EH, AS, and TD group) and post-intervention. (for EH and AS). VS\_STM = Visuo-spatial STM score; VS\_WM = Cumulative visuo-spatial WM score; VERBAL\_STM = Verbal STM score; VERBAL\_WM = Cumulative verbal WM score.

## Discussion

The aim of our study was to evaluate the impact of a school-based visuo-spatial WM training on the STM and WM skills of two individuals with DS. The results showed that the trained participants improved their WM and STM performance in some, but not all, of the WM tasks used for assessment.

With regard to visuo-spatial abilities, both EH's and AS's *visuo-spatial WM cumulative* scores (created by summing the scores of the *Visuo-spatial dual task*, the *Selective pathways*, and *Pathway recall backwards*) improved after the training. Indeed, while in the pre-test their performance was significantly impaired compared to the TD group, while in the post-test session their scores did not differ significantly from the performance of TD group. EH's scores were improved in all the visuo-spatial WM tasks after training. In particular, her performance in the *Selective pathways* was significantly impaired in the pre-test, while after training there was no longer significant difference from the TD group. AS improved his performance in all the visuo-spatial WM tasks after training except for the *Pathway recall backwards* task that, in any case, remained within the range of the TD group. In particular, his performance in the *Visuo-spatial dual task* was significantly impaired in the pre-test while after the training there was no longer a significant difference from the TD group. Moreover, AS's *Pathway recall* performance (visuo-spatial STM) was significantly impaired in the pre-test while after the training there was no longer a significant difference from the TD group.

It should be noted that both EH and AS significantly improved their visuo-spatial scores after training, mostly on those tasks on which they were significantly impaired in the pre-test session. These results suggest that our training successfully enhanced visuo-spatial abilities, improving also those skills in which they were deficient in the pre-test resulted compared to the TD group.

On the basis of the results of previous studies (Laws, 2002; Thorell et al., 2009) and given that our visuo-spatial WM training included complex memory tasks involving the central executive component of WM, a transfer of improvements to the verbal domain was expected. The results showed that AS's verbal STM and WM skills were significantly impaired compared to the control TD group prior to training. After the training his performance improved and there was no longer a significant difference from the TD group, except for the *Word span backwards* score. This improvement suggests that our WM training encouraged a generalization of learned strategies to the verbal domain. EH's performance did not differ significantly from the TD group in any verbal STM and WM task, either in the pre- or post-test session. There was no improvement from pre-test to post-test except for the *Word span backwards*. Therefore, there was a transfer of the visuo-spatial



WM training effects on verbal abilities for AS, while EH didn't showed any significant improvement in her verbal STM or WM performance. This result could be explained considering the different profiles of the participants which reflect the wide variation in the effects of the chromosomal abnormality on the development in the DS. In the pre-test assessment, AS showed a generally weak profile, with most of the verbal and visuo-spatial scores significantly below the mean of the TD group. In contrast, EH showed a stronger profile with all the verbal scores and most of visuo-spatial scores within the range of the TD group. Moreover, EH's scores in all verbal WM measures (*Word span backwards, Selective word recall, Verbal dual task, Verbal WM cumulative score*) both in the pre-test and in the post-test were equal or higher than the average scores of the TD control group. Taken together, these results indicate that the training had a beneficial effect, especially on those skills that were deficient (below expected standards), while it is more difficult to influence those skills that are already in line with what one would expect given individual's general level of ability.

To explain the strong memory profile of EH, it can be hypothesized that her good education path/career and her good verbal abilities encouraged the development of WM skills. In particular, participation in school activities may have led to a familiarity in processing verbal information. On the other hand, AS's dyspraxia and speech problems could explain his general low WM and STM profile (Alloway & Archibald).

Our study has some limitations. First, only two single case treatments were studied. The results are encouraging, but only extension with further data can fully demonstrate the effectiveness of the WM training outlined. A further limitation is that changes were only assessed immediately after the training so that there is no information about the durability of any gains made by training. Previous studies reported an increased affects of WM training at follow-up compared with immediate effects in the post-test (Holmes et al., 2009; Klingberg, Fernell, & Olesen, 2005; Van der Molen et al., 2010). It should be important in future studies to follow up post-intervention to see whether benefits of training last and to investigate the effectiveness of this kind of WM training with group studies.

The findings of the present study are promising and could have important practical implications for intervention. In fact, the training program successfully enhanced AS's and EH's WM, a central and important cognitive aspect for classroom and daily life functioning. Our results, in line with previous studies (Klingberg, Forssberg, & Westerberg, 2002; Thorell et al., 2009; Van der Molen et al., 2010), provide further evidence that WM abilities can be improved and that school-based visuo-spatial memory training can be effective for children with DS, also without the support of a computer. Given the importance of WM abilities for the development of a broad range

of learning achievement (e.g. Alloway & Alloway, 2010), further work is required to investigate possible transfer effects of visuo-spatial WM training on learning in individuals with DS.

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# Chapter 6

## General Discussion



The present dissertation addressed three general questions. Firstly, the relationship between the Approximate Number System (ANS) and early mathematical abilities in the preschool years was investigated (Chapters 2, 3). Secondly, the potential role played by Short-Term Memory (STM) and Working Memory (WM) skills in supporting domain-specific precursors of mathematics was examined (Chapters 2, 3, and 4). Finally, the malleability of cognitive precursors of mathematical learning (ANS, WM, early numeracy) in the preschool years was explored (Chapters 3, 4, and 5).

### **Approximate Number System and Mathematics**

In the last few years, several studies investigated the specific role played by ANS representations in the development of more formal mathematical abilities. The association between ANS and mathematics in preschool children was evidenced in some studies (Bonny & Lourenco, 2013; Libertus, Feigenson, & Halberda, 2011; Mazzocco, Feigenson, & Halberda, 2011; Mussolin, Nys, Leybaert, & Content, 2012), but not in others (Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Defever, Maertens, & Reynvoet, 2014; Soltész, Szűcs, & Szűcs, 2010).

Our research findings (Chapter 2) provide further evidence about the relationship between ANS and mathematical abilities in the preschool years. A positive correlation was found between ANS performance and different mathematical measures (cardinality, counting, number recognition and early number concepts). The children who showed a good performance in the numerosity comparison task also had higher abilities in manipulating numerical symbols than the children who were less accurate in the numerosity comparison task. Importantly, the link between ANS and mathematical performance held even when the verbal and non-verbal IQ were taken into account. By examining the differences between children with a higher ANS performance and children with a lower ANS performance, it was found that children in the high-performance group showed better mathematical abilities than their peers in the low-performance group. Indeed, they had significantly higher scores in early number concepts, cardinality, counting and number recognition. These findings provide further evidence for a link between ANS acuity and mathematical ability early in life and suggest that noisier ANS representations may cause difficulties in the development of mathematical concepts. However, past research provided mixed results concerning the association between non-symbolic number processing and mathematical skills. More information about the functional association between ANS and symbolic mathematics in preschool children could be provided by training studies.

In a first pilot study (Van Herwegen, Costa, & Passolunghi, under review) conducted in the UK, we explored the possibility to improve ANS acuity using a specific training procedure in preschool children. Moreover the transfer effects of the training on mathematical abilities was investigated. The results showed that improved ANS has a positive impact on children's counting

and overall mathematical abilities and provides further evidence of the importance of ANS abilities to overall mathematical abilities. In contrast, in a second study conducted in Italy (Chapter 3), despite improved ANS after the training sessions, no transfer effect on mathematical measures either immediately after training or five weeks later at the follow-up session was found. Even though no direct transfer effect of the ANS training on symbolic mathematical abilities was found, we can not exclude the possibility that the increased ANS acuity promotes the development of number sense access (or links between symbolic and non-symbolic representations of number) leading to better mathematical outcomes later in life. Indeed, performing training activities such as those presented in this study could support the mapping between the symbolic number system and non-symbolic numerical magnitudes, promoting the acquisition of symbolic arithmetic skills.

The different school context may have played a role in these contrasting results. The UK preschool system is mainly based on free play and doesn't usually involve school-based structured activities. In Italy, preschool education includes free play as well as more structured activities for the development of precursors of literacy and numeracy. In the UK context, where children did not receive mathematical education, ANS improvement led to better counting skills in the training group. However, in the Italian context, where all children (even those in the control group) benefitted from early mathematical instruction, the PLUS training may not have been sufficient to create a difference between the training group and the control group in mathematical abilities.

More research is needed to confirm the possibility that mathematical abilities can be enhanced using ANS training procedures, and thus to investigate the causal mechanism of these patterns of results.

### **The Role of WM in the Early Acquisition of Mathematical Skills**

Several studies demonstrated that WM is a key domain-general predictor of mathematical competence. WM abilities seem to be related both to early numeracy skills and to later mathematical skills (Alloway & Alloway, 2010; Alloway & Passolunghi, 2011; De Smedt et al., 2009; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013; Gathercole & Pickering, 2000; Gersten, Jordan, & Flojo, 2005; Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006; Passolunghi & Lanfranchi, 2012). Indeed, even the simplest mathematics calculations require WM processes: the temporary storage of problem information, retrieval of relevant procedures and processing operations to convert the information into numerical output (Brainerd, 1983). Moreover, some studies demonstrated that WM abilities also underlie non-symbolic approximate addition processing (Barth, Kanwisher, & Spelke, 2003; Xenidou-Dervou, De Smedt, van der Schoot, & van Lieshout, 2013; Xenidou-Dervou, van Lieshout, & van der Schoot, 2014). The extent to which the WM ability plays a role in ANS tasks involving simple magnitude discrimination remains at present

an open issue. Indeed, so far, no study has examined in detail the role of WM and STM in non-symbolic approximate comparison (Mussolin et al., 2012; Soltész et al., 2010). We were interested in uncovering which specific WM component was involved in this kind of ANS processing at preschool age (Chapter 2). A positive correlation between numerosity comparison performance and verbal WM, visuo-spatial WM and visuo-spatial STM was found. However, only the link with visuo-spatial STM held when verbal and non-verbal IQ measures were taken into account. This indicates that the visuo-spatial STM may play an important role in children's performance in numerosity comparison tasks, which require children to retain in memory a visual representation of multiple arrays for comparison. Moreover, by examining the differences between children with a higher ANS performance and children with a lower ANS performance it was found that children in the high performance group out-performed children in the low performance group in the visuo-spatial STM when verbal IQ, but not non-verbal IQ, was controlled.

On the other hand, by examining the possibility to improve ANS abilities through training, we found an enhancement of numerosity comparison skills, but no transfer effects of ANS training on WM or STM skills (Chapter 3). Even though it has been demonstrated that WM and STM abilities play a role in tasks involving the Approximate Number System (Mussolin et al., 2012; Soltész et al., 2010; Xenidou-Dervou et al., 2013, 2014), exercising ANS acuity for a short period of time does not seem sufficient to affect memory skills. In line with these findings, children who participated in early numeracy training (targeting counting, linear representation of numbers, relationships between numbers and quantities, and comparison of quantities) exhibited a significant enhancement of early numeracy abilities compared to the control group (Chapter 4). However, they did not significantly improve working memory abilities or short-term memory abilities. The improvement was neither significant with regard to the verbal component of short-term memory and working memory, nor for the visuo-spatial component of short-term memory and working memory. These results provide new insights about the direction of developmental associations between WM abilities and early numeracy skills, suggesting that early numeracy abilities and ANS abilities can not predict the performance in a more general domain as working memory.

Other information about the relationship between WM and mathematics comes from WM training studies. A positive effect of WM training on arithmetic abilities in primary school children has been found using computerized or school-based training procedures (Alloway, Bibile, & Lau, 2013; Holmes, Gathercole, & Dunning, 2009; Holmes & Gathercole, 2013; St Clair - Thompson, Stevens, Hunt, & Bolder, 2010; Witt, 2011). Other authors questioned the effectiveness of WM training concluding that there was no convincing evidence of the generalization of working memory training on other skills (Melby-Lervåg & Hulme, 2013). However, the possibility should be

considered that cognitive training applied to younger individuals tends to lead to significantly more widespread transfer of training effects (Wass, Scerif, & Johnson, 2012). In line with this suggestion, the possibility to improve early numeracy abilities by training WM skills in preschoolers (Chapter 4) was explored. The WM training significantly enhanced children's early numeracy abilities, showing that working memory training effects could be transferred to untrained and specific early numeracy skills. Moreover, comparing the effects of a domain-specific early numeracy training with the effects of a domain-general WM training interesting results were found. The early numeracy intervention specifically improved early numeracy abilities in preschool children, whereas working memory intervention improved not only working memory abilities but also early numeracy abilities. More importantly, the early numeracy gain obtained in the working memory training group did not differ significantly from the gain obtained in the early numeracy training group.

All these findings (Chapters 3 and 4) suggest the possibility of going beyond the correlational approach used in previous studies (De Smedt et al., 2009; Passolunghi & Lanfranchi, 2012; Passolunghi, Vercelloni, & Schadee, 2007) and support the idea of a causal relationship between domain-general working memory abilities and domain-specific numerical competence in preschool children (Kroesbergen, van't Noordende, & Kolkman, 2014).

### **Malleability of Cognitive Precursors of Mathematical Learning**

The central role played by domain-general and domain-specific precursors of mathematical learning emphasizes the importance of investigating the effectiveness of cognitive training in young children. A number of programs currently seek to target the emergent mathematical skills in preschool children (Greenes, Ginsburg, & Balfanz, 2004; Ramani & Siegler, 2008; Starkey, Klein, & Wakeley, 2004; Whyte & Bull, 2008; Young-Loveridge, 2004). These training programs include different activities designed to promote a range of skills, that the literature suggests are important specific precursors of mathematical learning, including counting, recognizing and writing numbers, one-to-one correspondence, comparisons, change operations, and understanding numbers and quantities. Our results (Chapter 4) confirm previous findings about the possibility of improving general early numeracy skills in preschool children using numerical games and activities before their entrance into primary school.

So far, only a few studies have examined the possibility to improve ANS abilities (Dewind & Brannon, 2012; Hyde, Khanum, & Spelke, 2014; Park & Brannon, 2013). These studies show that training on tasks that tap into ANS abilities could be possible, even if it is yet unclear whether earlier intervention focused on exercising the ANS would be effective in preschool children. In the study presented in Chapter 3 we investigated whether playing the Preschool Number Learning

Scheme (PLUS) that targets the ANS system on a daily basis would improve Italian preschool children's ANS abilities. Our positive result provides further evidence that the ability to make quantitative judgments based on the ANS can be ameliorated by intensive adaptive training over a relatively short period and confirms previous results about the malleability of ANS skills in both adults and children (Dewind & Brannon, 2012; Obersteiner, Reiss, & Ufer, 2013; Park & Brannon, 2013). This result is in line with our previous findings (Van Herwegen et al., under review) about the effectiveness of ANS training in the UK context.

In the field of domain-general precursors of mathematics several studies demonstrated that the working memory plays an important role in the development of mathematical competence (De Smedt et al., 2009; Gathercole & Pickering, 2000; Gersten et al., 2005; Jordan et al., 2006; Krajewski & Schneider, 2009; Passolunghi & Lanfranchi, 2012). However, WM has traditionally been considered a genetically fixed cognitive ability (Kremen et al., 2007). Therefore, in the past it wasn't considered the possibility to enhance WM skills by acting on an individual's environmental experiences and opportunities. Recently, a growing set of studies with TD children and adults has shown that WM skills can be improved through training (Alloway et al., 2013; Holmes et al., 2009; Kroesbergen et al., 2014; Olesen, Westerberg, & Klingberg, 2004; St Clair - Thompson et al., 2010; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009). In our studies (Chapters 4 and 5) we also found that working memory training proved to be effective in improving WM skills in both preschool children and individuals with Down Syndrome (DS). These findings provide further evidence that considerable cerebral plasticity exists and that the WM capacity may potentially be improved in both typically developing children and individuals with intellectual disabilities. Moreover, our results about the efficacy of WM training in individuals with DS are particularly important given that previous studies of memory training for individuals with DS focused mainly on the enhancement of STM abilities (Broadley & MacDonald, 1993; Comblain, 1994; Laws, MacDonald, & Buckley, 1996).

### **Educational Implications and Future Direction**

The findings of the present studies have several practical implications for the identification of children at risk to develop a mathematical learning disability and for intervention. We found a positive relationship between ANS abilities and mathematical abilities (cardinality, counting, number recognition and early number concepts) in the preschool years (Chapter 2). By examining the differences between children with a higher ANS performance and children with a lower ANS performance it was found that children in the high-performance group showed better mathematical abilities than their peers in the low-performance group. Moreover, the results of chapters 2 and 4 provide evidence about the relationship between WM abilities and mathematical abilities in

preschool years. In particular, our findings suggest that visuo-spatial STM is related to ANS skills and that WM abilities are related to general early numeracy abilities in preschool years. All these findings about the link between ANS, WM, and early mathematics may contribute toward efforts to identify core deficits that underlie difficulties in mathematics and suggest the possibility for early screening of risk for mathematical learning disability. However, future studies should further investigate the direction of the developmental association between ANS and mathematics, considering the possibility that it is the symbolic number abilities that predict later accuracy in numerosity comparison and not vice versa (i.e. Mussolin, Nys, Content, & Leybaert, 2014).

The findings of the present studies have also practical implications for intervention. Some previous studies used computerized training procedures to examine the possibility to improve WM abilities and early numeracy abilities in preschool years (Alloway et al., 2013; Holmes et al., 2009; St Clair - Thompson et al., 2010; Wilson, Dehaene, Dubois, & Fayol, 2009). In our studies, (Chapters 3, 4 and 5) we decided to develop group-based intervention programs because we considered this modality to be easy to integrate into school activities and because it promotes motivation and peer-based learning (Ramani, Siegler, & Hitti, 2012). The present results regarding the positive effects of the training procedures used may contribute to intervention plans for young children and individuals with intellectual disabilities in school settings. Indeed, performing training activities such as those presented in our studies may help children to improve cognitive precursors fundamental to future school learning (ANS, early numeracy abilities and WM) and thus encouraging the prevention of learning difficulties at preschool level.

In particular, our results stress the importance of WM training. Indeed, working memory intervention improved not only working memory abilities but also early numeracy abilities in preschool children (Chapter 4). The gain obtained in the working memory training group did not differ significantly from the gain obtained in the early numeracy training group. This result is in line with different studies that highlight the great importance of WM in a range of cognitive skills including mathematics (see Cowan & Alloway, 2008). Thus, the development of different types of WM training programs may be crucial in planning interventions for the prevention of learning difficulties in different school subjects.

Future research should investigate the effects of such domain-specific and domain-general cognitive training in preschoolers, who are considered to be at risk for developing learning disabilities. In fact, these training procedures could be particularly appropriate for low performing preschool children, in order to minimize their future learning difficulties. Moreover, it is also important to examine the long term effects of preschool training.

In the field of ID, some studies have suggested that the WM and STM deficits associated with DS play a key role in causing the learning difficulties seen in this condition (Byrne, MacDonald, & Buckley, 2002; Dodd & Thompson, 2001; Lanfranchi, Jerman, & Vianello, 2009; Sella, Lanfranchi, & Zorzi, 2013). In Chapter 5 we evaluated the efficacy of a school-based visuo-spatial WM training on STM and WM skills for two individuals with DS. The results showed that the performance of the trained participants improved in some of the WM tasks proposed. These findings are promising and could have important practical implications for intervention: they provide further evidence that WM abilities can be improved and that school-based visuo-spatial memory training can be effective for children with DS, even without the support of a computer. Given the importance of WM abilities for the development of a broad range of learning achievements (e.g. Alloway & Alloway, 2010), further work is required to investigate the possible transfer effects of visuo-spatial WM training on learning in individuals with intellectual disabilities.

### **Conclusion**

The results of this dissertation allow three main conclusion to be done. Firstly, WM abilities and ANS skills are related to the early acquisition of mathematical skills. Secondly, WM abilities, ANS skills and early numeracy abilities are malleable and could be improved by training in preschool years. In particular, the domain-general WM training proved to be effective in improving WM skills with a transfer effect on early numeracy in preschool children. Thirdly, WM abilities seem to be trainable even in individuals with Down Syndrome, which are typically characterized by significant delays and difficulties in WM and STM. Further studies should investigate the link between ANS, WM and mathematics in children at risk to develop a mathematical learning disability. Indeed, the investigation of these relationships could provide important information for the early identification and prevention of mathematical learning disabilities. Our findings stress the importance to intervene as soon as possible in order to improve basic academic skills and reduce future learning difficulties in different populations.

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