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Characterizing persistent Developmental Dyscalculia: A cognitive neuroscience approach

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Graduate Program in Psychology
A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of
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Characterizing persistent Developmental Dyscalculia: A cognitive neuroscience
approach

(Thesis format: Integrated Article)

by

Stephanie Bugden

Graduate Program in Psychology

A thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

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Abstract

Developmental dyscalculia (DD) is a specific learning disorder of calculation abilities. In the present thesis I report a series behavioural and functional neuroimaging studies to further elucidate the core numerical deficits underlying DD. I recruited a sample of children with DD who demonstrated persistent impairments in arithmetic. In Chapter 2, to validate the selection criteria, I compared the performance of children with and without persistent DD on a test of numerical magnitude processing. The data showed that only children with persistent DD presented with deficits in numerical magnitude processing, while those with inconsistent DD perform at the level of age-matched typically developing (TD) controls.

In Chapter 3, I compared the performance of children with persistent DD on tasks assessing symbolic (e.g. Arabic digits) and non-symbolic (e.g. dot arrays) processing skills. Children with DD performed significantly worse on symbolic but not non-symbolic numerical magnitude processing tasks. These findings suggest that DD arises not from a format-independent magnitude processing deficit, but rather from difficulties in processing symbolic number representations.

In Chapter 4, I investigated the influence of non-numerical variables (e.g. size) on non-symbolic numerical magnitude processing in children with and without DD. Children with DD were found to exhibit deficits in non-symbolic processing only when the visual perceptual cues were anti-correlated with numerical magnitude. When numerical magnitude and area were congruent no group differences in performance emerged. Therefore, rather than presenting with a core deficit in non-symbolic processing, children with DD have difficulties in disentangling numerical and non-numerical cues.

In Chapter 5, I used functional neuroimaging to investigate whether children with DD exhibit atypical brain activation during numerical magnitude processing (symbolic, non-symbolic and mixed comparison). The data from this study revealed atypical cortical activity in the Intraparietal Sulcus (IPS) during symbolic and mixed format (comparing symbolic with non-symbolic) tasks. In contrast, children with DD did not exhibit differences in the IPS during non-symbolic numerical magnitude processing. These neuroimaging findings complement the behavioral data in Chapter 3 and 4 by suggesting that children with DD have

a deficit in semantic representation of symbolic numerical magnitudes rather than a core deficit in representing both symbolic and non-symbolic numerical magnitudes. The findings from these studies provide converging evidence to support a core deficit in processing the semantic meaning of symbolic numerals in children with persistent DD.

Keywords

Developmental Dyscalculia, Mathematical learning disorder, numerical magnitude representations, fMRI, Intraparietal Sulcus, persistent arithmetic deficits, children, access deficit hypothesis, approximate numerical abilities, numerical discrimination, symbolic numerical processing.

Co-Authorship Statement

The research for this doctoral thesis was conducted in collaboration and under the supervision of my advisor Dr. Daniel Ansari. The sample of children who participated in the present thesis was recruited from a previous epidemiological study that was conducted in collaboration with Drs. Lisa Archibald, Janis Cardy, and Marc Joanisse. They contributed to the design and data collection of the first three testing sessions of the longitudinal study reported in chapter 2. Additionally, Dr. Nadia Nosworthy assisted with the data collection reported in chapter 2. Dr. Ian Lyons and Ahmad Moussa contributed and assisted with the preprocessing and analysis of the functional neuroimaging data reported in chapter 5. I hereby acknowledge that the present manuscript is my own work; however, it should be noted that Dr. Daniel Ansari contributed to the final manuscript.

Acknowledgements

I would like to extend my sincerest gratitude to everyone in my life who supported me through the process of completing my PhD. I could not have done it without my family, friends and colleagues.

I would first like to thank my examination committee: Drs. Janis Cardy, Marc Joannisse, Ingrid Johnsrude and Jo-anne LeFevre for taking the time to read my thesis and for challenging my thoughts and ideas, providing valuable feedback, and travelling from afar to be at my defense. Secondly, immeasurable appreciation goes to for Drs. Lisa Archibald and Marc Joannisse, who provided valuable feedback on my advisory committee.

A very special thank you goes to past and present members of my lab, whom over the years have become my family. Thank you to past members Dr. Christian Battista who has consistently offered his computer programming expertise to create task stimuli and to manage large amounts of data. Thank you to Dr. Gavin Price, who during the planning stages of my PhD project encouraged me to think critically about my ideas through many discussions, and inspired the development of better ideas.

To the present members, Anna Matejko, Celia Goffin, Moriah Sokolowski, Bea Goffin, Dr. Heather Brown, and Dr. Ian Lyons, I could not have asked for better friends. Each member (past and present) within the Numerical Cognition Lab has touched my life in many ways. Their brilliance, empathy, and passion for life and science have inspired me every day. I thoroughly enjoyed each day in the lab working with my peers sharing new and exciting challenges. A special thank you to Anna Matejko who spent countless hours working late with me, who ensured that I did not go hungry, and for just being there during the writing process. I could not imagine a better time without her friendship. I am going to miss our late night dates in the lab running analyses over takeout!

To my family, friends, and my fiancé, Philip, your enduring support, love and understanding has meant the world to me as I have worked endlessly to achieve my goals and pursue my dreams (and sometimes neglecting our relationships).

And most importantly, the biggest heart felt thank you goes to my supervisor, Dr. Daniel Ansari. Ever since I first met Daniel during my undergraduate degree, he opened my eyes to the world of science and research. These past years have been the most challenging and inspiring days of my life thus far, and I am eternally grateful to him for these life changing experiences. I will be forever indebted for his generosity, mentorship and guidance during my graduate studies.

Thank you all for the support and believing in me through this adventure.

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Chapter 1

1 Introduction

Early numeracy skills are the foundational building blocks of learning more complex arithmetic skills in school. For some children, learning basic numerical and arithmetic skills comes more naturally, but for others, acquiring these skills is laborious and problematic. Poor numeracy skills are associated with lower income and poor psychological and financial outcomes in adulthood (e.g. Parsons & Bynner, 2005). Furthermore, mathematics ability at age seven has been found to predict socioeconomic status (SES) later in adulthood even after controlling for SES at birth (Ritchie & Bates, 2013). Moreover, recent research has demonstrated that numerical and math skills predict academic and life success over and above reading skills (Duncan et al., 2006; Romano, Babchishin, Pagani, & Kohen, 2010). Therefore, children and adults who experience severe mathematical difficulties are at greater risk of poor societal outcomes. Consequently, it is important that we gain an understanding of the underlying deficits that characterize mathematical learning disabilities such as developmental dyscalculia (DD; characterized by a severe impairment in learning arithmetic), in an effort to find better, research-guided ways, to alleviate severe and pervasive difficulties.

Compared to our understanding of dyslexia, a specific reading disorder, mathematical learning disorders are understudied, thereby resulting in a poor understanding of the neurological and behavioural deficits that contribute to severe deficits in arithmetic performance. Knowledge of the core deficits of dyslexia have led to an empirically derived definition of the reading disorder (Mazzocco & Myers, 2003). For example, research supporting a phonological impairment in children with dyslexia (Melby-Lervag, Lyster, & Hulme, 2012; Vellutino, Fletcher, Snowling & Scanlon, 2004) has led to the development of successful interventions to stabilize reading impairments (for a review see: Gabrieli, 2009). However, researchers in the field of mathematical cognition are still struggling with the fundamental question of what constitutes the core deficit(s) of DD and how to define them.

Consequently, a wide variety of operational definitions and divergent sets of selection criteria have been used across DD studies, hindering the progression towards understanding the root causes of DD. Given that children's success in mathematics is scaffolded by early numerical processing skills (for a recent review see De Smedt, Noel, Gilmore & Ansari, 2013), investigating the cognitive mechanisms of numerical processing in atypically developing children is important for gaining insight into the core deficits of DD and thereby deriving an empirically based definition of DD. Taking a multidisciplinary approach, incorporating both neuroimaging techniques as well as behavioural measures, is optimal for constraining our understanding of developmental dyscalculia. Integrating neuroimaging techniques with behavioural methodology provides different levels of analysis and a fine grained approach to investigating how underlying cognitive and neurological processes involved in performing basic numerical and mathematical operations are different in children with DD. In addition, this understanding of atypical mathematical skill development is essential for the design of appropriate instruction and rehabilitation programs for children with a mathematical learning disorder such as developmental dyscalculia¹. These findings can lead to the development of evidence-based intervention programs that specifically target core deficits of DD. Moreover, these approaches can facilitate the development of reliable and valid assessment tools to identify children at risk for developing DD.

In view of this, the aim of the present thesis is to shed some light on the core deficits of DD by conducting a comprehensive study exploring both the behavioural and neural characteristics of children who demonstrate persistent arithmetic impairments over time. The focus of the following literature review will examine both behavioural and neurological underpinnings of basic numerical magnitude processes as well as working memory processes in children who have been identified as being dyscalculic. First, I will describe the current diagnostic criteria of Developmental Dyscalculia outlined in the Diagnostic Statistical Manual's (DSM-V; APA, 2013), followed by a description of the

¹ To date, there is no consistent evidence to support different subtypes of mathematical learning disorders; however, multiple frameworks for the origins and manifestations have been put forward (Rubinsten & Henik, 2009; Wilson & Dehaene, 2007)

² The defective number module, the approximate number system and the access deficit hypotheses are

cognitive characteristics displayed by children who have the disorder. Next, I will present research that support different causal theories of developmental dyscalculia. Additionally, neuroimaging methodology will be discussed to provide a context to understand the functional resonance imaging studies of the neural correlates of numerical magnitude processing and visuo-spatial working memory in DD. In conclusion, a description of the aims of the current thesis, as well as the structure of the chapters presented herein, will be reviewed.

1.1 What is Developmental Dyscalculia?

Developmental Dyscalculia (DD) is a specific learning disorder that is characterized by a persistent impairment in processing numerical information and learning arithmetic facts (Diagnostic and Statistical Manual of Mental Disorders-V; APA, 2013). DD is a neurodevelopmental disorder identified by Mathematical achievement scores that are *substantially* and *quantifiably* below those that are expected for the individual's chronological age and cause significant interference with educational and occupational performance, as well as interfere with daily activities. Severe difficulties must not be better accounted for by intellectual disabilities, uncorrected visual or auditory acuity or other neurological disorders, psychosocial adversity or inadequate educational instruction (APA, 2013). Given the ambiguity in quantifying achievement 'substantially' below what is expected for an individual's chronological age, the diagnostic criteria for identifying a specific learning disorder is constantly debated in the literature (Fletcher, Stuebing, Morris, & Lyon, 2013; Kavale & Forness, 2000). There is little research that supports a consensus of what core deficits constitute DD making it difficult to identify children with DD. Consequently, researchers use different criteria to identify samples of DD across studies. For example, some studies have investigated strict definitional criteria of DD by limiting their sample to children scoring below the 10th percentile on math achievement, but having average intelligence and reading scores (Mazzocco, Feigenson & Halberda, 2011). However, other researchers have used a more lenient cut off score by recruiting children who have math achievement scores below the 35th percentile. Such a cut-off may seem overly liberal, but it allows researchers to study a

larger group of children who struggle with mathematics than would be possible using a stricter criterion (Mazzocco, 2007).

Epidemiological studies have found that DD impacts both girls and boys equally (Shalev et al., 2000). Prevalence rates of DD are comparable to those for dyslexia and attention deficit hyperactivity disorder (Shalev et al. 2000), ranging from 3-6% of the normal population across studies conducted around the world (Shalev et al. 2000). At the behavioural level, children with DD exhibit difficulties in retrieval of arithmetic facts and arithmetic procedures (Geary & Hoard, 2001; Geary, 2010), and they use immature problem solving strategies, such as finger counting (Jordan, Hanich, & Kaplan, 2003) compared to their school aged peers, who easily retrieve arithmetic facts from memory.

Unfortunately, DD has consistently received far less attention than reading disorders such as dyslexia (Russell, Clarke, & Mazzocco, 2007), despite its similar incidence rates and its poor outcome (Shalev, 2004). Although, it is generally agreed upon that DD manifests as a problem in learning arithmetic facts and calculation procedures, it remains unclear what underlying deficits are contributing to the inability to learn basic arithmetic (Landerl, Bevan, & Butterworth, 2004). Therefore, various opposing hypotheses have been proposed to account for DD (Butterworth, 1999, 2005; Geary, 1993; Jordan, Hanich, & Kaplan, 2003).

1.2 Domain general causal account for DD

Historically, researchers sought to understand the causes of DD by investigating differences between children with DD and typical controls in domain-general abilities, such as working memory. Some studies have observed deficits in semantic long term memory and working memory abilities that impair children's ability to convert arithmetic facts into long term memory (Geary, 1993). Within the behavioural literature, results have been controversial with some studies finding working memory deficits in children with DD (Geary, Brown & Samaranayake, 1991; Geary, 2004; McLean & Hitch, 1999), while other studies found no working memory deficits compared to typically developing controls (Landerl et al., 2004). In an attempt to further understand the conflicting

findings, Passolunghi and Mammarella (2012) recently investigated the specific role of visuo-spatial working memory and visual memory processing tasks in children with DD. During the visual memory task, children were presented with a set of houses and had to remember and recognize the same houses on a following trial. During the complex visuo-spatial working memory task, participants were given sequences of dot positions in a matrix and had to recall the last position or last dot from the sequence, in addition to having to press the space bar every time a specific dot appeared on the screen. They found that only children with persistent and severe difficulties in solving mathematical word problems had impairments on the complex visuo-spatial working memory task, where high attentional control was necessary to complete it. But they showed no impairments on the visual memory recognition task. Additionally, Szucs et al., 2013 found that children with DD showed greater impairments in visuo-spatial working memory, and short term memory, as well as inhibition compared to typical controls. Taken together, children with DD have demonstrated specific impairments in visuo-spatial working memory (Ashkenazi, Rosenberg-Lee, Metcalfe, Swigart, & Menon, 2013; McLean & Hitch, 1999). From these data, it was suggested that visuo-spatial working memory provides a work space to hold and manipulate numerical magnitude representations. It is plausible that an impaired visuo-spatial working memory system in children with DD would negatively impact the initial stages of basic arithmetic development when children depend on visuo-spatial representations (Ashkenazi et al., 2013).

However, the nature of the relationships between visuo-spatial working memory, numerical magnitude representations and basic arithmetic are poorly understood. It remains unclear from these studies what the causal link is between a domain general deficit in visuo-spatial working memory and domain specific processes such as numerical magnitude and arithmetic skills in DD. Indeed, a recent meta-analysis has provided evidence that children with DD demonstrate numerically specific working memory impairment in comparison to typically developing controls. Specifically, working memory deficits among DD children are pronounced in working memory tasks that require numerical manipulations, such as backward digit recall; rather than domain general working memory impairment. Therefore, these findings reflect the domain-

specific nature of working memory deficits (Peng & Fuchs, 2014). However, it does not necessarily imply that these domain general mechanisms cause DD. If that were the case, then it is likely we would see widespread impairments in multiple cognitive domains (Alloway, Gathercole, Kirkwood & Elliot, 2009; Price & Ansari, 2013).

1.3 Domain specific causal accounts of DD

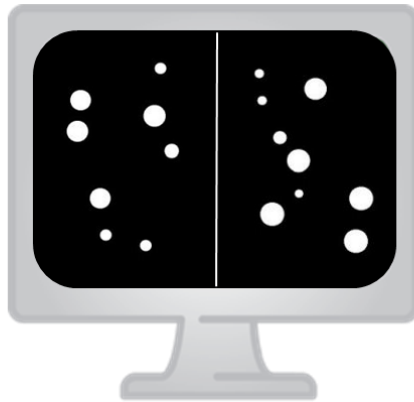
1.3.1 The 'Approximate Number System' (ANS)

In contrast to the search for domain-general deficits as proximal causes of DD, recent approaches have focused on low level, domain-specific numerical abilities as the potential root cause of DD. For example, it has been suggested that DD is caused by an impaired 'approximate number system' (ANS), a system responsible for manipulating and discriminating approximate numerical quantities (Dehaene, 1997; 2007; Wilson & Dehaene, 2007). The ANS is commonly assessed using a non-symbolic numerical discrimination task, where children are asked to choose the numerically larger dot array as quickly and accurately as they can without counting (see Figure 1.1). Response times and accuracy measures are used as indices for the precision of the ANS. As the numerical distance between the two dot arrays decrease, reaction time and error rates increase - this is referred to as the numerical distance effect (NDE) (Moyer & Landauer, 1967; Sekuler & Mierkiewicz, 1977). The numerical ratio effect (NRE), is a complementary effect that takes into account the numerical ratio between the compared dot arrays (e.g. ratio = small number/large number) – as the numerical ratio between the compared dot arrays increase (e.g. the largest ratio would be one, when the two dot arrays are equivalent), reaction time and error rates also increases (see Figure 1.2). The NDE and NRE have been explained by recourse to models of numerical representation which postulate that magnitudes are represented on a hypothetical internal mental number line where numerical values activate a Gaussian distribution, thus creating overlapping distributions of numbers that are separated by a relatively small numerical distance (see Figure 1.3) (Dehaene & Cohen, 1995; Dehaene, 1997; Gallistel & Gelman, 2000). Thus, these representations are characterized by scalar variability meaning that the signals encoding discrete representations are imprecise. According to Gallistel and Gelman

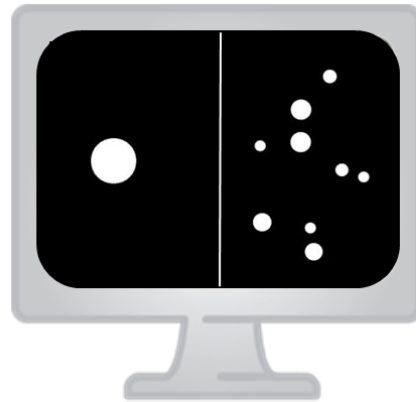
(2000), as magnitudes increase, the width of the distributions encoding them also increases meaning that representations of larger numerals are more imprecise than smaller magnitudes (see Figure 1.3a). In contrast, Dehaene proposed a logarithmic encoding of number, where the number line becomes more compressed and harder to discriminate between larger numerical magnitudes (Dehaene, 2003; Dehaene & Changeux 1993) (see Figure 1.3b). Distance and ratio effects are accounted for by both linear and logarithmic models of numerical magnitude representations and cannot be disentangled by behavioural observations alone.

Non-symbolic Numerical Discrimination

Close Distance (Large Ratio)



Far Distance (Small Ratio)



Symbolic Numerical Discrimination

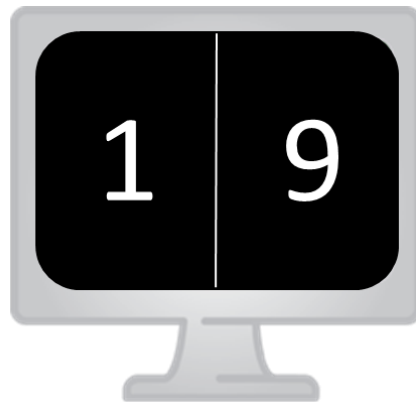
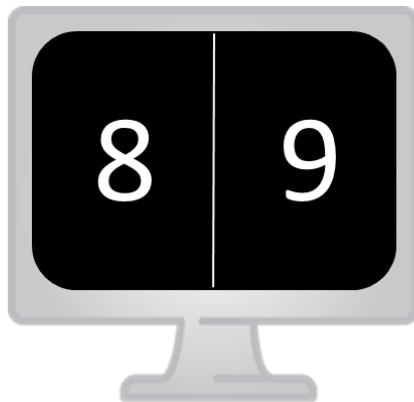


Figure 1.1. An example of the symbolic and non-symbolic numerical discrimination tasks.

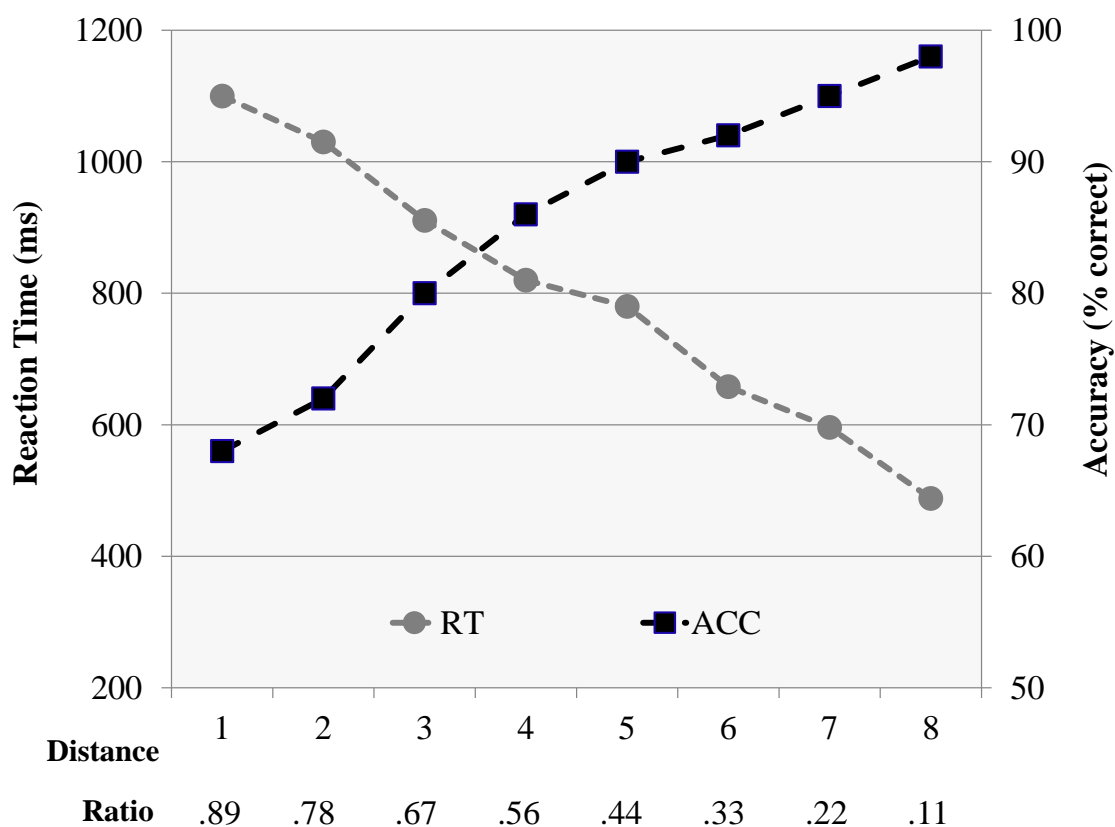


Figure 1.2: This figure illustrates a typical distance and ratio effect, whereby reaction time decreases and accuracy rates increase as a function of the numerical distance or ratio between the to-be-compared quantities. Distance and ratio is plotted on the x-axis, where ratio is calculated by dividing the smaller number by the larger number. The data plotted on this figure is hypothetical.

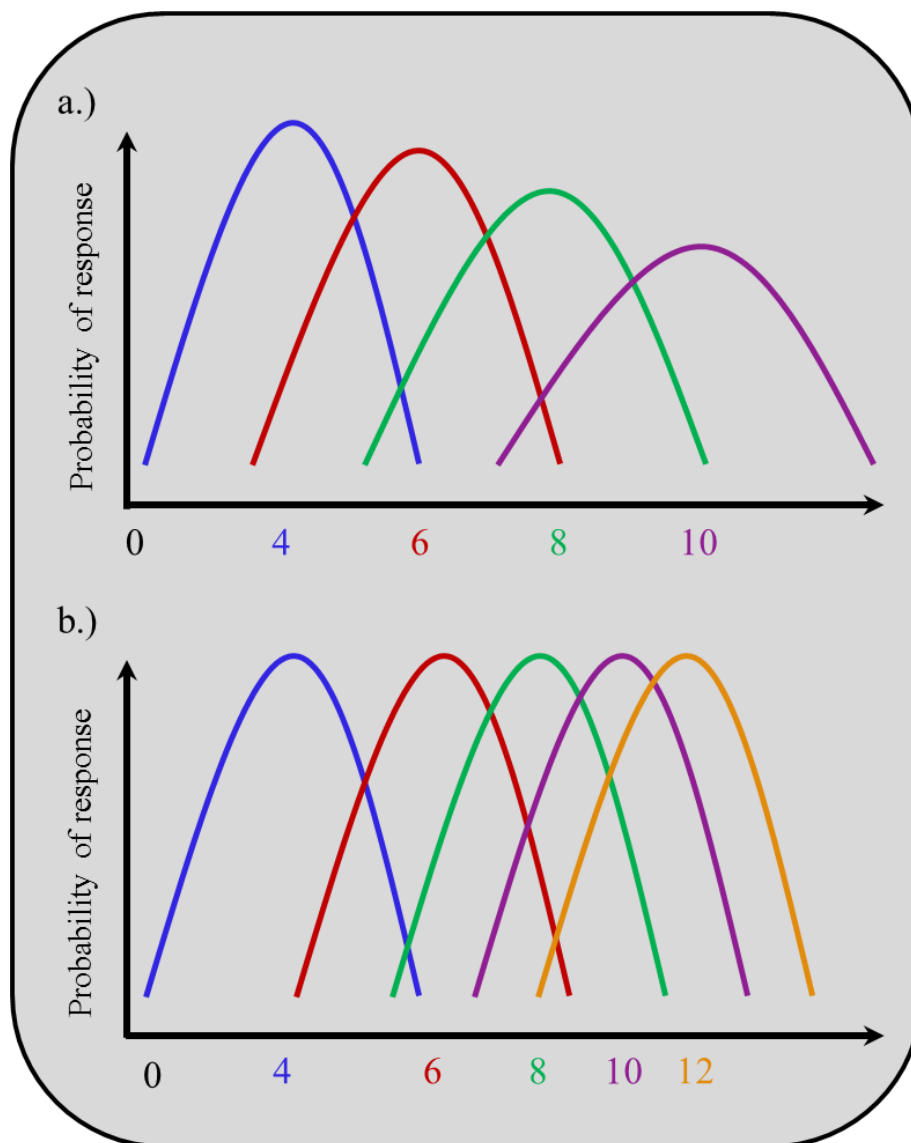


Figure 1.3: Illustrations of hypothetical mental number lines a.) An illustration of the ‘Scalar Variability’ model of the mental number line (Gallistel & Gelman, 2000). b.) An illustration of the ‘Logarithmic Compressed’ model of the mental number line (Dehaene, 2003).

Numerical distance/ratio effects, which are signatures of the ANS, are evident in animal species, as well as infants (Cantlon, Platt & Brannon, 2009; Roitman, Platt & Brannon, 2007; Star, Libertus & Brannon, 2013; Xu & Spelke, 2000), suggesting that

humans might have an innate ability to discriminate between non-symbolic numerical magnitudes. These findings lead to the proposal that the ANS is the phylogenetic and ontogenetic precursor to developing exact symbolic representations (e.g. number words and Arabic numerals), which enable children to carry out basic arithmetic problems and higher order mathematics (Piazza, 2010). It is hypothesized that semantic meaning of numerical symbols is acquired through the automatic mapping of symbols to approximate non-symbolic representations (Dehaene, 2007). Evidence supporting this notion comes from studies that demonstrate similar distance and ratio effects during a symbolic numerical discrimination task implying that symbols such as '6' evoke the same representations as their non-symbolic referents (Pinel et al., 1999; 2001; Piazza et al., 2004). Additionally, researchers have found that performance on non-symbolic numerical discrimination predicts individual differences in symbolic math achievement (Halberda et al., 2008); however, research supporting this finding is mixed (De Smedt et al., 2013, Holloway & Ansari, 2009; Sasanguie et al., 2013). More recently, research studies have found that the continuous properties of dot stimuli can influence the discrimination of dot arrays differently (Gebuis & Reynvoet, 2012; see chapter 4 for discussion).

Consequently, deficiencies in the ANS would lead to imprecise symbolic representations and poor arithmetic knowledge. The first evidence supporting the ANS core deficit theory in DD was obtained by Piazza and et al. (2010). These authors found that school-aged children with DD (age range 8 – 12 years) demonstrated severely impaired numerical acuity (as indexed by W 's, e.g. W is the standard deviation of the estimated Gaussian distribution of the internal representation of numerical magnitude, with a larger W indicating more imprecise representation of numerical magnitude – see chapter 4 for more detail description of W) on a non-symbolic numerical discrimination task in comparison to a group of typically developing peers. More specifically, children with DD obtained W scores equivalent to five-year-old typically developing (TD) children suggesting that their quantity representations are severely delayed. ANS acuity deficits in children with DD were further corroborated by a number of studies (Mazzocco, Feigenson & Halberda (2011); Mussolin, Meijas & Noel, 2010; Price et al., 2007). The finding of lower ANS acuity in individuals with DD has been largely taken to

reflect the impairment of the internal representation of numerical magnitude (i.e. a core representational deficit).

1.3.2 The 'Defective Number Module' hypothesis

In contrast to the ANS hypothesis, Butterworth and colleagues (1999, 2005) have proposed that DD is caused by a domain-specific impairment in the core capacity to represent and manipulate discrete (exact) rather than approximate numerical information known as the 'defective number module hypothesis' (Butterworth, 1999, 2005; Iuculano et al., 2008). The first evidence supporting this hypothesis came from a study conducted by Landerl and colleagues (2004) who found that children with DD demonstrated difficulties in processing numerical information, such as counting dots, accessing semantic (the numerical magnitude represented by Arabic numerals) and verbal numerical representations and reciting number sequences. However, in contrast to the domain general account, they found that children with DD were normal or above average on tasks involving phonological working memory and accessing non-numerical verbal information. The defective number module hypothesis assumes a deficit at the level of numerical magnitude representations regardless of the format of presentation. In other words, this hypothesis predicts that children with DD will be equally poor at judging which of two dot arrays is numerically larger (*e.g.* non-symbolic discrimination) as they will be at deciding whether the numeral 9 represents a numerical magnitude that is larger or smaller than the numerical magnitude referenced by numeral 7. Butterworth (2010) outlined several problems with the ANS hypothesis that can be accounted for by the defective number module hypothesis. First, he states that the ANS primarily involves the abstraction of approximate non-symbolic numerical representations, but it remains unclear how analogue magnitudes are used to add and subtract discrete quantities. And second, due to the approximate nature of analogue magnitudes, Butterworth states that adding and subtracting by one cannot be supported by the ANS. For example, when subtracting problems $2-1$ and $9-8$, the exact response to both of these problems is one. However, according to the properties approximate numerical representations, the overlap in representation distributions between nine and eight are greater than the overlap of two and one and therefore, it is less likely to produce the correct response of one.

1.3.3 The ‘Access deficit’ hypothesis

In contrast to both the ANS and ‘Defective Number Module’ hypotheses, Rousselle and Noel (2007) argue that children with DD do not have an impairment in a format-independent representation of numerical magnitude, but that their deficit lies in the connections between number symbols (Arabic digits, i.e. 3 or number words, i.e. three) and their respective meaning. They found that children with DD were slower and less accurate at discriminating between Arabic digits compared to children without DD; however, they failed to exhibit deficits when comparing non-symbolic quantities (i.e. arrays of dots). Similarly, De Smedt and Gilmore (2011) found that children with DD showed significant impairments on symbolic numerical tasks, while performance on non-symbolic numerical tasks remained intact compared to typical controls. These findings demonstrate that magnitude representation remains intact in children with DD; however, they have deficits in semantically encoding numerical symbols, also known as the ‘access deficit hypothesis’ – children with DD have more difficulties than children without DD in accessing the connection between numerical symbols and the quantities they represent (Rousselle & Noel, 2007).

Taken together, the behavioural evidence supporting all three theories is contradictory, making it difficult to make strong conclusions about the core deficits and manifestations leading to DD. With developmental dyscalculia being a relatively young field of research, these difficulties arise from the variability in selection criteria used to identify DD (see chapter 2 for an extensive discussion on selection criteria), as well as in the age groups used across a small body of studies. As a result, researchers are still uncovering the core competencies and underlying manifestations that define DD.

1.4 Numerical magnitude processing in the dyscalculic brain

To date, only a handful of neuroimaging studies have investigated the functional activation brain differences in children with pure DD compared to typically developing children. The following section will discuss what we know about the neural correlates of DD from functional neuroimaging studies. Studies investigating the integrity of

numerical representations in children with DD compared to typically developing controls have predominantly used the numerical discrimination task (both symbolic and non-symbolic) and have found differences between children with and without DD in the neural distance effect. A neural distance effect in the brain is evident when greater differences in activation are found during the discrimination of close distance pairs compared to far distance pairs (see Figure 1.2). Functional neuroimaging studies with typical adults have found that distance modulates activity in the bilateral intraparietal sulcus (IPS) (e.g. Holloway & Ansari, 2010; Pinel et al., 1999; Pinel, Dehaene, Riviere & LeBihan, 2001). Additionally, studies investigating the neural correlates of numerical magnitude processing in children and adults have found age related changes in the parietal cortex, whereby adults exhibit a greater effect of distance/ratio on IPS activation in comparison to children, suggesting an age related specialization of processing numerical magnitude (Ansari, Garcia, Lucas, Hamon, & Dhital, 2005; Ansari & Dhital, 2006). Furthermore, a larger ratio effect in the left IPS has been associated with higher arithmetic abilities (Bugden et al., 2012). Taken together, these findings suggest that a large neural distance effect in the parietal cortex is indicative of more precise neural representation of numerical magnitude.

Using a non-symbolic discrimination task (children select the numerically larger dot array from two sets of dots), researchers have found that children with DD did not show typical distance-related modulation of activation in the right intraparietal sulcus (IPS) (Price et al., 2007) (see Figure 1.4 for a map of brain locations). Children with DD showed atypical activation in the right IPS compared to typical controls. More specifically, children with DD demonstrated similar activation in the right IPS during both far and close distance trials, suggesting that their representation of quantity in this brain region may be less refined, whereas, a typical neural distance effect was found in age matched controls. In addition, the right IPS was recruited to a lesser extent in children with DD. Taken together; these findings demonstrated a parietal dysfunction may underlie reduced capability to process non-symbolic numerical magnitudes in children with DD. Atypical activation in the right IPS has also been implicated in processing symbolic numerical magnitudes. Mussolin and colleagues (2009) found that children with DD demonstrated weak modulation of the right IPS and the left superior

parietal lobule during a symbolic numerical discrimination task (e.g. the discrimination of Arabic numerals, such as 3 and 5). Additionally, Kaufmann et al., (2009) found atypical activation in bilateral regions of the IPS during non-symbolic numerical processing in nine-year-old children with DD. However, in contrast to previous findings, differences were driven by stronger activation in the left IPS and less pronounced deactivation in the right IPS. The majority of studies use arrays of dots or objects in a non-symbolic discrimination task; in the Kaufmann et al.'s study, children were instead asked to compare finger patterns (e.g. images of fingers that indicate a specific quantity). Therefore, it is difficult to interpret these conflicting findings.

In an attempt to ascertain whether these findings (and others) yield a consistent pattern of data, Kaufmann et al. (2011) conducted a meta-analysis synthesizing the functional neuroimaging data that have investigated the neuronal correlates of both symbolic and non-symbolic numerical magnitude processing in children with DD. They found that, when considering all available evidence and using meta-analytic tools, children with DD have distinct differences in activation patterns compared to typically developing controls. For example, control children demonstrated greater activation than children with DD in the left posterior IPS, right inferior parietal lobe, left paracentral frontal lobe, the superior frontal gyrus, the right middle frontal gyrus and the left fusiform gyrus. In contrast, DD participants showed greater activation in the left postcentral gyrus, superior frontal lobe, as well as the bilateral inferior parietal regions, more specifically in the right supramarginal gyrus and the left lateral IPS. The researchers interpreted these findings to indicate that children with DD have reduced specialization for processing numerical information in contrast to typically developing controls (Kaufmann et al., 2011). It is important to note that the meta-analysis only included three studies that investigated numerical processing abilities merging data from both symbolic and non-symbolic numerical discrimination in children with DD compared to typical controls. Thus any direct comparisons between the formats are difficult to make in view of the presently published neuroimaging data investigating differences between children with and without DD.

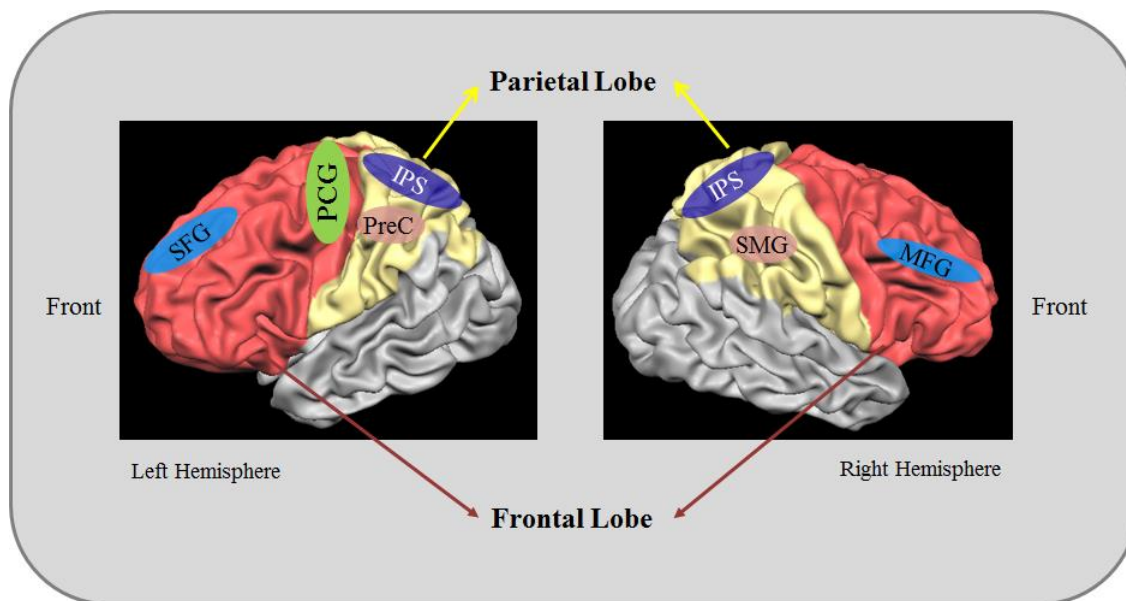


Figure 1.4: An illustration of the approximate locations of brain regions that have been associated with atypical activation during numerical magnitude processing tasks in children with DD. *Note.* SFG = superior frontal gyrus, PCG = precentral gyrus, PreC = Precuneus, IPS = intraparietal sulcus, SMG = supramarginal gyrus, MFG = middle frontal gyrus.

Taken together, these findings demonstrate atypical recruitment/organization of the intraparietal sulcus, a region known to process semantic representation of numerical magnitude (Butterworth, 1999; 2005; Dehaene, 1992; Dehane et al., 2003). To date, no study has investigated both symbolic and non-symbolic numerical processing abilities in the same sample of DD children, and as a result, there is presently no cognitive neuroscience evidence to support or refute the representational (i.e. ANS and defective number module) or access deficits hypotheses as the root mechanism underlying DD.

Very few neuroimaging studies have investigated the cognitive mechanisms that contribute to DD deficits and the current state of findings has yielded an inconsistent and difficult to interpret pattern of data (for a review see: Bugden & Ansari, 2014). Given the early stages of functional MRI research, it is nearly impossible to glean from the current set of data what neurobiology underlies cognitive deficits in children with DD. Future studies are required to understand the origins of numerical deficits in the brain, more

specifically, developmental cognitive neuroscience methods are necessary to pinpoint neural correlates of symbolic and non-symbolic processing difficulties. These difficulties cannot be fully explained by behavioural evidence – given that it is unclear whether symbolic processing deficits are caused by an underlying deficit in the ANS or in the decision level processes that involve accessing the semantic representation of numerical symbols leaving the actual representation intact. Therefore at the behavioural level, reaction time and accuracy measures are not informative for disentangling whether different mechanisms are contributing to the output of choosing the numerically larger number or dot array. However, functional imaging analysis can shed light on whether different brain regions that subserve different cognitive processes are recruited differently for format specific responses.

1.5 The neural correlates of visuo-spatial working memory deficits in children with DD

As is evident from the behavioural studies discussed above, children with DD often have working memory impairments and it has been hypothesized that such domain-general difficulties may be related to their arithmetic processing difficulties. As discussed above, behavioural studies have revealed deficiencies in visuo-spatial working memory, but not verbal working memory in children with DD; however, very few studies have investigated the neural correlates of visuo-spatial working memory in children with DD.

To explore whether children with and without DD exhibit different neuronal correlates of visuo-spatial working memory, Rotzer et al. (2009) conducted a functional neuroimaging study to explore brain activation differences during a visuo-spatial working memory task in children between 8-11 years with DD compared to typical peers. They found that both groups of children showed activation in brain networks including occipital and parietal regions during visuo-spatial working memory tasks. However, children with DD elicited weaker activation in the right IPS, right insula and the right inferior frontal gyrus during a visuo-spatial working memory paradigm adapted from the Corsi Block tapping task (Klingberg et al., 2002). During this task, participants were presented with a 4 x 4 grid on the computer screen and asked to remember the location of

three red dots presented sequentially in the grid. Following the presentation of the three dots, a red circle appeared on the grid, and participants had to indicate whether it appeared in the same location as the previously presented three dots. These findings give rise to the hypothesis that spatial working memory abilities provide the foundation for building a numerical representational system and therefore, deficits in spatial working memory may lead to numeracy (Price et al., 2007) and arithmetic impairments. This hypothesis was further substantiated by a study conducted by Dumontheil and Klingberg (2011), who found that activation in the left IPS during a visuo-spatial working memory task, relative to the rest of the brain, predicts arithmetic performance two years later in 6-16 year old participants. These findings are at odds with the suggestion that the IPS is involved in the domain-specific representation of numerical magnitude and instead, suggest that the IPS is associated with individual differences in visuo-spatial working memory. Activation differences in these regions among children with DD reflect the impairment of working memory circuitry rather than the domain-specific representation of numerical magnitude.

It is possible, of course, that these two accounts of atypical IPS functioning in DD are not mutually exclusive, but that there is an interaction of the brain circuits for working memory and numerical magnitude processing within the IPS over the course of developmental time. Future studies should investigate the neural correlates of both numerical magnitude processing and working memory within the same groups of children with and without DD to uncover more about the specific nature of the association between atypical activation of the IPS and DD in both working memory and basic number processing tasks.

1.6 The structural organization of the dyscalculic brain

Consistent with functional neuroimaging evidence, studies investigating the anatomical structure of the dyscalculic brain found grey matter volume differences in the right IPS, left superior parietal lobule, as well as frontal regions in comparison to typical controls (Rotzer et al., 2008; Rykhlevskaia et al., 2009). Additionally, diffusion tensor imaging (DTI) studies have found lower white matter integrity in tracts connecting parietal

regions to other areas of the brain (e.g. superior longitudinal fasciculus) in children with DD compared to typical controls (Kucian et al., 2013). White matter deficiency may be associated with poor myelination (a process whereby white matter tracts become ‘insulated’ over development allowing for progressively faster transmission of neuronal information) and atypical axonal development in children with DD. It is plausible that structural abnormalities in regions that are involved in the storage and manipulation of numerical information or the transmission of information within brain networks might underlie differences in brain activation found using fMRI. Future research is required to understand how coarse measures of brain structure are related to functional impairments in the brain.

1.7 Summary

It is well known that there is significantly less research on developmental impairments of math abilities compared to the burgeoning literature on reading impairments (Gersten, Clarke & Mazzocco, 2007), such as developmental dyslexia. This is true of behavioural studies but is even more striking when reviewing investigations into the neurobiology of developmental dyscalculia. Within the behavioural literature, there is little consensus supporting the causal theories² of DD. Specifically, it is unknown whether DD is caused by a specific ‘representational’ impairment in processing numerical magnitude or a specific ‘access deficit’ in processing the semantic meaning of numerical symbols.

As is clear from the review above, the small number of studies that have investigated the neural correlates of DD at the functional level do not allow for a clear-cut consensus concerning the brain correlates of DD. Thus, there currently does not exist a sufficient body of research to make definitive conclusions about the functional neuronal mechanisms underlying DD. Notwithstanding, both the studies of numerical magnitude processing and visuo-spatial working memory reviewed above have revealed that,

² The defective number module, the approximate number system and the access deficit hypotheses are referred to in the literature as well as in the thesis as being possible causal theories of DD; however, the present thesis does not test for a true cause.

consistent with predictions from the study of the brain circuitry in children and adults without DD, the parietal cortex shows functional and structural abnormalities in neuroimaging studies comparing children with and without DD. Furthermore, the above review shows that there is great variability in specifically which brain regions differ between TD and DD children across studies. Such variability might arise from a number of factors, which may not be mutually exclusive, such as a.) the different tasks used by different research groups, b.) their definitions of DD c.) the age groups studied.

Additionally, the heterogeneity in tasks and definitions used to identify DD contributes to the difficulties of capturing one core deficit (Fias, Menon & Szucs, 2013); it is therefore probable that various cognitive and neural mechanisms may contribute to different behavioural profiles of dyscalculia (Henik, Rubinsten & Ashkenazi, 2011; Karagiannakis, Baccaglioni-Frank & Papadatos, 2014; Skagerlun & Traff, 2014). Taking a multidisciplinary approach by including both behavioural and cognitive neuroscience methodology is optimal for furthering our conceptual understanding of DD. Exploring the functional composition of the dyscalculic brain will advance our knowledge of the source(s) of cognitive deficits at the neurobiological level in children who have DD.

1.8 The current project

In order to gain a better understanding of the variability across studies and to increase our understanding of the core cognitive and neurological deficits of DD, it is necessary to conduct studies in which children with DD are selected on the basis of strict classification criteria that are aligned with the recently published DSM-V criteria (APA, 2013).

Therefore, the aim of the current thesis was to conduct a thorough study investigating the core deficits of DD using both behavioral and neuroimaging methods. To address the limitations within the current literature surrounding the variability of selection criteria used across studies to identify children with DD, the studies presented in this thesis recruited a group of children who demonstrated persistent arithmetic deficits using standardized tests of speeded and un-speeded arithmetic abilities. This sampling method was used to reduce the probability of recruiting children who obtained below average performance on standardized tests due to educational or environmental influences (e.g.

poor educational environment, or influences of having a bad day). Therefore, introducing a stability criterion, consistent with DSM-V, reduces the number of false positive cases (Chapter 2). To shed light on causal accounts of DD (Chapter 3), multiple numerical processing tasks were administered to assess whether children with DD experience difficulties on both symbolic and non-symbolic processing tasks or whether they show format specific impairments. Researchers have begun to question whether non-symbolic numerical discrimination tasks are a pure measure of numerical magnitude representations or whether they involve visual perceptual or inhibitory control processes as a result of the construction of dot displays. Therefore, deficits in the ANS were further investigated in the persistent DD sample to explore whether performance is influenced by task construction (Chapter 4). And finally, the neural correlates of symbolic and non-symbolic magnitude processing were examined (Chapter 5).

1.8.1 Chapter 2 outline

The aim of chapter 2 is to describe the procedures and methods used to identify children with persistent DD and typically developing children, who were recruited from a previously conducted epidemiological study. In addition, I provide data to verify the validity of the persistency criterion. In this study, a large battery of cognitive standardized tasks were administered over two years to assess mathematical skills, reading, working memory as well as IQ performance in elementary school children. Performance across both testing sessions was assessed to identify children who demonstrated persistent deficits on measures of math achievement, as well as to identify children who demonstrated persistent typical performance on math, reading and IQ. First, I examined the utility of the stability criterion used to identify children with DD for the current thesis, in comparison to the children who would have been identified as DD based on one single time point, and typically developing controls using a paper and pencil version of the number comparison task. Second, an exploration of the domain general cognitive profiles was conducted in a subset of children with DD who participated in the following studies compared to their typically developing controls.

1.8.2 Chapter 3 outline

The aim of chapter 3 was to disentangle whether children with DD have a core numerical representational deficit, which supports the ‘number module hypothesis’ or whether they have impaired performance on tasks involving numerical symbols, which would support the ‘access deficit hypothesis’. During this phase of data collection, a large battery of numerical processing tasks such as symbolic and non-symbolic number comparison, number line estimation, size congruity comparison as well as an audio –visual matching tasks were administered to understand which theoretical hypothesis of DD best accounts for basic number processing deficits in the population of DD children examined in this thesis.

1.8.3 Chapter 4 outline

Studies commonly use the non-symbolic comparison task to measure the precision of one’s internal representation of numerical magnitude. However, recently, studies have demonstrated that visual parameters of the dot stimuli influence performance on the non-symbolic comparison task in typically developing children (Gilmore et al., 2013).

Therefore, the aim of chapter 4 is to investigate whether children with DD performed differently on trials in which the number of dots and their overall surface area (e.g. size of the dots) were either congruent or incongruent.

1.8.4 Chapter 5 outline

The neural correlates of symbolic and non-symbolic numerical magnitude processing will be examined in the same group of children who demonstrated persistent DD, compared to typical controls. This is the first study that explores both symbolic and non-symbolic numerical processing in the same sample of children. Additionally, a mixed format comparison was administered to examine the neural underpinnings of mapping between formats to directly assess the ‘access deficit hypothesis’. The aim of chapter 5 will to provide some neurological insight into the source of numerical deficits in children with DD.

1.9 References

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Chapter 2

2 Cognitive profiles of children with DD – Sample description

The overall aim of the present thesis is to provide a thorough examination of both the behavioural characteristics as well as the neurological correlates of numerical magnitude processing in children with developmental dyscalculia (DD). To address some of the inconsistencies that were discussed in the introduction surrounding the DD literature, a sample of children with DD who demonstrated stable low arithmetic achievement over multiple time points were recruited for the present thesis. The same sample of children was followed longitudinally in the studies conducted in the present thesis. Therefore, the aim of the current chapter is to describe the methodology employed in the present thesis, as well as to describe the sample criteria used to identify and recruit children with DD from a previously conducted longitudinal screening study.

For the first part of this chapter, a historical and current definitional framework used to identify children with general learning disabilities (LD) as well as developmental dyscalculia will be discussed to provide a rationale for which the criteria for identifying children with DD for the present thesis were derived. Additionally, the validity of the definitional criteria implemented in the current thesis was examined by using a paper and pencil numerical magnitude processing measure that was collected independently of assessments used to select children with DD. In the second part of this chapter, the cognitive profiles of a subset of children with persistent DD who are recruited for studies presented in chapters 3-5 . Children with persistent DD were compared to persistent typically developing controls on standardized tests of domain general cognitive performance such as reading, IQ and working memory. The present chapter provides an overall description of the composition of experimental and control groups recruited, and it provides a context for the studies conducted in subsequent chapters of the thesis.

2.1 Historical conceptual framework of learning disabilities (LD)

A longstanding and constant debate has continuously plagued the field of learning disabilities (LD) regarding the definition, classification, and identification of a *specific* LD (Kavale & Forness, 2000). Less controversy has surrounded the general conceptual basis of LD, which has historically revolved around the concept of “unexpected underachievement”; meaning that one must be struggling to read, write, or perform arithmetic operations in conditions where nothing is interfering with the learning process (APA, 2013). From a practical standpoint, an issue with this conceptual definition is that it only provides a framework for understanding LD without any precise operational criteria that researchers and clinicians can use to identify or diagnose children with a specific LD. Furthermore, this conceptual definition identifies LD by using exclusion criteria to rule out extraneous factors that cause low achievement, such as other psychological disorders that are impacting the ability to learn (e.g. intellectual or sensory disorders), or contextual/environmental factors (e.g. economic disadvantage, language status, or poor instruction). Using exclusion criteria to identify children with LD is not informative for understanding the specific nature of a child’s learning difficulties. The lack of specificity provided in a conceptual framework does not provide criteria of symptoms for clinicians to identify an individual as having specific learning disorder in a given domain. Without a specific operational definition, researchers develop their own criteria to identify children with LD, making it difficult for different researchers to describe and compare a phenotype for a group of children with LD with the same underlying etiology. Therefore, researchers and clinicians are struggling to attain consensus on the operational definition of LD. Reaching a consensus for defining LD is not only important for the identification and diagnosis of children with LD, but research results describing characteristics of a specific LD depend on the criteria we use to define it. The results of any given study significantly depend on the underlying classification framework. Vagueness of the operational definitions used to identify LD in general, leads to barriers in defining DD.

2.2 Operational definitions of LD

2.2.1 IQ-achievement discrepancy model.

Given the lack of specificity in the conceptual definition of LD, the field has operationalized “unexpected underachievement” in different ways. The practice of using IQ tests to assess children’s “expected” ability or potential to learn in a given academic context dates back to the early 1960’s when Kirk and Bateman (1962) first introduced the concept of IQ-achievement discrepancy. It was soon adopted as a common approach to identifying children with LD in schools, as well as a criterion for defining LD in empirical research. The IQ-Achievement discrepancy model is commonly used to identify children with LD by assessing whether there is a significant difference between a student’s score on a general IQ test and an obtained score on a specific achievement measure (see Figure 2.1). IQ is a limited predictor of academic achievement, even though it was originally developed to predict whether children would succeed in school (Ceci, 1991). The discrepancy method calls for concern when identifying students with learning disabilities and has often been referred to as the “wait to fail” approach (Dunn, 2010; Lyon et al., 2001). Before the allocation of a diagnosis, a child’s achievement level must be sufficiently low to achieve discrepancy; children who are failing to learn to read, write, and do math between Kindergarten and Grade 2 do not receive special education services until they complete IQ or achievement tests in the third grade. Therefore, it does not allow for an early identification of difficulties.

The use of IQ in assessing learning disabilities has been widely criticized among researchers and educators, and there is presently a large amount of research discrediting its validity (Fletcher et al., 2005; Siegel, 1989). Using IQ-Achievement discrepancy model has the tendency to over-identify children who have average achievement levels, but high IQ. Ideally children with low achievement and typical IQ would be identified as having a learning disability. Furthermore, children with low achievement and low IQ would be omitted from receiving a diagnosis resulting in exclusion from beneficial special education services. Research exploring the definitional criteria in children with dyslexia has found that children with low achievement and low IQ have similar cognitive

abilities on measures related to reading as children identified as dyslexic using the IQ-discrepancy model. These findings question the validity of using IQ to identify children with dyslexia since it could be more harmful than pragmatic (Fletcher et al., 1992; Shaywitz, Fletcher, Hoahan & Shaywitz, 1992; Stuebing et al., 2002). Moreover, evidence from brain imaging studies on children with dyslexia has not revealed any significant brain activation differences between children who are identified as dyslexic based on IQ-discrepancy model, and those who had both low IQ and low reading scores. Specifically, Tanaka and colleagues (2011) showed that brain activation patterns during the completion of reading real words and pseudowords did not differentiate between children with reading disabilities identified using the IQ-achievement discrepancy model and non-discrepant IQ scores. Taken together, these findings provide converging neurological and behavioural evidence that poor readers experience similar reading difficulties in relation to phonological processing regardless of IQ.

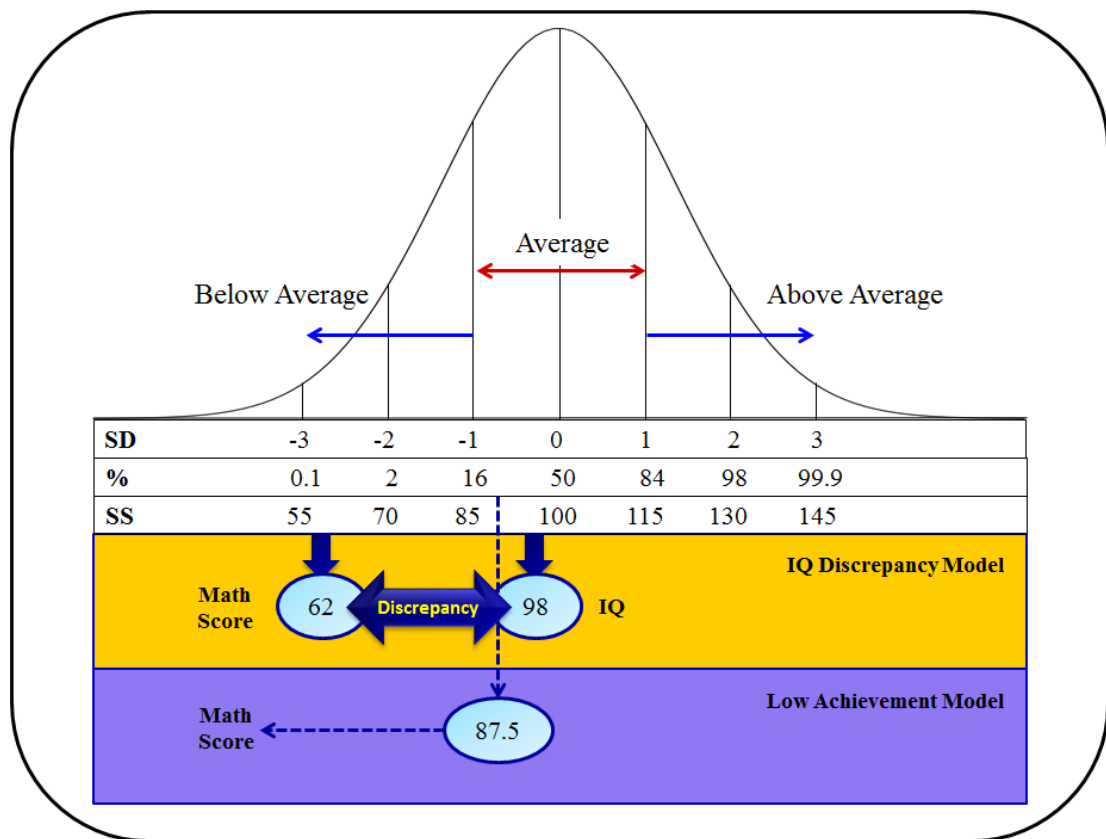


Figure 2.1: An illustration of the IQ discrepancy and the low achievement models of identifying children with a learning disability.

2.2.2 Cut-off criteria.

An alternate approach to identifying children with LD, involves identifying children based on absolute low achievement in the absence of considering their IQ (see Figure 2.1) (Siegel, 1992). However, other problems arise from using low achievement models of LD. For example, selecting an arbitrary cut off, such as using more stringent criteria, can result in type II error. Selecting children who demonstrate more pervasive deficits in the specific academic domain and will result in excluding children with less severe difficulties, but who still have a specific learning disability. In contrast, using a more liberal threshold can increase the probability of making a Type I error. Therefore, children who do not have a specific LD can be mistakenly identified as having the disorder. Increases in errors can lead inconsistent and unstable diagnosis of LD.

Additionally, LD represents a distinct group of children's whose low achievement is unexpected. Therefore, identifying children based solely on low achievement without considering other factors essentially equates children with LD to children who are low achieving (e.g. expected low achievers due to environmental or social reasons). Accordingly, it is necessary to rule out other causes for low achievement. Despite evidence demonstrating that there are no meaningful differences between LD groups assigned based on IQ-discrepancy compared to low achievers regardless of IQ, it remains problematic to identify LD using a low performance criterion since poor performance can be attributed to emotional disturbances, economic disadvantages, or inadequate instruction (Lyon et al., 2001). Although identifying children based solely on low achievement remains problematic, adding an IQ measure does not increase the validity of the low achievement model of identification (Fletcher, Lyon, Fuchs and Barnes, 2007).

2.3 Challenges to operationally defining developmental dyscalculia

The challenges researchers and clinicians face surrounding the definitional criteria of LD are especially problematic in the field of research on DD. Relative to the widespread

research attention devoted to dyslexia, less is understood about the underlying deficits of DD. There is general consensus on the underlying core deficits of dyslexia, and this knowledge has led to an empirically derived definition of dyslexia (Mazzocco, 2007). Murphy et al. (2007) conducted a literature review on mathematical learning disabilities and found that only 231 articles were published between the years 1985 and 2006 in comparison to 1077 articles published during those same years on dyslexia. Against this background, it is not surprising that numerical cognition researchers are trailing behind reading researchers in the pursuit of understanding the core deficits of DD.

Developmental dyscalculia was first defined in 1970 in a seminal paper published by Kosc as a math-specific, genetically determined learning disorder in children with typical IQ. “Developmental dyscalculia is a structural disorder of mathematical abilities which has its origin in genetic or congenital disorder of those parts of the brain that are the direct anatomico-physiological substrate of the maturation of the mathematical abilities adequate to age, without a simultaneous disorder of general mental functions” (p. 192). This definition is consistent with the conceptual framework of LD, and has remained an accepted method for identification of children with DD in subsequent years. Although researchers are making progress in understanding the core deficits of DD, there has been no consensus for defining DD, leading to little advancement in amending criteria used to identify children with DD. Therefore, investigators have developed their own criteria resulting in some researchers adopting the low achievement model to identify DD, and using a more strict criterion, such as math achievement scores below the 10th percentile (Mazzocco & Myers, 2003; Murphy, Mazzocco, Hanich & Early, 2007; Mazzocco, Feigenson, Halberda, 2011), whereas others use more lenient cut off criteria (20-35th percentile) (Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Hanich, Jordan, Kaplan & Dick, 2001) (see Table 1 for a summary of different definitional criteria). Using a liberal cut-off criterion is commonly used within the math learning disability literature, allowing researchers to study a larger sample of children that struggle with math, which otherwise would not be possible using a strict criterion (Mazzocco, 2007). Adopting a more lenient threshold to identify children with DD would lead to the study of both children who have severe DD and children with less severe math difficulties; this practice remains problematic for drawing conclusions about either group.

To address these limitations, several investigations have compared children who were identified as math learning disabled using a strict criterion (e.g. < 10th percentile) to children who demonstrated low math achievement scores (11-35th percentile) and typically developing children (Geary et al., 2007; Murphy et al., 2007). Specifically, Murphy, Mazzocco, Hanich and Early (2007) conducted a longitudinal study investigating whether using different classification methods resulted in divergent cognitive profiles specifically in reading, visual spatial ability, and working memory in early elementary school children. Their findings demonstrated qualitative differences between children identified as DD using a more stringent criteria (< 10th percentile) compared to children with DD who were identified using a lenient cut off criterion (> 11th & < 25th percentile). Specifically, they found that children with DD identified using more stringent criteria demonstrated severely impaired math performance than children in the 11-25th percentile group during initial assessment. Children with DD in the 11-25 group showed greater growth trajectories in math as well as visual-spatial ability in contrast to the DD < 10 group, who did not improve. Performance on a working memory task as well as rapid naming tasks also differentiated between children in the DD < 10 group and the DD 11-25 group (with the DD < 10 group showing worse performance). However, these differences in performance were not consistent over time. It remains unclear from this study whether specific numerical skills (e.g. numerical magnitude processing) differentiate between groups who were identified using stringent criteria.

2.3.1 IQ–discrepancy criteria and DD

There is little empirical evidence to support the use of discrepancy models in defining LD, specifically in the reading literature (described above); however, using various IQ cut off scores to identify samples of DD remains commonly employed in the mathematical literature (see Table 1). Given the wealth of evidence suggesting that implementing the IQ discrepancy criteria does not identify a qualitatively different reading disabled sample, it is expected that IQ would not be useful in identifying children with DD (Brankaer et al., 2014; Mazzocco & Myers, 2003). Consistently, Brankaer, Ghesquière & De Smedt (2014) examined whether there were qualitative differences on a numerical processing measure between children identified as having DD as a function of

whether they had low or high IQ scores. The authors found that numerical magnitude processing (e.g. symbolic and non-symbolic numerical discrimination) impairments were found in both children whose IQ was discrepant with math difficulties (low math, average IQ) and children who had non discrepant math difficulties (Low math, below-average IQ) compared to a typical control group. There were no numerical magnitude processing differences between children with non-discrepant math difficulties and children with discrepant math difficulties. These findings suggest that impairments in numerical magnitude processing in DD occur independently from IQ. Although IQ has not been effective in identifying children with reading disabilities, this study is the first piece of evidence to suggest that foundational competencies that are hypothesized to be causally related to DD do not differ between children with DD with low or high IQ. These findings suggest that IQ scores are impractical for identifying children with DD. A modern approach to identifying children who have an intellectual disability involves removing children with specific learning disorders who obtain IQ scores below 70, rather than relying on using IQ-discrepancy methods.

2.3.2 Standardized assessment for identification of DD

It is important to recognize that mathematical learning disorders can occur in one or many processes related to math achievement (e.g. geometry, number sense, arithmetic, algebra, and measurement) (Geary et al., 2004), and that symptoms may not fully manifest until specific demands of those skills exceed the individual's limited capacities (APA, 2013). In addition to considering how various definitional criteria contribute to the challenges of uncovering the core deficits associated with DD, the standardized tests that measure different mathematical concepts also contribute to difficulties in identifying and comparing children with DD across studies. Children with DD are often identified as a function of the specific skills that are measured in the standardized tests used to assess math achievement. For example, children are often selected based on below average performance on standardized tests of arithmetic abilities (either tests measuring calculation, fluency, or both), but also, mathematical reasoning, and word problem solving. These standardized tests generally cover a wide range of mathematical skills, and often capture other abilities that are not specific to mathematics, such as verbal and

spatial skills. Therefore globalized measures are diverse and vary across studies, adding to the difficulty of pinpointing specific deficits of DD.

Table 2.1: Examples of definitional criteria used to identify children with DD

Studies	Diagnostic Criteria	Non-mathematical inclusion & exclusion Criteria	Terminology
D'Amico & Passolunghi, 2009	< 30th Percentile AC-MT standardized Math test (Cornoldi, Lucangeli & Bellina, 2002)	Typical performance on Vocabulary, Non-word reading, reading comprehension, Non-verbal abilities	Arithmetic learning disabilities
DeSmedt & Gilmore 2011	< 16th Percentile standardized achievement test of mathematics, Math Up to 10 (Dudal, 1999)		Math learning disabilities
Geary, Hoard, Byrd-Craven & DeSoto, 2004	< 30th Percentile on Math Reasoning subtest (WIAT, 1992)	80<IQ<120, children with a combination of low reading <30th % and above 30th on math were excluded	Math learning disabilities
Hanich, Jordan, Kaplan, & Dick, 2001; Jordan, Hanich & Kaplan, 2003	Composite scores \leq 35th percentile on Calculation & Applied Problem subtests (WJTEA, 1990)	10 point discrepancy between Math & IQ	Math Difficulties
Landerl et al., 2004	3SD below control group mean on arithmetic performance		Dyscalculia
Lindsay et al., 2001	15 point difference between FSIQ and arithmetic score		Dyscalculia
Mazzocco & Myers, 2003; Mazzocco et al., 2013; Mazzocco, Feigenson & Halberda, 2011	< 10th Percentile on WJ-R Calculation subtest		Math learning disabilities
McLean & Hitch, 1999	Bottom 25th percentile of raw scores on Graded Arithmetic Mathematics Test (Vernon & Miller, 1976)	< 25th & > 75th Percentile on Primary Reading Test (France, 1979)	Arithmetic Difficulties
Mussolin, Mejias & Noel, 2010	< 15th percentile on Multiplication Fluency Test (based on a distribution of 187 children)	FSIQ > 85	Dyscalculia
Passolunghi & Mammarella, 2012	< 25th Percentile on Italian Standardized Math Test (Amoretti et al., 1994)	Typical Verbal IQ	Math learning disabilities
Rousselle & Noel, 2007	< 15th Percentile a battery of mathematics subtests (based on a distribution of 427 children)	< 15th Percentile in reading	Math disability
Shalev, Manor, Auerbach & Gross-Tsur, 1998; Gross-Tsur, Manor, & Shalev, 1996	Performance at least 2 years below grade level of control group on arithmetic battery based on McCloskey et al., 1985	Full IQ > 80	Dyscalculia
Szucs et al., 2013	< 16th Percentile on standardized MaLT and WIAT-II UK numerical operations	WISC Vocabulary, WIAT Word Reading, WIAT Pseudoword reading, Raven WISC & Block Design < 1 SD & > 1SD from the mean	Dyscalculia

Note. WJTEA = Woodcock Johnson Tests of Educational Achievement; WIAT = Wechsler Individual Achievement Test, Wechsler, 1992; WIAT-II = Wechsler Individual Achievement Test, Wechsler, 2005. Criteria are specific to Math Learning Disability/Developmental Dyscalculia groups not subgroups that include math and reading comorbid groups.

2.3.3 Persistency criteria

The approaches to definition and diagnosis of DD discussed thus far are primarily based on assessing children at one single time point. Reliability issues arise from identifying children with DD based on arbitrary cut off points, especially considering the measurement error associated with using standardized tests of achievement at a single time point (Fletcher, Steubing Morris & Lyon, 2013). Therefore incorporating a stability criterion is an alternate approach to identifying children with DD. Mathematical skills have been shown to vary throughout development (Geary et al., 2000; Mazzocco & Myers, 2003), therefore, an individual may or may not continue to meet the specific criteria for DD over time. The fact that math difficulties are not stable over time suggests that children might outgrow any developmental delays, and would consequently not have a mathematical learning disability (Geary et al., 2000). To date, there is no evidence to support a specific set of criteria that can reliably identify a child with DD at one time point. As a result, assigning a diagnosis based on one time point of data is not a valid and reliable indicator of true mathematical ability. Shalev and colleagues (1998) were the first to conduct a longitudinal study to examine the persistence of DD in eighth grade students who were identified as having DD in fifth grade. They found that only 47% of children who were first identified as having DD in Grade 5 continued to have persistent DD in Grade 8 (scored below the 5th percentile on math achievement measure – using norms from control group). Similarly, Mazzocco and Myers (2003) recruited children in kindergarten and followed them longitudinally for four years. Persistent DD was defined as obtaining below 10th percentile during two of the four years of study. They found that 63% of the children who met the criterion for DD (< 10th percentile) were identified as having a persistent math deficit. Longitudinal studies assessing the cognitive profiles of children with DD provide a unique contribution to our understanding of the developmental trajectories of arithmetic deficits (Mazzocco & Rasanen, 2013).

2.4 The present selection criteria

To address the limitations surrounding the definitional criteria of DD, a stability criterion was included in the sampling method used in the current thesis. Mathematical skills have

been shown to vary over development; therefore, assigning a DD diagnosis based on multiple time points reduces the number of false positives and false negatives and increases our confidence that the sample of children recruited have a true impairment in arithmetic performance.

Children with DD who demonstrated persistent impairments on standardized measures of arithmetic achievement were recruited from a previously conducted epidemiological study. Children who exhibited persistent typical performance on math achievement in addition to reading and working memory were recruited as a control group. Children with DD were selected based on performance below one standard deviation from the normed mean on two measures of arithmetic performance. Considering the lack of evidence validating IQ-discrepancy models (Dunn, 2010; Siegel, 1999), the usage of IQ-discrepancy was abandoned for the purposes of examining children with severe persistent difficulties in arithmetic. However, children with DD obtained stable IQ scores greater than 70 to ensure none of the children had other intellectual disabilities (APA, 2013). This method of sampling also removes the possibility of educational and environmental influences that may affect math achievement measures taken at one time point. The goal of this chapter is to describe the epidemiological study, as well as characterize the sampling method used to identify children with DD and typically developing controls for the present thesis.

2.4.1 Overview of selection criteria validation methods

The current chapter presents two methods for validating the selection criteria used to identify children with DD. In the first method, performance on a paper and pencil numerical discrimination task, also referred to as the Numeracy Screener, was compared among children who demonstrated persistent arithmetic deficits, those who demonstrated inconsistent arithmetic performance, and typically developing children. The Numeracy Screener was used to verify the efficacy of including a stability criterion to identify children with DD for the present studies. The numerical discrimination paper and pencil tool is an independent assessment of both symbolic and non-symbolic numerical magnitude processing skills. This measure was not used in the identification of children

with persistent DD, but measures numerical processing skills that are thought to be core deficits underlying DD. The aim of these analyses were not to investigate differences in non-symbolic and symbolic numerical processing skills in children with persistent DD (This question is investigated in chapter 3), but to use the Numeracy Screener as a global measure of numerical processing ability and to examine whether there were differences in

Second, differences in cognitive profiles were examined between children with stable low arithmetic performance and children with stable typical performance who were recruited for the subsequent studies reported in chapter's 3-5 of the thesis. Standardized tests were administered to participants over three years assessing verbal and visuo-spatial working memory, reading, IQ, as well as math calculation and math fluency skills. Average performance across time was examined between groups to characterize children with DD, as well as typically developing controls. Very few studies have investigated the cognitive profiles of children who have demonstrated persistent impairments on standardized tests of math achievement and who are selected solely based on arithmetic achievement measures; therefore, the aim of the second part of this chapter is to provide an overall description of the cognitive skills associated with recruiting children with stable low arithmetic skills.

2.5 Methods

2.5.1 Recruitment strategy

Participants from the current study were recruited from a longitudinal screening study conducted in schools across the local school board (Thames Valley District School Board) and surrounding area (see Archibald, Cardy, Joanisse & Ansari, 2013). During the fall of 2009, 1277 children from Senior Kindergarten - Grade 4 classrooms were screened on a sentence recall test, a Math Fluency measure, and a reading efficiency test. Children who either scored below one standard deviation of the mean on any one of the screening tasks (low performers), or who obtained scores within one standard deviation of the mean on all screening tasks (typical performers) were recruited for the follow-up studies. From the epidemiological sample, a selected group of 384 children were

followed longitudinally in the spring of 2010 and 2011 (see Figure 2.2). An extensive battery of standardized tests of math, reading, working memory, and IQ were administered during each testing session (see materials section for a complete description of standardized measures) (see Figure 2.2 for a time line of testing sessions and measures administered). Additionally, a paper and pencil version of a numerical comparison task was administered during testing session three. From the sample of children who were followed longitudinally, participants who had a known, neurological disorder, an uncorrected auditory impairment, a full scale IQ score below 70, or had not completed the numerical comparison paper and pencil task were removed from the study leaving the final sample of 233 participants.

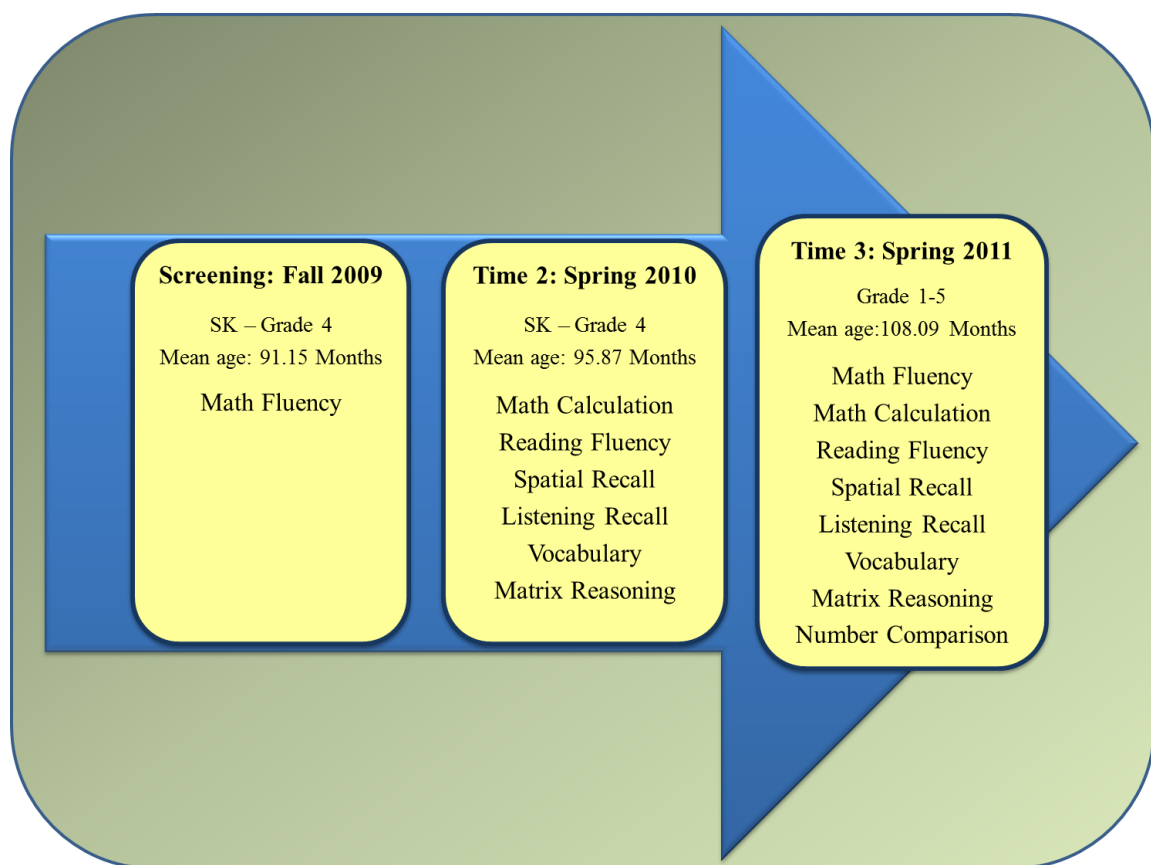


Figure 2.2: The longitudinal time line illustrating when the standardized tests of cognitive performance were administered for each testing session of the epidemiological study. The Vocabulary and Matrix Reasoning subtests were used to calculate a full scale IQ score.

2.5.2 Participants: Selection criteria of children recruited for the present thesis

2.5.2.1 Persistent DD selection criteria

Children were identified as having low arithmetic achievement during screening if they had a score equal to or below one standard deviation of the normed average, which is a standard score equal or less than 85, on the Math Fluency subtest (speeded measure of arithmetic performance – see section 2.5.3.1.1 for more details) of the Woodcock Johnson Standardized Tests of Achievement (Woodcock, McGrew, & Mather, 2001). Children were classified as having developmental dyscalculia if they continued to meet these criteria, in addition to achieving at a level one standard deviation below the mean on Math Calculation subtest (non-speeded measure of arithmetic performance – see section 2.5.3.1.1 for more details) from the Woodcock Johnson Standardized Tests of Achievement during the following testing sessions (see Figure 2.3 for the total number of children who met the criteria across testing sessions). In accordance with DSM-V (APA, 2013) criteria for DD, all children demonstrated stable standardized IQ scores greater than 70. This ensured that arithmetic deficits were not caused by intellectual impairments. There were 32 children (24 male, 8 female) who met the stability criterion of having DD (Age range: 87 – 136 months (7-11 years), Mean age: 116.78 (9.73 years), $SD = 13.96$ (1.16 years)) (see Figure 2.3).

2.5.2.2 Inconsistent DD selection criteria

Children who no longer met the criteria for DD (e.g. obtaining a standard score above 85 on either math fluency or math calculation subtests) or TD (e.g. obtaining a standard score below 85 on either Math Fluency or Math Calculation subtests) during the second and/or third testing sessions, were identified as demonstrating inconsistent math performance over time (see Figure 2.3 for total number of children who no longer met the criteria for developmental dyscalculia or typically development). To select a comparison group of inconsistent math performers to evaluate the efficacy of our DD selection

criteria, children with inconsistent DD were operationally defined as meeting the criteria during 50% of the testing sessions. More specifically, children were identified as having inconsistent DD if they obtained one standard deviation below the mean on Math Fluency and a Math Calculation subtest two out of the four times (twice each) they were administered. Using other definitional criteria, these children could have been selected as having DD if they were classified based on one testing session alone. There were 22 children (12 male, 10 female) who met the criteria for being inconsistent DD (Age range: 93 – 136 months (7-11 years), Mean age: 110.73 (9.23 years), $SD = 12.40$ (1.03 years)).

2.5.2.3 Typically developing (TD) selection criteria

Children were identified as being typically developing (i.e. typical on arithmetic performance) if they obtained a standard score that was within the typical range or above (e.g. greater than a standard score of 85) on math fluency subtest of the Woodcock Johnson Test of Achievement during the screening testing session. To continue to meet the typically developing criteria, children needed to obtain a standard score above 85 during subsequent testing sessions on both Math Fluency and Math Calculation subtests (Woodcock, McGrew, & Mather, 2001). Consistent with previous group selection criteria, all typically developing children were required to have IQ scores above 70 during all testing sessions. There were 106 typically developing children who met these criteria; however, 32 children were selected to match age and gender as best as possible to the DD and inconsistent DD samples. From the 32 typically developing children, there were 19 male, and 13 female participants (Age range: 90-136 months (7-11 years), Mean age: 113.97 (9.38 years), $SD = 12.48$ (1.12 years)) (see Figure 2.3).

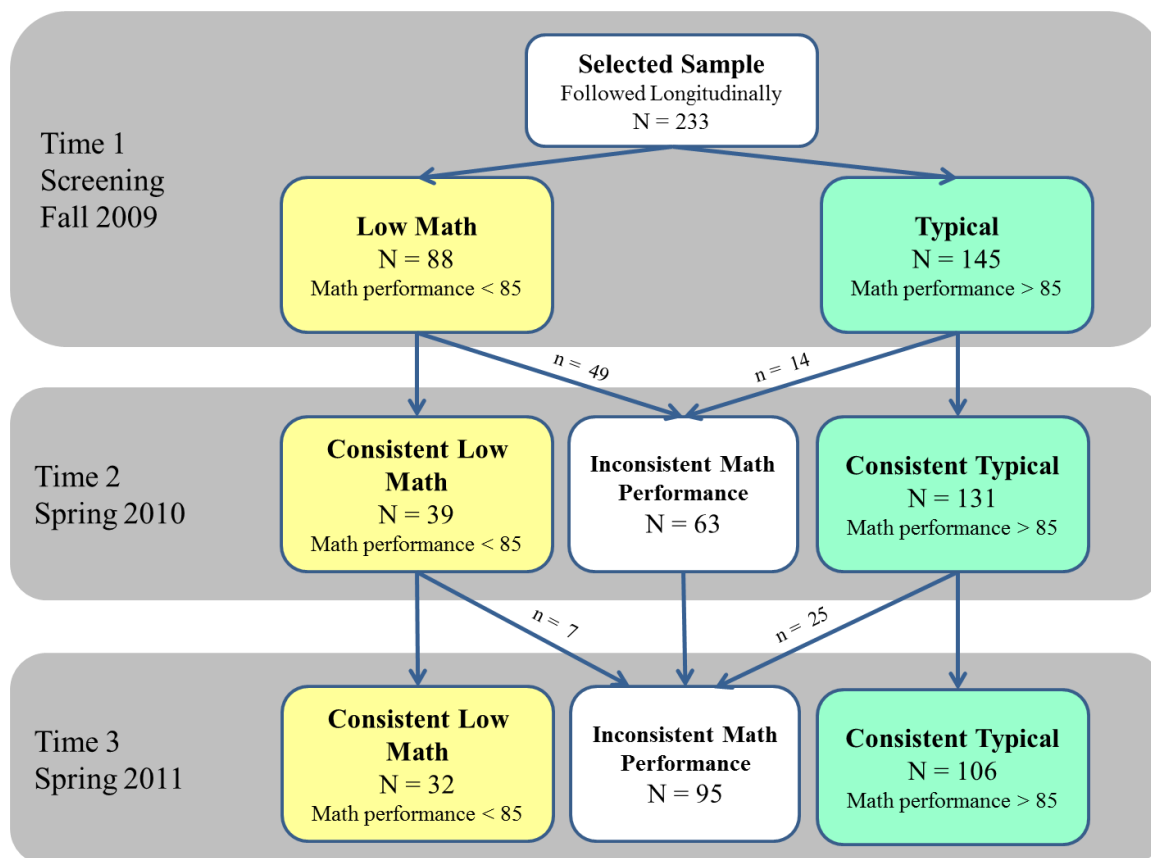


Figure 2.3: Frequency chart demonstrating how many children met the criteria for Dyscalculia during each testing session. Math performance included scores on both Math Fluency and Math Calculation subtests independently, meaning that children met the specific criteria on both subtests.

2.5.3 Assessments

2.5.3.1 Standardized tests of cognitive performance

2.5.3.1.1 Mathematical skills.

The Math Calculation and Math Fluency subtests from the Woodcock Johnson standardized tests of achievement (Woodcock, McGrew, & Mather, 2001) were administered to each participant. First, the Math Calculation subtest was administered to assess basic arithmetic skills. This test begins with simple addition and subtraction

problems and progressively becomes more difficult. Participants had no time constraints and were asked to inform the experimenter when he or she was finished. Second, the Math Fluency subtest assessed participants' ability to solve as many simple arithmetic problems as possible in three minutes without making any errors (see Woodcock et al., 2001 for a detailed review of the reliability analyses conducted for the subtests administered from the Woodcock Johnson Standardized Tests of Achievement)

2.5.3.1.2 Reading skills.

The Reading Fluency subtest from the Woodcock Johnson-III (Woodcock, McGrew, & Mather, 2001) was administered to measure participants' ability to quickly read simple sentences and answer yes/no questions about each sentence. Participants were asked to read as many sentences as possible in three minutes.

2.5.3.1.3 Working memory skills.

Two subtests from the Automated Working Memory Assessment (AWMA; Alloway, 2007) were administered to assess visuo-spatial and verbal working memory abilities. The Spatial Recall subtest required participants to mentally rotate shapes while maintaining and remembering the location of a red dot. The Listening Recall subtest required participants to process the veracity of a simple sentence while remembering the final word. Both subtests progressively increased in difficulty as participants had to hold more items in memory.

2.5.3.1.4 Intelligence.

Children completed two subtests from the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1995). The Vocabulary subtest was administered to assess verbal intelligence. Children are asked to provide definitions for words that became increasingly more difficult. Children reached ceiling when they could not produce the correct definitions for three consecutive words. The internal consistency split-half reliability coefficient for the Vocabulary subtest across all ages in the child sample is .91. The test-re-test reliability coefficient across all ages in the child sample is .90.

The Matrix Reasoning subtest was administered to measure non-verbal intelligence where children had to view a series of incomplete matrices and they were asked to select an image to complete the presented pattern. The internal consistency split-half reliability coefficient for the Matrix Reasoning subtest across all ages in the child sample is .87. The test re-test reliability correlation coefficient for the Matrix Reasoning subtest across all children in the sample is .79. A full scale IQ score was calculated from both verbal and non-verbal subtests of IQ. The split half reliability correlation coefficient for the FSIQ (full scale IQ) score using the Vocabulary and Matrix Reasoning subtests is .93. The test re-test reliability correlation coefficient for the FSIQ using the two subtests is .89.

2.5.3.2 Paper and pencil symbolic and non-symbolic numerical discrimination.

Participants were presented with the classical numerical discrimination task in booklet form (the Numeracy Screener), where they were asked to put a line through the numerically larger quantity as fast and as accurately as they could (www.numeracyscreener.org) (Nosworthy, Bugden, Archibald, Evans, & Ansari, 2013). Stimuli were presented in either symbolic (e.g. Arabic numerals) or non-symbolic (e.g. arrays of dots) formats ranging from 1-9. The ratio (small number/ larger number) between the pairs of numbers were manipulated so that easier pairs (e.g. 1 vs. 9 = ratio: .11) were presented first to keep participants motivated. Items became progressively more difficult as the ratio between pairs increased (e.g. 8 vs 9 = ratio: .89). Children had one minute to complete as many items as possible on each of the symbolic and non-symbolic conditions of the Numeracy Screener. For the non-symbolic task, children were instructed to not count the dots by making their best guess at which array of dots was larger. The non-symbolic dot stimuli were controlled for area and density. More specifically, half of the dot stimuli trials were controlled for total area, meaning that the area of dot stimuli were equal within the pair. The other half of the dot stimuli were controlled for total perimeter meaning that the perimeters of the two dot arrays in each pair were matched. Both area controlled and perimeter controlled stimuli were intermixed and presented in random order to reduce the likelihood that children rely on

visual perceptual cues to inform their judgment about which dot array is more numerous (see Figure 2.4 for example of stimuli). Children were given three practice items that they completed with the help of the examiner, and nine practice items that they completed independently to ensure they understood the task before the administration of the assessment. For the present study, raw scores (e.g. total number of items correct) were summed across both the symbolic and non-symbolic conditions of the test to gain an overall measure of numerical magnitude processing performance. Test-re-test correlation coefficient for the number comparison task was .73 (Nosworthy, 2013).

a

Sample Items

1	7	8	2	2	5
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Practice Items

1	6	7	2	3	8
4	5	5	7	6	1
2	9	6	3	8	7

1

GO

1	9	8	1		
7	1	9	2	3	7
7	2	2	5	8	2
1	6	9	3	1	5
3	8	9	4	3	6

2

5	1	2	9	6	1
1	8	2	8	3	9
8	3	5	2	4	9
9	1	7	3	1	7
2	7	4	8		

3

b

Sample Items

•••	••••	•••••
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Practice Items

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1

GO

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3

Figure 2.4: Paper-and-pencil measure of numerical magnitude processing. a.) An example of the first three pages of the booklet in the symbolic condition. b.) An example of the first three pages in the non-symbolic condition.

2.5.4 Procedures

The initial screening included an unselected sample of 1277 children who were recruited from rural (5 rural) and urban (29 urban) schools across the Thames valley District School Board. Following the screening a selected sample of children were followed up in the spring of 2010 (Time 2) and once again in the spring of 2011 (Time 3). The duration of the screening protocol was 10 minutes. Each of the following testing sessions was completed over three visits occurring a week apart to collect the large battery of standardized measures. All children were tested in a quiet room within their respective schools by a trained research assistant. All parental consent forms were signed before participation in the longitudinal study.

2.6 Results

There were no significant differences in age between the three groups, $F(2, 83) = 1.41, p = .25$. To evaluate whether children with persistent DD had distinct differences in numerical magnitude processing skills compared to children with inconsistent math performance and typically developing controls, a univariate ANOVA was conducted with number comparison raw scores (total number of items correctly solved) as the dependent variable. The results of this analysis was significant $F(2,83) = 7.39, p = .001, \eta^2 = .15$. Independent samples t-tests revealed that typically developing children ($M = 83.06, SD = 13.20$) performed significantly better than children with persistent DD ($M = 70.44, SD = 15.55$), $t(64) = -3.56, p < .001, d = .88$. Children who demonstrated inconsistent math performance ($M = 78.91, SD = 12.43$) were more accurate than children with DD $t(52) = -2.13, p = .04, d = .59$. However, there were no significant differences in performance between the typically developing children and inconsistent math performers $t(54) = 1.18, p = .25, d = .32$ (see Figure 2.5). These findings suggest that children with persistent DD show distinct disabilities in processing numerical magnitude compared to children who demonstrated inconsistent math performance over time and therefore do not reliably meet the criteria for DD.

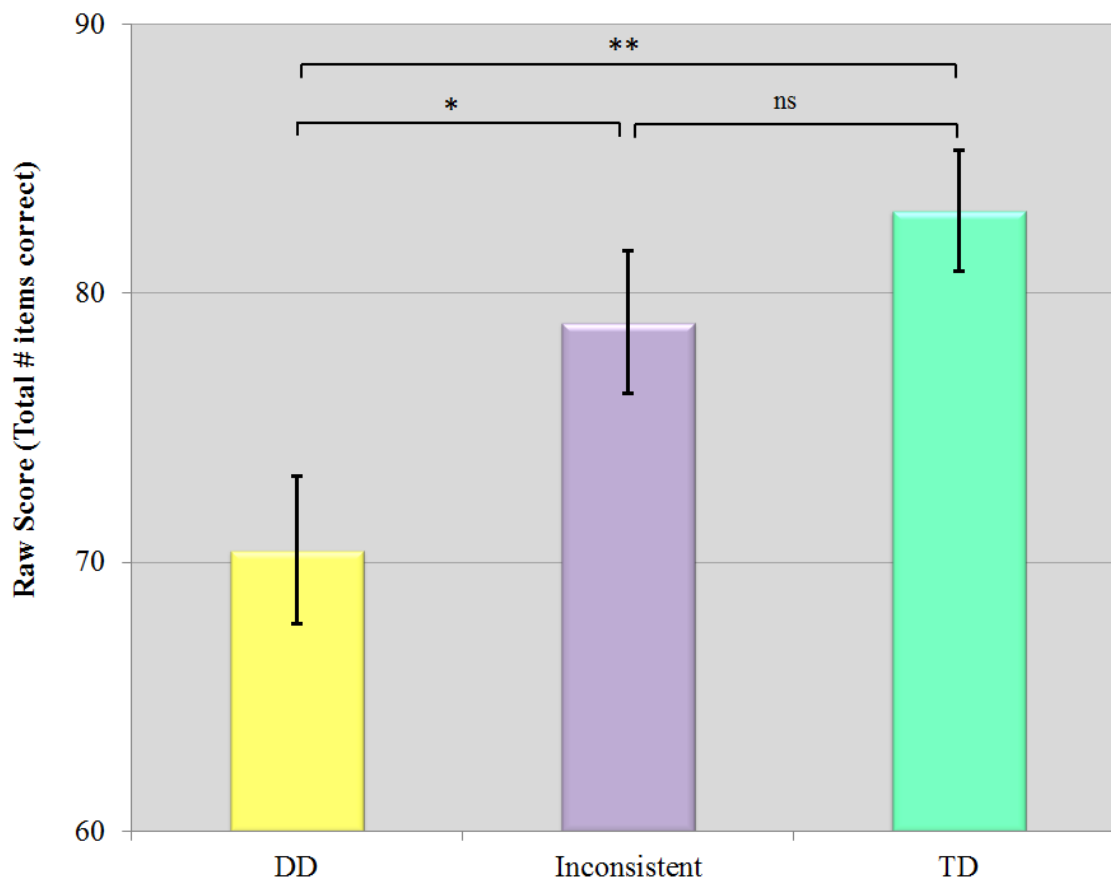


Figure 2.5: Children with persistent DD demonstrated significantly lower numerical comparison raw scores compared to children with inconsistent DD and typically developing children. Children with persistent DD, inconsistent DD and typically developing children were identified using standard scores on the Math Fluency and Calculation subtests independently, meaning that they either had below average, inconsistent or typical performance on both subtests.

2.6.1 Evaluation of DD selection criteria

To probe the reliability of these findings, I examined whether the same pattern of results are found when different operational definitions are used to identify children with persistent DD and inconsistent DD. This second analysis was conducted to examine whether performance differences on the numerical magnitude assessment found in children with stable DD compared to inconsistent DD was a product of the selection

criteria described above. Therefore, a slightly different set of selection criteria was used to identify a different group of children with stable DD and inconsistent DD.

2.6.2 Alternate selection criteria of DD

Rather than selecting children with DD based on below average performance on both Math Fluency and Math Calculation subtests separately (which was the method used to select children in the previous analysis and for the remaining studies conducted in the thesis), a math composite score was calculated for each participant by calculating mean performance on Math Fluency and Math Calculation subtests at each point. Math fluency during screening (first testing session) was combined with the math calculation scores during testing session two since they were administered approximately four months apart. Children with persistent DD were selected if they obtained math composite scores for all sessions below one standard deviation of the mean (standard score below 85). The method to select children with persistent DD for this analysis is more liberal, because it combines both math fluency and calculation measures into one score per testing session, rather than considering performance separately for each subtest at each time point. Using this criteria, there were 49 children who met the criteria for persistent DD (32 male, 17 female; Mean age = 113.69 months, $SD = 15.45$).

Using the new set of selection criteria, inconsistent DD was defined as a math composite score below 85 either during the first and second testing session combined *or* third testing session. In other words, if the data were collected during one testing session, a diagnosis of DD would be applied. There were 49 children who demonstrated inconsistent math performance over time (26 male, 23 female; Mean age = 108.41, $SD = 12.00$), meaning that they performed below average on the math composite measured during one testing session (e.g. either the combination of screening and testing session 2 or testing session 3). Forty-nine typically developing children were selected to best match age and gender of the persistent DD and inconsistent DD groups (30 male, 19 female; Mean age = 108.98, $SD = 11.34$). Both sets of selection criteria were applied to the entire sample of children ($n=233$), there were some participants who met both sets of criteria for persistent DD, inconsistent DD and typically developing. There were 27

children who met both sets of criteria for persistent DD, 21 children who met both criteria for inconsistent DD, and 16 children who were selected for both typically developing groups. There was a marginally significant difference between groups in age, $F(2,144) = 3.01, p = .052, \eta^2 = .04$ with children with DD being slightly older. Consistent with the selection criteria applied, math composite scores collected during the third testing session significantly differed between the three groups, $F(2,144) = 79.32, p < .001, \eta^2 = .52$. Children with persistent DD had significantly lower math composite scores ($M = 71.60, SD = 11.25$) than children who had inconsistent math performance ($M = 85.09, SD = 9.75, t(96) = -6.35, p < .001, d = 1.28$), and both DD groups had poorer math performance compared to typically developing children ($M = 96.27, SD = 7.82$) (persistent DD vs. TD, $t(96) = -12.60, p < .001, d = 2.55$; inconsistent DD vs. TD, $t(96) = 6.26, p < .001, d = 1.27$).

To evaluate the reliability of the definitional criteria used to identify children with persistent DD, a one-way ANOVA was conducted to see whether differences were found on the numerical discrimination task (e.g. total raw score for both symbolic and non-symbolic conditions) between children who demonstrated persistent low arithmetic composite scores compared to children who demonstrated inconsistent math performance and typically developing children. The results demonstrated a significant difference between groups, $F(2, 144) = 6.72, p = .002, \eta^2 = .09$. An independent samples t-test revealed that typically developing children ($M = 80.55, SD = 11.70$) obtained a significantly higher raw score on the numerical discrimination task compared to children with persistent DD ($M = 70.80, SD = 13.95$), $t(96) = -3.75, p < .001, d = .76$. Children who demonstrated inconsistent math performance ($M = 76.47, SD = 13.93$) were significantly more accurate compared to children with persistent DD, $t(96) = -2.02, p = .047, d = .41$. However, there was no significant difference between inconsistent DD and typically developing children, $t(96) = 1.57, p = .12, d = .32$ (see Figure 2.6).

Although there was some overlap in children who met both sets of criteria used to identify samples of persistent and inconsistent DD, the same pattern of results were found even with greater sample sizes and slightly different operational definitions of persistency. Specifically, there were no significant differences between typically

developing children and children with inconsistent DD. However, children with persistent DD demonstrated a significant impairment on a measure of numerical magnitude processing compared to children who would have identified as being DD if they were tested during one session.

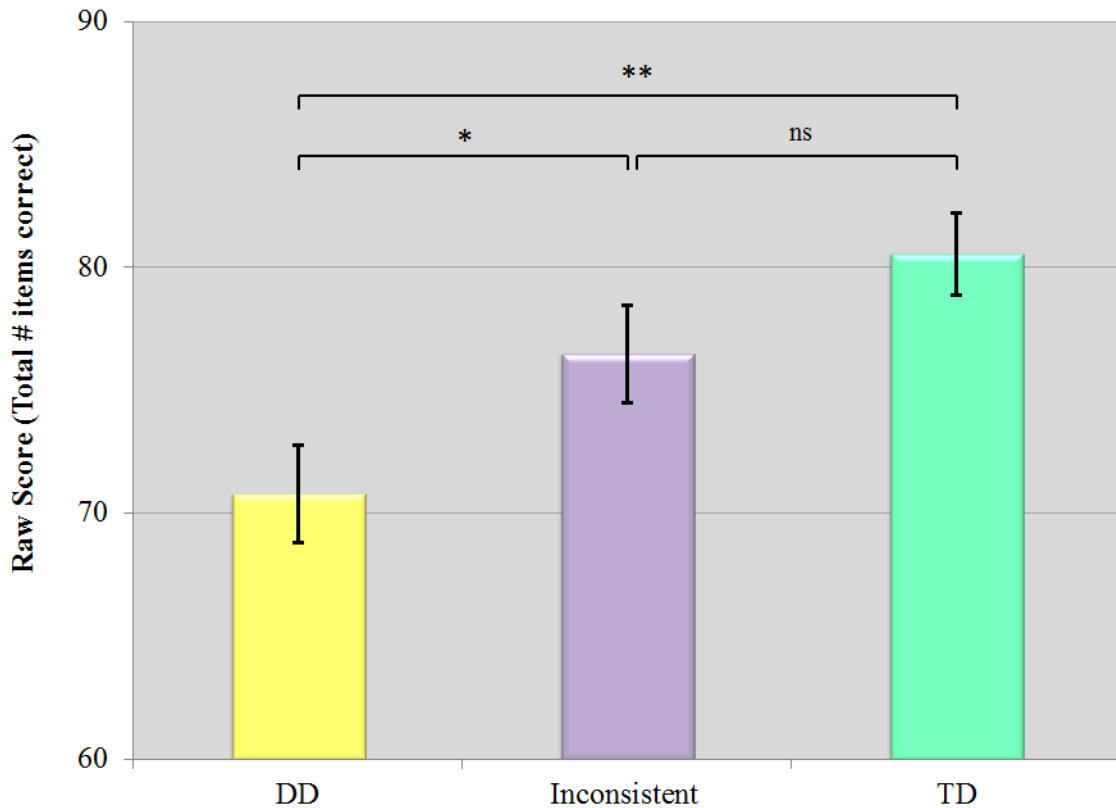


Figure 2.6: Children with DD identified using persistent math composite scores, demonstrated significantly lower numerical comparison raw scores compared to children with inconsistent DD and typically developing children. Children with persistent DD, inconsistent DD, and typically developing children were identified using math composite scores.

2.6.3 Severity analysis

Children with persistent DD demonstrated lower math composite scores in comparison to children with inconsistent DD and therefore, it is plausible that performance differences in the numerical magnitude processing measure are a product of severely impaired math

abilities in the persistent DD group. To examine whether performance differences change as a function of math ability or whether the difference can be characterized by distinct profiles between persistent DD and inconsistent DD, both groups were matched in math composite scores collected during time three. Group level matching was conducted on math composite scores collected during the third testing session, because the number comparison task was administered during this session. As a result of matching, there were 33 (out of 49) children in each group, and there were no significant differences between persistent and inconsistent DD groups on math composite scores at time 3, (persistent DD: $M = 77.94$, $SD = 4.27$; inconsistent DD: $M = 79.91$, $SD = 5.35$, $t(64) = -1.65$, $p = .103$, $d = .41$). An independent samples t-test was then conducted on the matched groups on the numerical comparison task. This analyses was consistent with previous findings, further supporting differences in numerical magnitude processing between persistent DD ($M = 71.61$, $SD = 12.51$) who were matched to inconsistent math performers ($M = 78.49$, $SD = 13.89$), $t(64) = -2.11$, $p = .038$, $d = .52$. Therefore, independent of math ability measured at time three (the same testing session that the number comparison task was administered), children who were identified as having persistent low arithmetic abilities demonstrated impaired numerical magnitude processing skills compared to children who would have been identified as being DD at one single time point.

2.7 Domain general cognitive profiles of children with DD

Children with DD, who were also not intellectually impaired ($IQ < 70$), were selected based on speeded and un-speeded arithmetic measures. As a result, it remains unclear whether the current sample of children with persistent DD has additional impairments on an array of non-numerically specific cognitive measures. Therefore, the aim of this analysis was to investigate domain general cognitive characteristics of children with DD in comparison to typically developing children, who were recruited for the subsequent studies presented in chapters three through five. This investigation allows for a comprehensive understanding of the domain general cognitive processes that are associated with having persistent low arithmetic skills. Furthermore, this analysis reveals whether working memory, specifically verbal or visuo-spatial working memory, characterizes children with persistent DD. Additionally, I examined whether individual

differences in math performance related to domain general processes such as reading, working memory, and IQ in children with DD compared to typically developing children.

2.7.1 Participants

Children with DD who participated in the subsequent studies of the thesis were recruited from the 32 children who demonstrated persistent math impairments on both Math Fluency and Math Calculation subtests (using the first selection criteria described in the participants section). Fifteen children returned the following year for the fourth testing session (Spring 2012). From those 15 children, 12 returned for the fifth testing session, which was conducted in the fall of 2013, in addition to 3 children who did not participate in time four, but participated in time five (see Figure 2.7). From the children with DD who participated in the fourth and fifth testing sessions, there were three children with DD who obtained a standard score on either the Math Fluency or Math Calculation subtest above 85, but below 90. In addition, there were two children with DD who obtained a standard score of 94 and 95 on the Math Calculation and Math Fluency subtests respectively. However, those five children demonstrated average performance across all testing sessions on both standardized tests of arithmetic achievement below what was expected for their chronological age (below or equal to 1 SD of the mean). There were five children with DD who demonstrated persistent low reading performance (e.g. standard score below 85) over all testing sessions and therefore, may have had comorbid dyslexia. In contrast, children with DD did not have persistent impairments in either verbal and visuo-spatial working memory or IQ. In other words, they did not obtain persistent standard scores below one standard deviation of the mean during all testing sessions on these measures. To examine the cognitive profiles of children with DD in the present study, analyses were conducted on the sample of children who participated in testing session five; therefore, there were 15 children with DD (11 male, 4 female) who were included in the analysis.

In the control group, from the 106 children who were identified as having persistent typical math performance, children who demonstrated persistent reading performance, IQ, as well as working memory composite scores in the typical range or

above (e.g. above standard score of 85) were asked to participate in the fourth and fifth testing sessions. Working memory composite scores were calculated by computing a mean standard score based on the Listening Recall and the Spatial Recall subtest standard scores, which are verbal working memory and visuo-spatial working memory measures respectively. From the typically developing children who participated in the fourth and fifth testing sessions, there were three children who achieved a standard score below 85 on the Math Fluency or Math Calculation subtest during the fourth session. There were three children who obtained a standard score below 85 on either the Math Fluency or Math Calculation subtests (see Figure 2.7 for the number of children who participated in fourth and fifth testing sessions). In the present analyses, 15 typically developing children (8 male, 7 female) were selected from the 22 typically developing children who were matched as best as possible to the persistent DD group based on age and gender.

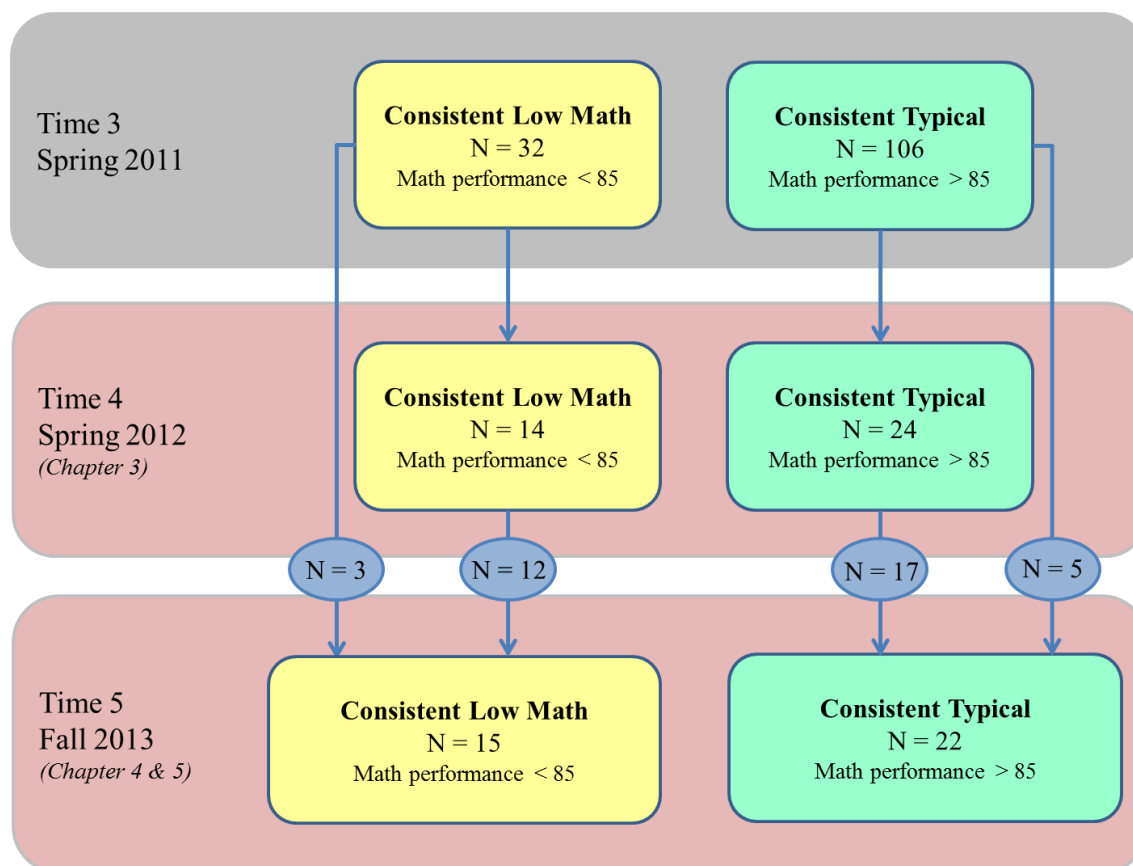


Figure 2.7: An illustration of the number of participants who continued to meet the criteria for persistent DD and TD and who participated in testing sessions four and five that were conducted in the spring of 2012 and the all of 2013 (studies presented in chapters 3 – 5). Note that Time 3 testing session is also depicted in Figure 2.3.

2.7.2 Materials and procedures

The standardized tests of Reading Fluency, Vocabulary and Matrix Reasoning (e.g. verbal & non-verbal IQ), Math Fluency and Math Calculation, Listening Recall and Spatial Recall (e.g. Verbal & Visuo-spatial working memory) that were administered either administered during screening and/or the second and third testing session, were administered again during the fourth testing session. A description of these standardized tests can be found above on p. 50. During the fifth testing session, only the Math Fluency, Math Calculation and Reading Fluency subtests were readministered. Measures of working memory and IQ were collected over three consecutive years, and measures of

math and reading achievement were collected over four consecutive years (See Figure 2.8). A detailed description of the procedures used to collect data during the fourth testing session will be described in chapter 3, and a detailed description of the procedures used for the fifth testing session will be described in chapters 4 and 5.

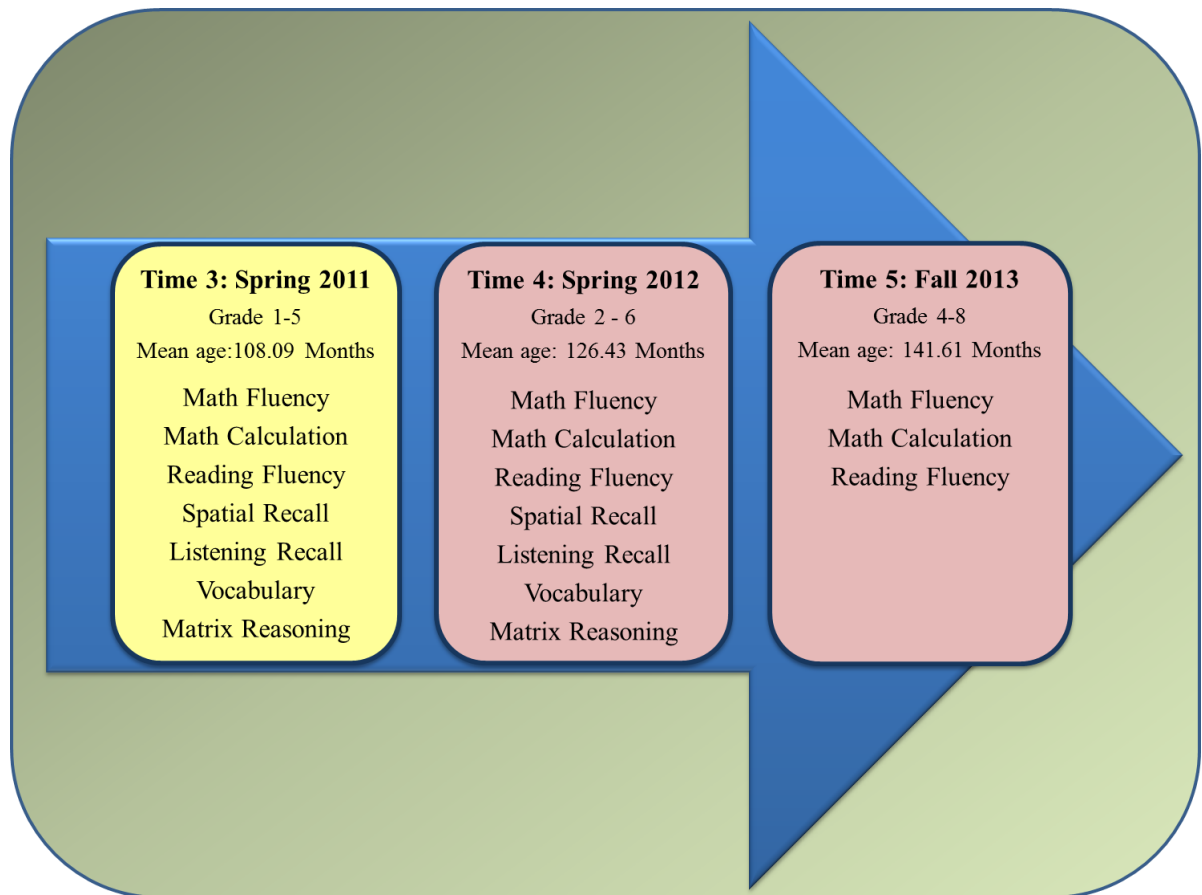


Figure 2.8: A time-line illustrating the standardized tests of cognitive performance administered during the fourth and fifth testing sessions (outlined in pink). Time 3 measures are also depicted in Figure 2.2.

2.7.3 Results: Cognitive performance across groups

Composite scores of Math Fluency, Calculation, Reading Fluency, Listening Recall (e.g. verbal working memory), Spatial Recall (e.g. visuo-spatial working memory), and full scale IQ were calculated by computing the mean standard score for measures collected

across all testing sessions. Subsequent analyses, including standardized scores of cognitive performance (e.g. math achievement), were conducted using the mean composite scores representing their ‘mean performance’ on the specific measure of interest. For example, the math average composite score was calculated using standard scores collected from the Math Fluency and Math Calculation subtests for all testing sessions (e.g. screening – Testing session 5). Similarly, verbal working memory ability was calculated by computing the mean standard score for the Listening Recall subtest across all three testing sessions in which it was administered (e.g. testing session 2 through 4). Standard scores were specifically used to calculate ‘mean performance’ to account for varying age related changes. Mean performance measures were calculated for each cognitive construct across all testing sessions to reduce the impact of psychometric errors and environmental factors in order to gain a more accurate estimate of true ability.

Given that children with DD demonstrated variable performance on measures of reading and working memory (see Table 2.2 for ranges and standard deviations for cognitive measures), a Mixed ANOVA with Measure (math, reading, IQ, verbal WM & visuo-spatial WM) and Group (DD, TD) was performed to investigate whether children with persistent DD demonstrated greater impairments on math achievement tests relative to performance on tasks measuring IQ, reading and working memory abilities. Mauchly’s test of sphericity was not violated, and therefore no correction for inflated p-values was applied. An interaction was found between measure and group, $F(4,112) = 5.03, p = .001, \eta^2 = .39$ (see Figure 2.9). A main effect of group was found, $F(1, 28) = 101.24, p < .001, \eta^2 = .78$, indicating that children with DD obtained significantly lower scores on all standardized measures compared to their typically developing peers (see Table 2.2 for means and significant group differences for all measures).

Table 2.2: Mean cognitive performance on standardized measures across all testing sessions in both persistent DD and typically developing samples.

	TD (n = 15)	DD (n = 15)	Sig.	d
	Mean (SD) [Min-Max]	Mean (SD) [Min - Max]		
Math Composite^a	96.45 (5.91) [87.38-105.17]	72.50 (5.70) [64.63-81.75]	$p < .0001$	4.13
Math Fluency	96.73 (6.50) [86.50 - 104.75]	75.74 (6.76) [65.25-86]	$p < .0001$	3.17
Math Calculation	96.20 (7.24) [87.00-111.33]	69.26 (6.94) [55.25-79.50]	$p < .0001$	3.8
Reading Fluency	110.39 (8.91) [98.25-135.75]	85.50 (15.59) [57.00-109.75]	$p < .0001$	1.96
Full IQ	107.29 (8.72) [94.33 - 121.00]	89.68 (7.13) [76.67-101.00]	$p < .0001$	2.21
Vocabulary ^b	52.94 (4.97) [46.33-64.00]	43.02 (6.39) [34.00-57.00]	$p < .0001$	1.73
Matrix Reasoning ^b	55.41 (6.18) [47.00-67.00]	45.26 (6.04) [38.00-57.33]	$p < .0001$	1.66
Verbal WM	105.84 (9.68) [96.00-128.00]	91.37 (8.45) [77.50-109.33]	$p < .0001$	1.59
Visuo-spatial WM	105.23 (11.26) [83.83-125.33]	98.26 (8.12) [86.33-114.07]	$p = .062$	0.71

Note. TD = Typically developing; DD = Developmental Dyscalculia; WM = working memory.

^a Math composite scores for each participant were calculated by computing the mean of the Math Fluency and Math Calculation subtests

^b Vocabulary and Matrix Reasoning standard scores are based on a normal distribution with a mean of 50 and a standard deviation of 10.

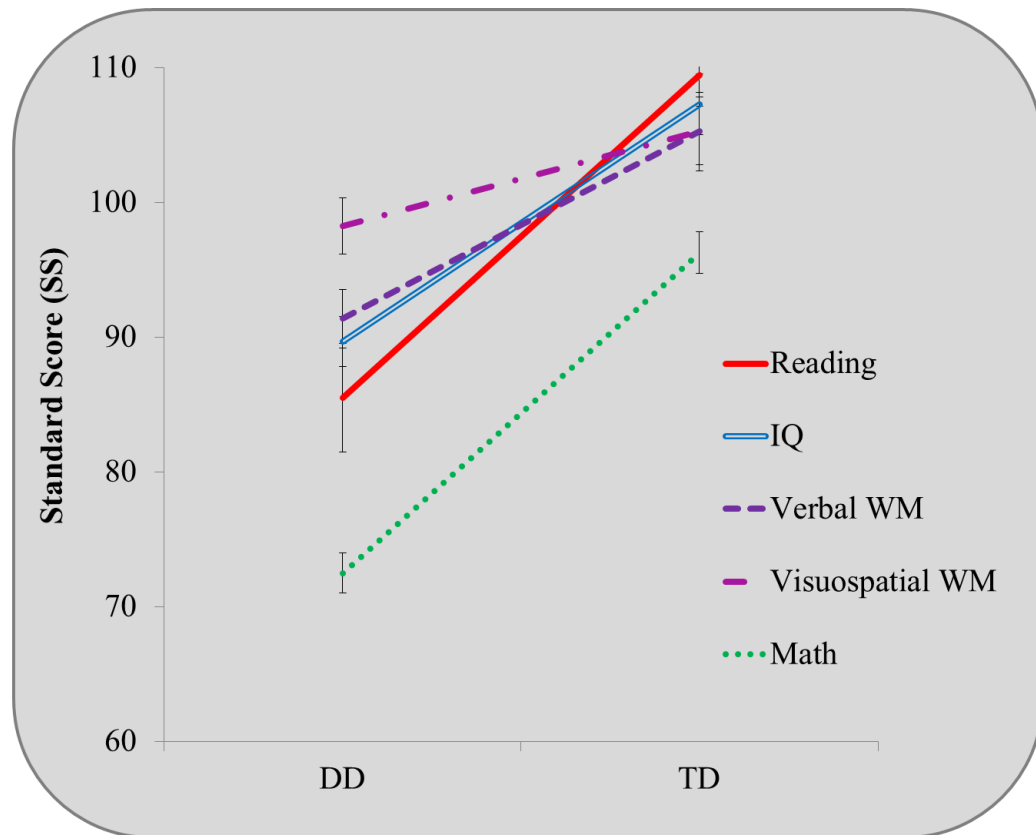


Figure 2.9. Cognitive Measure x Group interaction demonstrating that children with DD have the greatest impairment in math performance.

Multiple two-way ANOVAs that included math composite scores were conducted to establish the locus of the interaction between Measure (including all cognitive tests) and Group. With math composite scores and visuo-spatial working memory included in the model, a significant Group by Measure interaction was found indicating that math performance was significantly lower than visuo-spatial working memory in the sample of children with DD, $F(1, 28) = 16.83, p < .001, \eta^2 = .38$. In addition, a significant interaction between Group and Measure was found when including math composite scores and verbal working memory, $F(1, 28) = 5.44, p = .027, \eta^2 = .16$. A marginally significant interaction was found between Measure and Group when math and IQ were included in the model, $F(1, 28) = 3.06, p = .09, \eta^2 = .10$. These findings demonstrate that math performance was significantly more impaired in children with DD relative to their working memory ability and IQ. However, there was no significant interaction found

between Group and Measures when math and reading achievement were included demonstrating that children with DD also exhibited impaired reading performance when compared to other cognitive measures ($F < 1$) (see Table 2.2). Taken together, these findings demonstrate that although children with DD have poor performance on reading, IQ, and working memory, they have the greatest impairment in mathematical performance (see Figure 2.9).

2.7.3.1 The relationship between severity of DD and cognitive performance

Children with DD demonstrated lower scores on measures of reading, working memory, and IQ compared to their typically age matched peers. However, it remains unclear from the above analysis whether severity of math impairment was associated with lower IQ, working memory, and reading scores. Therefore, individual differences in math abilities were investigated by conducting correlation analyses between math composite scores and all measures of cognitive performance. More specifically, the relationship between math performance and reading, working memory, and IQ were examined independently in children with DD and typically developing children to investigate the relationship between domain general cognitive processes and severity of DD. The results of the spearman's correlations within the sample of children with DD demonstrated that math performance significantly correlated with visuo-spatial working memory and reading fluency. There were no other significant correlations in the DD sample (see Table 2.3 for correlation matrix). No significant correlations were found among cognitive measures in the typically developing sample. These findings suggest that severity of DD was associated with poor visuo-spatial working memory abilities and reading performance.

Table 2.3: Correlation matrix of standardized tests of cognitive performance in children with DD (n = 15) and typically developing children (n = 15).

	1	2	3	4	5
1 Math Composite		.35	-.11	-.07	-.50†
2 Reading Fluency	.52*		.28	.09	-.22
3 IQ	-.12	-.16		.17	.03
4 Verbal WM	-.13	-.04	.24		.23
5 Visuo-spatial WM	.72**	.30	.14	-.41	

Note. ** = $p < .01$; * = $p < .05$; † = $p < .1$; WM = working memory

Yellow cells: correlations conducted with sample of developmental dyscalculia

Green cells: correlations conducted with sample of typically developing children

2.8 Discussion

The definitional criteria for general LD have been constantly debated in the literature (Fletcher et al., 2013), and to a greater extent in the field of mathematical learning disorders, such as Developmental Dyscalculia (Mazzocco, 2007). The aim of the present studies was to investigate the number specific and domain general deficits of children with persistent DD with the intent of improving our understanding of cognitive deficits that characterize DD. To further explore the core deficits of children with DD, and to address the limitations surrounding the definitional criteria of DD within the literature, the current thesis recruited a unique sample of children with DD from a previously conducted epidemiological study who demonstrated persistent impairments in basic arithmetic skills.

2.8.1 Definitional criteria of DD

The aim of the current chapter was to provide a comprehensive description of the previously conducted longitudinal screening study in which children with persistent DD as well as persistent typical math performers were recruited. The validity of the

definitional criteria used to identify the present sample of children with persistent DD was evaluated by comparing their performance on a number comparison test (www.numeracyscreener.org), which is an independent measure that assesses basic numerical processing skills, to a group of children who demonstrated inconsistent math performance over time.

Previous research has found that math performance varies over time in elementary school children (Mazzocco & Myers, 2003), and given the psychometric properties of standardized tests, diagnosing children with DD based on a single administration of standardized tests is an unreliable measure of one's true mathematical ability. Furthermore, using different cut-off criteria for identifying children with DD would result in an increase in false positives (e.g. mistakenly identifying a typically developing child as having dyscalculia) and false negatives (e.g. mistakenly identifying a child with DD who does not have the disorder). To reduce the number of children who are erroneously identified as DD, the present study included a stability criterion consistent with the DSM-V (APA, 2013) to sample children with DD. Additionally, children with DD were required to show below average performance on timed and untimed tests of arithmetic achievement. Including a stability criterion as well as using multiple measures of arithmetic performance increases our confidence that children recruited in the present study have DD.

Consistent with Mazzocco and Myers (2003), we found that over time, children fell in and out of different definitional criteria of DD. More specifically, children who demonstrated low arithmetic fluency scores during the first testing session did not necessarily continue to demonstrate low arithmetic performance in subsequent testing sessions. The present study extended previous findings by showing that children with persistent DD exhibited distinct differences on an independent mathematical measure that assesses basic numerical magnitude processing. The paper and pencil numerical discrimination task is optimal for validating the selection criteria implemented in the present study, because it is an independent measure of numerical abilities that was not used to identify children with DD. Children with persistent DD demonstrated significantly lower scores on a measure that assesses the core competencies of

mathematical development compared to children with inconsistent math performance and typically developing controls. Moreover, even when both samples of children were matched on math ability, children identified with persistent DD exhibited significantly lower numerical magnitude processing skills compared to children who met the criteria for inconsistent DD. These differences in performance highlight qualitative differences between children who obtain stable low arithmetic impairments compared to children who would have met the criteria for DD during a single assessment. Taken together, these findings emphasize the importance of exercising caution when relying on one assessment to identify or diagnose a child with DD. From a practical standpoint, these findings highlight the complexities of psychometrically derived definitions of DD and how differences in criteria will inherently identify children with different cognitive strengths and weaknesses.

From the current sample where strict selection criteria were implemented, it remains unknown whether children who met our criteria for inconsistent DD do in fact experience deficits in learning basic arithmetic as a result of having DD or a mathematical difficulty, but did not meet our criteria of DD. However, for the purposes of ensuring the current sample of DD children experienced a severe mathematical learning disorder, only children who demonstrated stable low math performance over all testing sessions were included. As a result of using stringent criteria, the current sample of persistent DD is rather small. However, I opted to err on the side of excluding potential participants with DD in order to decrease the number of false positives included the current study. Thus, the present sample is ideal to assess the core deficits of DD, but may not be the best way of clinically diagnosing all children with mathematical difficulties who could benefit from remediation.

2.8.2 Cognitive profiles of children with persistent DD

The second aim of the present chapter was to examine the domain general cognitive processes associated with identifying children with DD based exclusively on persistent arithmetic deficits ($IQ > 70$). Measures of reading, verbal and visuo-spatial working memory and IQ in children with persistent DD were compared to typically developing

age matched peers to capture the cognitive profiles of the present sample of DD. This investigation is important to a.) understand the nature of persistent DD, as well as the relationships between domain general processes and severity of mathematical achievement and b.) to explore the domain general hypothesis of DD that proposes that domain general cognitive processes such as working memory cause impairments in arithmetic performance. The results of this analysis indicated that children with persistent DD exhibited on average poor performance on measures of reading, verbal working memory, and IQ (and marginally significant lower visuo-spatial working memory ability) as indicated by the large effect sizes, however, children with DD did not have persistent impairments in any of these measures, with the exception of five children who had persistent impairment in reading fluency. Although children with DD obtained lower standard scores on reading, working memory, and IQ compared to their typical age matched peers: the majority of children with DD received scores within the normal range. Furthermore, they suffered from a greater and more severe impairment on measures of math achievement compared to other cognitive measures.

2.8.3 Domain general causal hypothesis of DD

It is interesting to note that children with DD did not exhibit persistent working memory impairments associated with persistent arithmetic deficits. Although weaknesses in working memory abilities appear to characterize arithmetic disabilities (Geary, 1993), I found that children with persistent DD obtained variable working memory performance, with the majority of scores collected across time points falling within the normal range (refer to Table 2 for ranges and standard deviations). Children with DD demonstrated greater variability in performance across domain general cognitive measures. Previous research examining various components of working memory in children with DD are contradictory and the role of working memory in learning basic arithmetic and the execution of procedural operations remains unclear (Geary, 2004). For example, some research has found evidence to suggest that working memory abilities contribute to the source of counting errors during the arithmetic problem solving (Geary, 1990). In contrast, Landerl et al., (2004) found that children with DD did not differ in working memory performance compared to typical age matched peers. In the present investigation

I found that children with persistent DD demonstrated inconsistent working memory abilities, with an overall greater impairment in verbal working memory. The precise nature of the relationship between working memory and math ability in children with DD remains unknown.

Even though children with DD had significantly lower verbal working memory scores compared to visuo-spatial working memory, I found that severity of mathematical impairment correlated with visuo-spatial working memory, indicating that children with more severe DD had lower visuo-spatial working memory abilities. This is consistent with a study conducted by Passolunghi and Mammarella (2012) who found that only children with severe mathematical learning disabilities demonstrated poor performance on a spatial working memory task compared to children with low mathematical achievement. More recent studies have found converging evidence to suggest that visuo-spatial working memory, specifically, plays a greater role in poor arithmetic abilities in children with DD (Swanson, 2006; Szucs et al., 2013).

Overall, working memory is a complex construct and these findings maintain that working memory abilities are associated with mathematical abilities, and often accompany learning difficulties both in the fields of reading and mathematics (Gathercole, Alloway, Willis & Adams, 2006; Geary et al., 2007 respectively). The specific role of different components of working memory in mathematical learning disorders remains controversial. While some researchers suggest that working memory deficits are closely related to domain specific skills, evidence supporting this notion comes from working memory training studies. From a domain general perspective, it is hypothesized that training working memory skills would transfer to improving skills in multiple academic subjects. However, some research has shown that training visuospatial working memory did not transfer to the verbal or numerical domains of academic performance (Shipstead, Redick & Engle, 2012). In contrast, there is some evidence to suggest that training visuo-spatial working memory with and without a numerical component, improves basic counting skills and quantity comparison in kindergarten children (Kroesbergen, van't Noordende & Kolkman, 2014). It is possible that working memory deficits found in children with DD are domain specific, whereby

children with DD exhibit greater difficulties in numerically specific working memory tasks. In a recent meta-analysis, Peng and Fuchs (2014) found that children with DD showed more severe numerical working memory deficits (e.g. backwards digit recall or counting span tasks) in comparison to verbal working memory tasks such as listening recall that did not involve numbers as stimuli. Taken together, it is hypothesized that children with DD do not demonstrate a global working memory deficit, but exhibit difficulties in working memory when they are reaching the limits of their capabilities in areas of numerical and arithmetic processing.

2.8.4 Comorbidity of Dyscalculia and Dyslexia

Dyslexia (RD) and developmental dyscalculia commonly co-occur with comorbidity rates estimated as high as 50% (Lewis, Hitch & Walker, 1994; Shalev et al., 2000). In the present sample of DD, five children demonstrated persistent impairments on a measure of reading fluency, resulting in 33% of the current sample containing children with comorbid RD-DD. Few studies have examined the etiology of comorbid RD-DD and whether both learning disorders originate from a common deficit or whether comorbidity arises from domain specific deficit (Landerl Fussenegger, Moll, & Willburger, 2009). Jordan and colleagues (2001) found that children with comorbid RD-DD performed worse on exact calculation and word math problems compared to children with only DD. Children with comorbid RD-DD used fewer verbal strategies during calculation compared DD-only and typically developing children. However, there were no significant group differences on language independent skills, such as approximate arithmetic. Landerl and colleagues (2004) corroborated these findings, but additionally found that children with comorbid RD-DD did not differ from children with DD-only on numerical magnitude processing tasks, such as numerical discrimination, counting and number naming. These findings suggest that having comorbid dyslexia adds increasing difficulty during mathematical tasks that require word/language component and therefore evidence suggests that there are no qualitative differences between children with comorbid RD-DD and children with DD-only on basic numerical processing skills.

2.8.5 Conclusion

In conclusion, the results of the present chapter demonstrate the utility of incorporating a stability criterion in identifying samples of DD for research purposes and to further understand the core cognitive deficits of children who have a true mathematical learning disorder. Although diagnosing children after four years of assessment is not practical in clinical settings, assessing the behavioural and neural correlates of foundational competencies in children with persistent DD has the potential to inform current methods of identifying children who are potentially at risk for developing DD. Additionally, these findings demonstrated that children with persistent DD exhibited deficits in foundational skills measured using the Numeracy Screener, which are necessary to learn basic arithmetic. The aim of the subsequent chapters is to explore the nature of these deficits using different tasks of numerical magnitude processing.

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Chapter 3

3 Basic numerical processing in children with DD: A behavioural approach.

3.1 Introduction

Basic numerical processing (Siegler & Opfer, 2003) abilities encompass a variety of skills including, but not limited to, object enumeration and approximation, mapping numbers onto space, and discrimination of numerical symbols. These abilities are fundamental cognitive processes for the development of arithmetic skills in school. Quantitative deficits in any one of these areas have the potential to negatively impact mathematical development in children. Efforts to understand the typical and atypical developmental trajectories of basic numerical processes have used an array of tasks to measure different numerical processing abilities. The ability to approximate sets of objects is commonly assessed using a non-symbolic discrimination task, where children are asked to discriminate between sets of dots as fast as they can without counting. Symbolic processing skills are often assessed using a symbolic version of the numerical comparison task (Moyer & Landauer, 1967), which measures children's ability to discriminate symbolic magnitudes. A physical numerical Stroop task is often used to investigate the automaticity of processing symbolic numerals (Henik & Tzelgov, 1982). The number line estimation task is used to investigate children's ability to estimate the location of symbolic numeral on a visually presented number line (Siegler & Opfer, 2003). All of these tasks are commonly used to understand various components of numerical processing skills. Yet, it remains unclear which tasks and parameters better characterize both typically and atypically developing numerical trajectories.

Several domain specific theories postulate that DD is associated with deficits in basic number processing required to learn arithmetic skills. According to the '*Defective number module hypothesis*', DD is caused by impairment in representing and manipulating discrete numerical quantities (Butterworth, 1999, 2005). The '*Approximate number system*' (ANS) hypothesis proposes that DD is caused by a deficit in the

representational system required to approximate between large sets of objects (Wilson & Dehaene, 2007; Piazza, 2010). Both theories describe impairments in numerical magnitude representations (*representational* hypotheses) and predict that children with DD have deficits in tasks involving both symbolic and non-symbolic representations. In contrast, the '*Access deficit hypothesis*' predicts that DD is caused by a deficit in processing and accessing the semantic representations of symbolic numerals (Rousselle & Noel, 2007) (see introduction for complete description). Studies investigating these theories have predominantly used non-symbolic and symbolic numerical discrimination tasks; consequently, it is unclear whether these difficulties in processing symbolic and non-symbolic numerical representations are evident in other numerical processing tasks.

Studying the relationship between numerical constructs assessed using different tasks and DD has both theoretical and practical importance. From a theoretical perspective, understanding differences in performance across various numerical tasks can shed light on the specific deficits children with DD experience. For practical purposes, understanding markers of core deficits in children with DD, as well as understanding which specific tasks should be used to assess those skills, could improve the early identification of children who may develop DD. Furthermore, it can provide evidence for interventions to target specific deficits.

Given that there are few empirical studies investigating the core deficits in children with DD compared to dyslexia (as discussed in chapter 2) (Mazzocco, 2007), it is necessary to conduct studies that characterize the numerical deficits in children who are identified as having a persistent impairment in arithmetic achievement. Integrating the results across studies that have employed various versions of numerical processing tasks can be challenging, especially when there is variability in the definitional criteria used to identify samples of children with DD, as well as in sample sizes. Therefore, the present study aimed to use multiple paradigms to determine whether children with persistent DD have impairment in representing numerical magnitudes resulting in poor performance across tasks and formats, or whether they demonstrate selective impairments in symbolic numerical processing tasks. The current chapter will begin by reviewing the published studies that have investigated a variety of basic numerical magnitude tasks in

both typically developing children and children with DD. This review will be followed by a presentation of the hypotheses for the present study.

3.1.1 Numerical discrimination task

The numerical discrimination task is often used to gain insight into the nature of internal representations of numerical magnitude. During such tasks, individuals are presented with either two dot arrays (non-symbolic numerical discrimination) or two symbolic numerals (symbolic numerical discrimination) and are requested to select the numerically larger number or quantity (For an example, see Figure 1.1 in the introduction). In a seminal paper, Moyer and Landauer (1967) were the first to demonstrate that response times and error rates were inversely related to the numerical distance between the two numbers, such that, response times and error rates increased as the distance between the two numbers decreased (e.g. $1 - 8$ versus $7 - 8$; see introduction for a discussion and example of the task). A similar effect is the so-called ratio effect. The ratio effect is a phenomenon that occurs when the time required to make numerical comparisons is systematically related to the numerical ratio of magnitudes (Moyer & Landauer, 1967). According to Moyer and Landauer, the ratio between the two numbers being compared is more closely related to reaction times than the absolute difference between them. For example, although the number pairs 1 and 2 or 8 and 9 both have a numerical distance of 1, their ratio is significantly different (0.5 and 0.89 respectively). It should be noted that there is a high colinearity between the numerical distance effect and the ratio effect, but the ratio effect is thought to explain more variance in number comparison reaction times and accuracy data (Moyer & Landauer, 1967).

Several models have emerged to account for these effects by hypothesizing about the internal structure of numerical magnitude representations. A prevalent theory has purported that numerical magnitudes are represented by an analogue system (also referred to as the approximate number system) where numerical magnitudes activate a Gaussian distribution located on an internal hypothetical mental number line (for a review see: Dehaene, 2007). The precision of numerical magnitude representations are characterized by the standard deviation of the Gaussian distribution. Numbers that are

close together in distance would activate overlapping distribution during discrimination, making them more difficult to disambiguate (see introduction for more discussion).

There is evidence that primates, as well as infants as young as six months old, can discriminate between non-symbolic magnitudes, which precedes the development of formal language abilities (Lipton & Spelke, 2003; Xu & Spelke, 2000). It has been suggested that this evidence supports the notion that the approximate number system is an evolutionary ancient system with the predisposition for learning numbers (Piazza, 2010). The numerical distance/ratio effects are evident in both symbolic and non-symbolic versions of the task throughout development. It has been theorized that Arabic numerals develop meaning through the automatic attachment to their non-symbolic quantity representations. Therefore, the Arabic numeral '5' activates the same underlying representation (e.g. Gaussian distribution) as a set of five objects (for a review see: Dehaene, 2007).

Developmental studies have shown that reaction times decrease with increasing age, such that the slope relating numerical distance and response time decreases as a function of increasing chronological age (Duncan & McFarland, 1980; Holloway & Ansari, 2009; Sekuler & Mierkiewicz, 1977). Taken together these findings would suggest that as children grow older, internal representations of numerical magnitude become more precise (standard deviation of the Gaussian distributions become smaller). Furthermore, there is evidence to suggest that both non-symbolic and symbolic distance/ratio effects predict individual differences in symbolic math achievement (Holloway & Ansari, 2009; Libertus, Feigenson, & Halberda, 2011). However, in a recently published review paper, the symbolic distance effect appears to be a more robust and reliable predictor of math achievement (De Smedt et al., 2013).

Numerical discrimination tasks are most commonly used to investigate the development of non-symbolic and symbolic numerical magnitude processing, and are most frequently employed to assess numerical magnitude processes in participants with DD. Studies using both symbolic and non-symbolic versions of the numerical discrimination task in children with DD have found supporting evidence for the

'representational' hypotheses (e.g. both the *'defective number module'* and the *'approximate number system'* hypotheses), as well as the *'access deficit'* hypothesis. For example, Landerl, Bevan and Butterworth (2004) found that children with DD exhibited greater response times during the symbolic numerical comparison task compared to typically developing controls, in addition to other numerical tasks (such as dot counting and number naming). The authors interpreted these data as supporting evidence for the *'defective number module hypothesis'* of DD. However, in their study, Landerl and colleagues did not examine performance on the non-symbolic version of the task, but found that children with DD displayed deficits rapidly enumerating small sets of dots. Therefore, it remains unclear whether performance differences were specific to a deficit in the number module for processing discrete quantities or whether differences were driven by a deficit in processing and accessing symbolic numerals. Studies in support of the *'approximate number system'* hypothesis have found that children with DD demonstrated larger distance effects in the non-symbolic numerical discrimination task. Piazza and colleagues (2010) found that children with DD (ages 8-12) performed at the same level as typically developing five year olds on the non-symbolic discrimination task. Similarly, Mussolin and colleagues (2010) found that children with DD performed significantly worse on both the symbolic and non-symbolic numerical discrimination tasks, supporting the notion that impaired approximate representations is detrimental to symbolic numerical development in children with DD.

In contrast to the previous findings, Rousselle and Noel (2007) administered a non-symbolic and symbolic discrimination task and found that children with DD had significantly greater RT during the symbolic comparison task characterized by a slightly larger distance effect compared to TD controls; however, there were no group differences on the non-symbolic discrimination task. These findings suggest that children with DD do not have an impaired approximate number system, but rather that DD is caused by a deficit in processing the semantic meaning of symbolic numerals (Rousselle & Noel, 2007).

In a study conducted by Landerl and colleagues (2009), it was found that children with DD exhibited longer response times (DD and TD accuracy rates reached ceiling)

during both the symbolic and non-symbolic versions of the numerical comparison task. They examined the numerical distance effect in the symbolic condition and found there were no qualitative differences between TD children and DD children with regards to the size of the distance effect (distance effects were not examined in the non-symbolic discrimination task) (Landerl, Fussenegger, Moll, & Willburger, 2009). These authors suggested that children with DD do not have qualitatively different cognitive representations of numerical magnitude, but rather they were slower at processing the numerical magnitudes. These conclusions were supported by a study conducted by Landerl and Kollé (2009). Additionally, they did not find any differences in performance between groups in the non-symbolic discrimination task, suggesting that they do not have an impairment in representing approximate numerical magnitudes, but that children with DD have difficulties in accessing and processing representations of numerical magnitude. Taken together, it is unclear from present literature which causal theory of DD is supported by the symbolic and non-symbolic numerical discrimination tasks.

3.1.2 Numerical ‘Stroop’ task: The size congruity effect

To perform basic arithmetic and more complex mathematical processes, it is important to automatically process the semantic meaning of symbolic numerals effortlessly. Automaticity is defined as a process that occurs rapidly without attentional and conscious monitoring (Tzelgov, 1997) and automaticity can occur when the particular dimension being processed is not specific to the task at hand. The physical size congruity version of the Numerical Stroop paradigm has been used to assess the automaticity of processing numerical magnitudes. In this paradigm, stimuli presented vary in both physical size and numerical magnitude. Participants are asked to select the physically larger numeral while ignoring their semantic meaning. During this task, presented trials are either congruent (the numerically larger number is also physically larger, e.g. 8 4), incongruent (the numerically larger number is physically smaller, e.g. 8 4) or neutral (numerals differ in physical size, but not numerical magnitude, e.g. 8 8). The size congruity effect (SCE) manifests in longer reaction times and less accurate responses during the incongruent

trials in comparison to the congruent and neutral trials. The magnitude of the effect is indicative of the interference or facilitation the task irrelevant dimension of numerical magnitude has on the task at hand. Accordingly, the SCE can be decomposed into *facilitation* (congruent trials are processed more efficiently compared to neutral trials where the numerically irrelevant dimension is not altered) and *interference* effects (incongruent trials are processed less efficiently compared to neutral trials). In other words, interference effects occur when the physical size and the numerical magnitude associated with the correct response conflict with one another, producing a longer response. In contrast, facilitation effects are a product of the task-irrelevant dimension of numerical magnitude matching the physical size, which results in shorter response times. Several studies have shown that typically developing adults automatically activate numerical magnitude when it is not directly relevant to the task during the physical size congruity task (Duncan & McFarland, 1980; Henik & Tzelgov, 1982). Additionally, developmental studies have demonstrated different developmental trajectories for the onset of automatically activating symbolic numerals. For example, Girelli and colleagues (2000) found the SCE was absent in first grade, a small SCE was evident in third grade, but did not fully develop until the fifth grade (Girelli, Lucangeli, & Butterworth, 2000). The findings suggest that the SCE gradually emerges over the course of development. In a study that was conducted in parallel to the Girelli et al., Rubinsten and colleagues (2002) investigated the SCE and the distance effect in children at the beginning and end of first grade, as well as students in third grade, fifth grade and university. They found that the physical SCE did not appear in children at the beginning of Grade 1, but found that the numerically irrelevant stimuli interfered with physical judgments by the end of Grade 1.

It has been hypothesized that the ability to automatically associate numerical symbols with the magnitudes they represent is impaired in DD (Rouselle & Noel, 2007). If that were the case, the semantic representations of numbers during the size congruity task would not be automatically activated to either interfere or facilitate with physical size judgment. Therefore, a size congruity effect would not be present in participants with DD. To test this hypothesis, Rubinsten and Henik (2005) investigated the automaticity of processing symbolic numerals using size congruity task in university

students who were diagnosed with DD. University students with DD demonstrated a significant size congruity effect that was driven by a greater interference effect but no facilitation effect. In comparison, typical controls demonstrated both effects. It was suggested that interference component reflects attentional processes, whereas facilitation effects involve more automatic processes, because they are subject to less strategic control (Tzelgov et al., 1992). These results were later replicated, indicating that adults with DD exhibited significant interference effects, but did not demonstrate a significant facilitation effect in comparison to typical controls (Ashkenazi, Mark-Zigdon, & Henik, 2009). These findings suggest that individuals with DD have an intact representation of numerical magnitude but fail to develop automatic associations between internal representations of magnitude and Arabic numerals (Ashkenazi et al., 2009).

In a group of elementary school children with DD (Grades 2-4), Landerl and Kölle, 2009) found that in comparison to typical controls (who were not matched on any variable to the DD group), children with DD did not exhibit a significant SCE. This suggests that the task irrelevant feature of numerical magnitude did not interfere with participants' selection of the physically larger number. The SCE was not present even at fourth grade, which suggests that even by Grade 4, children with DD did not develop sufficient skills to automatically process numerical representations. In contrast to these findings, Landerl et al., (2009) found that children with DD demonstrated typical size congruity effects characterized by both interference and facilitation effects in comparison to typically developing children. Both typically developing children and children with DD showed a significant influence of the irrelevant numerical value during physical size discriminations at the beginning of Grade 2. These results indicate that automatic processes measured by the size congruity effect tap into distinct numerical processes that are not differentiated in children with severe arithmetic deficits and typical controls. These findings were further corroborated by a recent study that recruited children with persistent arithmetic impairments (Landerl, Göbel, & Moll, 2013).

In summary, studies on the size congruity task have produced conflicting results, which has led to an incomplete story about the development of numerical automaticity skills in children with DD. However, there appears to be stronger evidence to suggest

that children and adults with DD are automatically accessing the semantic representations of numerical magnitude to a certain degree. The typically developing findings have demonstrated that in some cases children as young as seven have not developed numerical automaticity skills as measured by the physical size congruity tasks, but in numerical discrimination tasks, children can rapidly discriminate between symbolic numerals in what appears to be an automatic fashion. Some researchers have argued that distance effects found during numerical discrimination tasks reflect the automatic processing of numerical magnitude (Dehaene & Akhavein, 1995). Although both tasks have previously been referred to as measures of basic numerical processing, recent evidence has suggested that the physical size congruity and numerical discrimination tasks measure two distinct cognitive processes (Bugden & Ansari, 2011; Rubinsten et al., 2002). First, the numerical discrimination task is a measure of intentional numerical magnitude processing where the distance effect emerges from individuals activating numerical representations and relating them to one another to make a decision. In contrast, the physical size congruity task reflects automatic processes of numerical magnitude which are accessed through memory based procedures. According to the *independent encoding postulate* (Tzelgov, Meyer & Henik, 1992), irrelevant numerical values are not processed independently but rather are encoded dichotomously as “large” or “small” and those dichotomous classifications interfere with physical size judgments. In studies where individuals with DD have demonstrated significant size congruity effect, these findings may not reflect automatic processing of individual symbolic magnitude, but children with DD show interference through coarse classifications of numbers into small or large categories. It is plausible that the automatic classification of symbolic numerals into small or large categories is a coarse measure of automaticity that may not have functional relationships with measures of math achievement (Bugden & Ansari, 2011).

3.1.3 Number line estimation (NLE)

Number line estimation (NLE) tasks are commonly used to assess children’s ability to identify the spatial location of a numerical magnitude on a visually presented number line. During this task, children are presented with a horizontal line in the middle of a

sheet of paper with an anchor on either end of the line (e.g. 0 and 100). Children are asked to make a mark on the number line to indicate the spatial location of the presented numeral. Using NLE tasks is thought to be ecologically valid since they are commonly used in the classroom to teach numerical concepts. It has also been argued that the NLE is a direct measure of internal numerical magnitude representations – according to the ‘*mental number line*’ hypothesis (Dehaene, 1997; 2003). Children’s numerical estimates on the number line provide a window into the structure of their underlying representations by examining whether linear or logarithmic functions best fit their responses. (see Figure 1.3 in the introduction).

In a study conducted by Siegler and Opfer (2003) they found that sixth grade children and adults relied on linear representations of numerical magnitude, indicating that they were more accurate at estimating the locations of numerical magnitude on both the 0 to 100 and 0 to 1000 number lines. In contrast, second grade children and about half of the fourth grade children generated a logarithmic pattern of estimates on the 0 to 1000. In other words, they overestimated the location of smaller numbers but as they approached 1000 their estimates became more accurate. In a follow up study, Siegler and Booth (2004) provided further support that children as young as kindergarten generate logarithmic patterns of estimates and gradually shift to more linear representations. Additionally, performance on NLE tasks predicts individual differences in concurrent math achievement (Siegler & Booth) and mathematical learning over time (Booth & Siegler, 2008; Geary, 2011). Moreover, training using number line games have been shown to improve numerical processing and mathematical achievement (Siegler & Ramani, 2009), indicating that number line estimation performance is critical for the development of arithmetic skills. Contrary to the evidence supporting a logarithmic-to-linear representational shift, recent studies have found that estimations are highly influenced by strategies, such as the use of reference points, and therefore NLE may not necessarily reflect the underlying representation (Barth & Paladino, 2011; Huber, Moeller, & Nuerk, 2014; Slusser, Santiago, & Barth, 2013).

In the limited studies conducted with DD participants, children with DD have been found to show pronounced differences in performance on the 0 to 1000 number line

condition compared to typical controls, where DD children show a logarithmic pattern of estimates compared to controls (Landerl., et al., 2009). However, the same patterns of findings were not replicated in a study conducted by Landerl et al., (2013). Therefore, it is unclear whether performance on the NLE task can reliably differentiate between children with DD and typically developing controls.

3.1.4 Audio-visual matching task

During the audio-visual matching task, children hear a number, and immediately thereafter presented with a visual number on the computer screen. Children are asked to decide whether the visual and auditory stimuli are the same or different. The auditory visual integration of symbolic numbers has only been investigated in one previous study. In this study, Lyons et al. (2014) administered a battery of numerical processing tasks in a group of typically developing children in grades one through six. They found that the audio-visual integration task did not significantly predict individual differences in arithmetic achievement. It is unclear whether the audio-visual integration of numerical symbols is a marker for children with DD. The development of reading and language skills the integration of speech sounds to corresponding letters and words. There is strong evidence to suggest that phonological awareness and letter-sound mapping are core deficits of developmental dyslexia (a specific reading learning disorder) (for a review see: Vellutino et al., 2004). The present study incorporated an auditory visual integration task with symbolic numerals to examine whether deficiencies in processing numerical magnitude are evident in other presentation modalities.

3.1.5 The present study

Studies examining basic numerical processing skills in DD have used an assortment of tasks in an attempt to shed light on the core deficits associated with DD. Although the numerical processing tasks discussed above fall under the umbrella of measures assessing the proficiency of numerical magnitude processing, it is not the case that each task necessarily taps into the same cognitive mechanisms. Moreover, it is difficult to make strong conclusions across all studies that have used relatively different definitional

criteria to identify samples of DD and typical controls. The aim of the present study was to take a comprehensive approach by administering a battery of numerical processing tasks to examine the precise nature of numerical magnitude deficits in children with persistent DD. Rather than focusing on numerical discrimination tasks to inform our understanding of the representational and access deficit hypotheses of DD, the validity of these theories can be examined using an extensive battery of tasks to gain a more comprehensive insight into how children with DD process symbolic and non-symbolic representations of numerical magnitude in a variety of commonly used tasks.

Each computerized numerical task allows for the investigation of specific effects (e.g. the distance effect) that are informative of participants' representations of numerical magnitude; however, these effects are not directly comparable with one another. For example, it is not possible to directly compare the magnitude of the symbolic numerical distance effect with performance on the number line estimation task, since the task effects are fundamentally different in nature. Furthermore, some studies have questioned the validity and reliability of specific task effects (Inglis & Gilmore, 2014; Maloney et al., 2010).

Using a similar approach developed by Lyons et al. (2014), performance measures (similar to inverse efficiency scores used in a very similar study conducted by Landerl et al., 2013) were calculated for all computerized task to allow for the direct comparison of performance across all computerized numerical tasks using the same dependent variable. This method allows for a systematic investigation of group differences between various measures of basic numerical magnitude processing. It is hypothesized that, if children with DD have a core deficit in processing numerical magnitude, it is expected that they would perform worse on all basic numerical processing tasks. Conversely, if children with DD have a select deficit in accessing the semantic representations of symbolic numerals, it is expected that they would perform worse on symbolic numerical tasks, but not on the non-symbolic tasks, compared to typically developing children.

3.2 Methods

3.2.1 Participants

There were 14 children with DD (12 male, 2 female) who were recruited for the present study (Mean Age: 11.31 years, $SD = 1.19$). From the 24 typically developing children who were recruited for the present study, there were 7 children who were not included in the data analysis, because of the failure of E-prime software in saving the data collected during the administration of one of the computerized tasks. From the remaining 17 typically developing children, 14 (4 male, 10 female) who were closer in age to the DD children were included in the present study (Mean age: 10.34 years, $SD = .77$). Despite efforts to match the groups on age, children with DD were significantly older than the typically developing sample, $t(26) = -2.57, p < .05$.

3.2.2 Materials

3.2.2.1 Standardized tests of cognitive performance

The same battery of standardized tests that were administered during the second and third testing sessions were administered during the present testing session (see Figures 2.3 & 2.8 for a chronology of testing sessions). The Math Fluency, Math Calculation, and Reading Fluency subtests were administered from the Woodcock Johnson-III tests of achievement (Woodcock, McGrew, & Mather, 2001) to assess both reading and arithmetic achievement. The Vocabulary and Matrix Reasoning subtests from the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1995) were administered to assess verbal and non-verbal intelligence respectively. To assess visuo-spatial and verbal working memory, the Spatial Recall and the Listening Recall subtests from the Automated Working Memory Assessment (Alloway, 2007) were administered. See chapter two for a complete description of the standardized tests of cognitive performance.

3.2.2.2 Computerized numerical processing tasks

All computerized tasks were administered on an HP laptop (15" computer screen) using E-prime stimulus presentation software (Psychological Software Tools, Pittsburgh, PA). Responses were made using the "s" and "l" buttons on the keyboard.

3.2.2.2.1 Symbolic numerical discrimination task.

To measure children's ability to process discrete single digit numerals, a numerical discrimination task was administered. During this task, children were presented with two single digit numbers on a computer screen and asked to select the numerically larger number as fast as they could without making any errors (see Figure 3.1a). Numbers ranged from 1 – 9 and appeared on either side of the centrally located fixation dot for 800ms. Both numbers were presented in courier new font and had a font size of 58. Following stimuli presentation, a response screen appeared and remained until a response was made or for 3000ms. There were 16 stimulus pairs selected so that the ratio between the pair of numbers ranged from .11-.89 (16 different ratio pairs) (see Table 3.1). Each pair was administered four times in random order for a total of 64 trials. To ensure that the larger number appeared equally on both sides of the computer screen, each number was counterbalanced across trials. Each participant received a break halfway through the run.

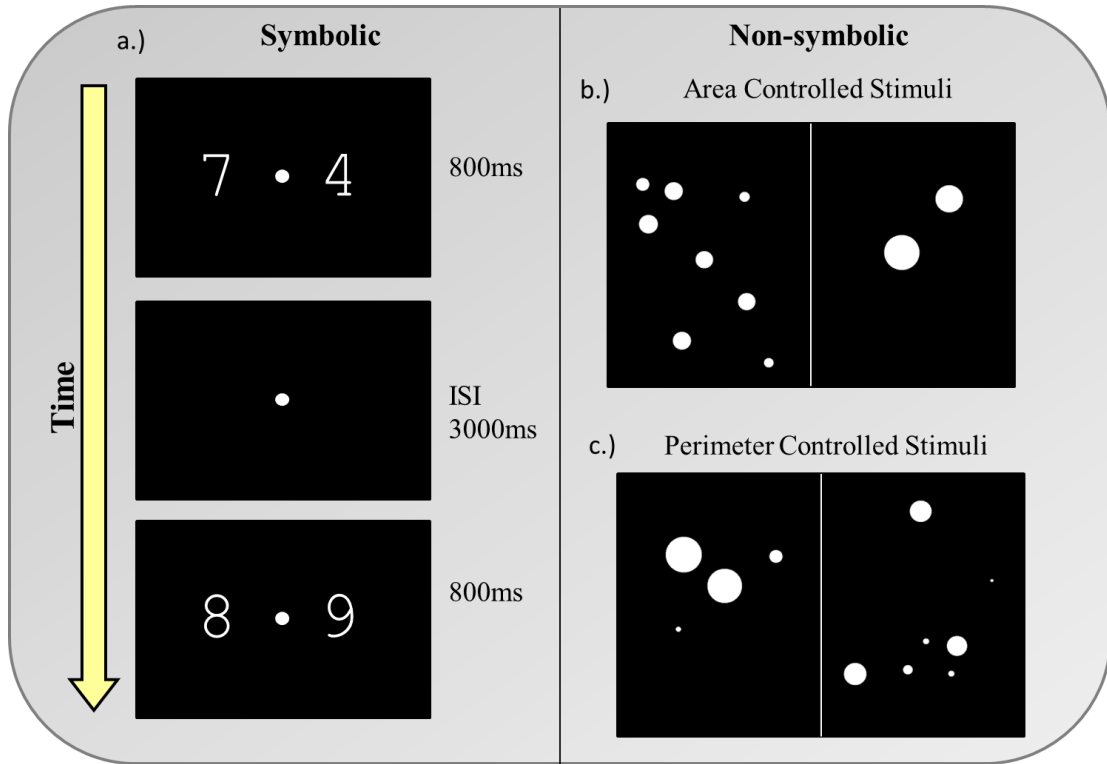


Figure 3.1: An illustration of the symbolic and non-symbolic stimuli. a.) The timing procedures of the trials in the non-symbolic and symbolic numerical discrimination tasks b.) An example of the area controlled non-symbolic stimuli. c.) An example of the perimeter controlled non-symbolic stimuli.

Table 3.1: Stimulus pairs for the symbolic and non-symbolic numerical discrimination tasks.

Ratio Group	Stimulus Pair		Ratio
.11 - .30	1	9	0.11
	1	7	0.14
	2	9	0.22
	2	8	0.25
.31-.5	2	6	0.33
	3	8	0.38
	3	7	0.43
	4	8	0.50
.51-.71	4	7	0.57
	3	5	0.60
	4	6	0.67
	5	7	0.71
.71-.89	3	4	0.75
	4	5	0.80
	6	7	0.86
	8	9	0.89

3.2.2.2.2 Non-symbolic numerical discrimination task

Non-symbolic numerical discrimination task was administered to assess children's ability to discriminate between approximate quantities. During this task, children were presented with two dot arrays simultaneously on the computer screen and were asked to select the larger dot array as fast as they could without counting the dots (See Figure 3.1b & c).

The non-symbolic version of the task was modelled after the symbolic task such that the same numerical pairs were administered and the timing parameters remained the same (see Table 3.1). Dot arrays were created using a Python script that controlled for visual

properties of the dot stimuli, such that half of the trials were controlled for total surface area and the other half of the trials were controlled for total perimeter (see Price, Palmer, Battista, & Ansari, 2012 for the same stimulus design procedure). When the total surface area was equated across both dot arrays, the larger dot array had greater total perimeter (see Figure 3.1b). However, for the trials where perimeter was equated across both dot arrays, the total cumulative surface area was greater for the larger dot array (see Figure 1c). Trials were administered in random order to prevent children from relying on visual perceptual cues rather than numerical cues to inform their decision.

3.2.2.2.3 Physical size congruity task.

In order to measure children's implicit processing of numerical magnitude, a 'Numerical Stroop' paradigm was administered (also referred to as the physical size congruity task). Participants were presented with two single digit numbers (ranging from 1-9) with one number physically larger than the other on a computer screen (see Figure 3.2a). Children were asked to choose the physically larger number as fast as they could without making any errors. The stimuli remained on the computer screen until a response was made by pressing either the 's' or 'l' keys. Each participant's reaction time and accuracy score was recorded upon response. There were a total of 72 trials administered with 24 congruent trials, 24 incongruent trials, and 24 neutral trials. Congruent trials occurred when the physically larger number was also numerically larger (e.g. 2 7) (see Figure 3.2a). In the incongruent trials, the physically larger number was numerically smaller (e.g. 2 7) (see Figure 2b), and for the neutral trials, pairs had the same numerical magnitude and only differed in physical size (e.g. 2 2) (see Figure 3.2c). For the incongruent and congruent trials, six pairs had small ratios (ranging from .11-.22) and six pairs had large ratios (ranging from .78-.89) (see Table 3.2). Each ratio pair was presented four times for the incongruent and congruent trials for a total of 48 trials, with the physically larger number appearing equally on both sides of the computer screen. For the neutral trials, each number was paired with itself and the physical size of one of the numbers was larger than the other. Each pair was presented twice, with pairs 1, 2, 4, 5, 7, and 8 being presented for a third time to equal 24 trials. The physically larger numeral

had a font size of 58 and the smaller number had a font size of 30, with the larger number being approximately double the size of the small number. Each number appeared equidistant from the centre of the screen. Participants were given a break halfway through the task. The same task was administered by Bugden and Ansari (2011).

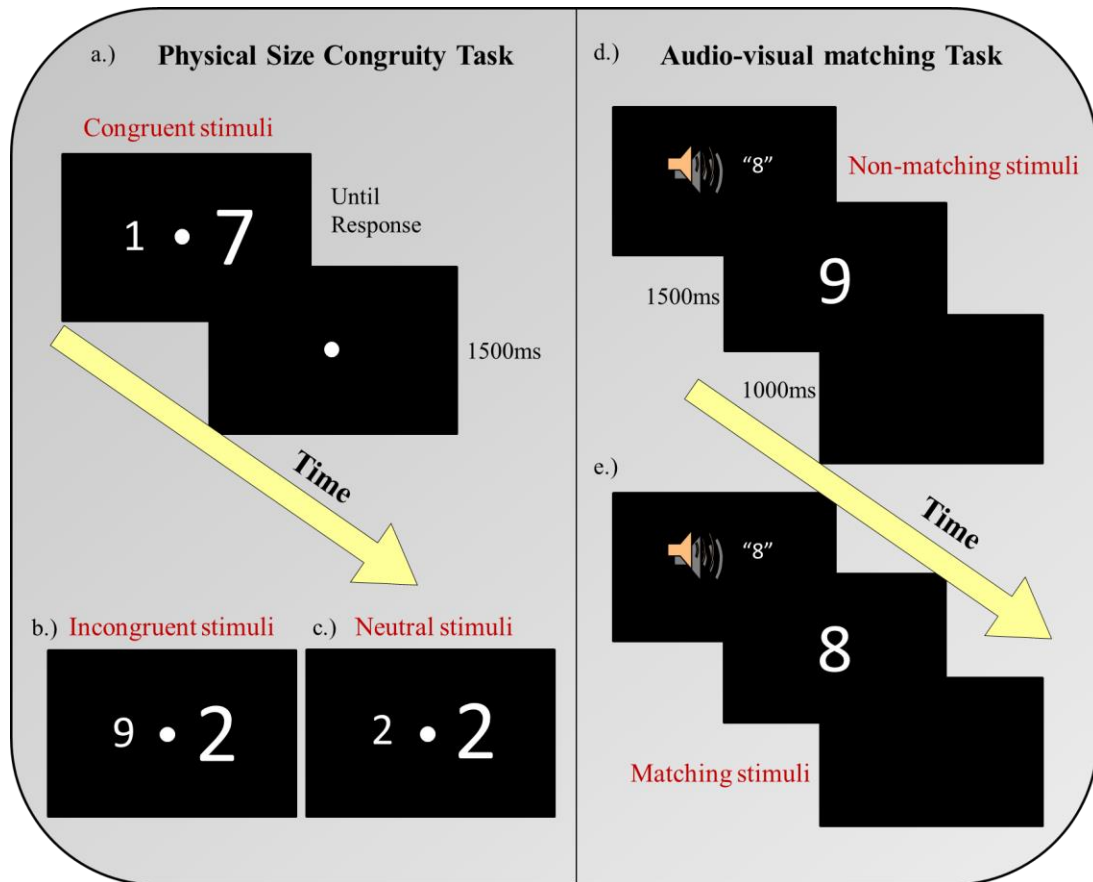


Figure 3.2: Experimental paradigms. a.) An illustration of timing procedures of the physical size congruity using an example of congruent stimuli. b.) An example of incongruent stimuli. c.) An example of neutral stimuli. d.) An illustration of timing procedures the audio-visual matching task using an example of non-matching stimuli. e.) An example of matching stimuli.

Table 3.2. Stimulus pairs administered in the physical size congruity task.

Stimulus Pair		Ratio
1	9	0.11
1	8	0.13
1	7	0.14
1	6	0.17
1	5	0.20
2	9	0.22
7	9	0.78
4	5	0.80
5	6	0.83
6	7	0.86
7	8	0.88
8	9	0.89

3.2.2.2.4 Audio-visual matching task.

Children's ability to process verbally and visually presented numbers was examined by using an audio visual matching task. During this task, children heard a number followed by an Arabic numeral visually presented computer screen (see Figure on a 3.2d). They were asked to press a button indicating whether the two numbers were the same or different (e.g. "s" = same, "l" = different). One syllable numbers were presented in a female voice to control for length of the audio stimulus. The visual stimulus was presented in the center of the screen and remained on the screen until a response was made. In half of the trials, the auditory and visually presented stimuli were the different (non-matched trials) (see Figure 3.2d) and on the other half of the trials they were same (matched trials) (see Figure 3.2e). For the non-matching trials, the distance between

stimuli ranged from 1-4 with four pairs of stimuli presented twice as both the auditory and visually presented stimuli. For the matching pairs, all numbers were administered with the exception of the number seven, because it is a two-syllable number. There were 32 non-matching and matching pairs that were presented twice for a total of 128 trials (see Table 3.3). Participants were given a break halfway through the task.

Table 3.3: Pairs of stimuli administered in the non-matched trials of the audio-visual matching task.

Non-matching Trials		
Stimulus Pair	Distance	
1	2	1
3	4	1
5	6	1
8	9	1
1	3	2
2	4	2
4	6	2
6	8	2
1	4	3
2	5	3
3	6	3
5	8	3
1	5	4
2	6	4
4	8	4
5	9	4

3.2.2.3 Non-computerized numerical processing

3.2.2.3.1 Number line estimation (NLE).

To measure children's estimation abilities, the NLE task was administered. The NLE task is commonly used to assess children's ability to estimate the spatial location of numerical representations (Siegler & Booth, 2004). Children were first presented with a practice item, where a 25cm line was presented on the middle of sheet of paper. On either end of the number line, 0 was printed just below the left side of the line, and the number 100 or 1000 was printed just below the right side of the line (NLE 100 and NLE 1000 respectively) (see Figure 3.3). On the 0 to 100 NLE practice item, 50 was presented 2cm above the center of the middle line and children were asked to draw a line where they thought 50 belonged on the number line. On the following page, children were shown the identical item with the correct response and were asked whether they knew why 50 goes in the middle (for the 0 to 1000 NLE, 500 was the practice item). Following their response, all participants were told that "50 is half of 100, it goes directly in the middle, which is half way between 0 and 100. Fifty is the only number that goes exactly in the middle. Children were then presented with 26 experimental items, with each trial item printed just above the center of the number line. The 26 trials consisted of the following numbers: 3, 4, 6, 8, 12, 14, 17, 18, 21, 24, 25, 29, 33, 39, 42, 48, 52, 57, 61, 64, 72, 79, 81, 84, 90, and 96. For the 0 to 1000 number line, children were asked to estimate the location of the following numbers: 2, 5, 18, 34, 56, 78, 100, 122, 147, 150, 163, 179, 246, 366, 486, 606, 722, 725, 738, 754, 818, and 938 (Opfer & Siegel, 2007). Items were presented in random order of each participant, and the order in which conditions were administered was counter balanced across participants (see Figure 3.3).

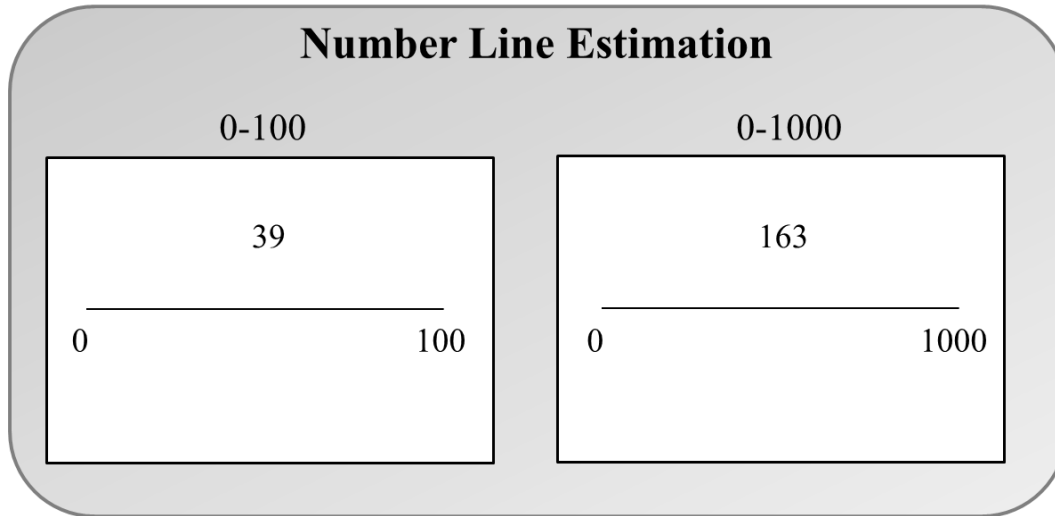


Figure 3.3: An illustration of the number line estimation task including an example of the 0-100 and 0-1000 versions of the task.

3.2.3 Procedures

Once permission was granted by the principals of participating schools, information letters and consent forms were sent home with the children who met the criteria for either persistent DD or typical development. Testing began once signed consent forms were returned to the school. Participants were assessed individually in a quiet room in their school. Children, who could not be tested in the school, but agreed to participate in the present study, were tested in a small testing room at Westminster Hall at Western University. Participants were tested in two, one hour long sessions approximately a week apart. Standardized tests of cognitive performance as well as the numerical processing tasks were administered in a counterbalanced order across participants, as well as within the session to ensure that mathematical and non-mathematical tasks were not administered together. After each session was completed, any questions were answered and children were given a \$25 gift card for a local bookstore as a token of our appreciation for participating in the study. Ethics approval through the University of Western Ontario non-medical research ethics board (see Appendix A).

3.2.3.1 Task scoring

To directly compare the tasks with one another, a similar approach was taken from Lyons et al., (2014). Performance measures were calculated across the computerized tasks. Measures of reaction and error rates were combined according to the following performance formula: $P = RT(1+2ER)$. Higher performance values represented worse performance (see Lyons et al., 2014). Performance can range from the participant's true mean reaction time (with no errors) to double their mean reaction time if participant's performance is at chance (Lyons, Price, Vaessen, Blomert, & Ansari, 2014). Trials where An outlier analysis was applied to the current data set on an individual basis, whereby reactions times that were three standard deviations above and below the mean performance were removed for each participant. The mean percentage of trials removed across all participants for each task is as follows: symbolic numerical discrimination: 1.9%, non-symbolic numerical discrimination: 1.64%; size congruity task: 1.63%; audio-visual matching task: .71%.

The mean percent absolute error was calculated as the dependent measure for both number line estimation tasks using the following formula: (child's estimate – true estimate quantity/scale) (Siegler & Booth, 2004). For example, if a child was asked to estimate the location of the number 36, and placed their mark on the number line that corresponded to the number 42 on a 0 to 100 number line. Then the difference of 8 would be then divided by 100. This was calculated for each item per participant, and the mean of percent differences were calculated for each participant.

3.3 Results

The descriptive statistics for each computerized task are reported in Table 3.4 for typically developing children and children with DD. A multivariate analysis of variance was conducted to examine group differences in performance measures on the numerical computerized tasks as well as the percent absolute errors on the number line estimation tasks. To control for group differences in age, age was included as a covariate in the analysis. The multivariate test indicated that there was a significant effect of group

across all numerical tasks, $F(6, 20) = 3.91, p < .01$. The results from the between subjects analysis demonstrate that there were significant differences in the mean percent absolute error during the 0 to 1000 NLE task, $F(1,25) = 14.61, p < .001, \eta^2 = .37$, and the symbolic numerical discrimination task $F(1, 25) = 4.89, p < .04, \eta^2 = .16$. There were marginally significant differences in performance during the audio visual matching task $F(1, 25) = 3.24, p = .08$ and the mean percent absolute error on the 0 to 100 NLE task $F(1, 25) = 3.23, p = .08$. However there were no significant differences in performance on the non-symbolic discrimination task $F(1,25) = 2.09, p = .16$ or the physical size congruity task $F(1, 25) = 1.06, p = .31$ (see Figure 3.4)

Table 3.4: Descriptive statistics for performance on the computerized numerical processing tasks.

	TD		DD	
	Mean RT (SD) [Min-Max]	Mean ACC (SD) [Min-Max]	Mean RT (SD) [Min-Max]	Mean ACC (SD) [Min-Max]
Symbolic NC	665.46 (131.70) 482.114-956.56	.89 (.12) .58-.98	779.87 (220.16) 441.54-1139.70	.89 (.07) .69-.97
Non-symbolic NC	696.37 (159.83) 528.91-1115.33	.87 (.04) .78 - .92	791.83 (229.99) 467.74 - 1183.98	.91 (.04) .83-.98
Physical size congruity (Stroop)	615.33 (180.16) 375.09 - 1001.15	.95 (.04) .78-.99	637.71 (196.18) 365.73-1114.19	.97 (.05) .80-1.0
Audio-visual matching	696.69 (150.06) 473.27-933.46	.88 (.04) .81-.97	697.36 (145.97) 452.59 - 977.21	.86 (.08) .70-.95

Note. TD = Typically developing; DD = Developmental Dyscalculia; RT = Reaction time; SD = Standard deviation; ACC = Accuracy; NC = Number comparison

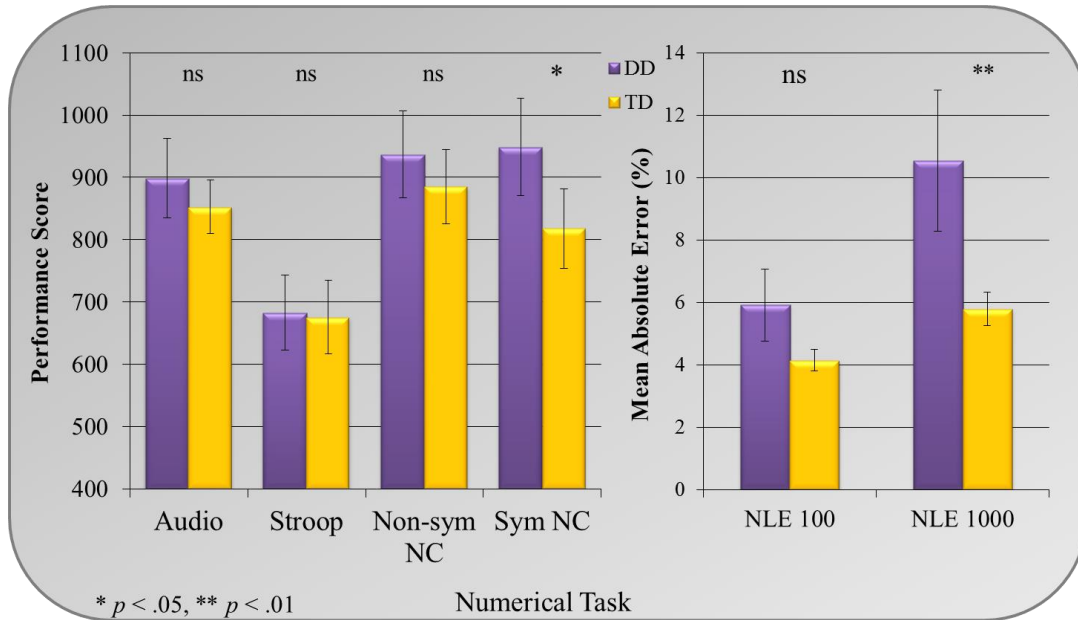


Figure 3.4: A figure illustrating group differences on performance measures on the computerized numerical processing tasks, as well as the mean absolute error on the number line estimation tasks between children with DD and typically developing children. Error bars represent one standard error on either side of the mean.

3.4 Discussion

The aim of the present study was to conduct a comprehensive investigation into the core deficits of DD by administering multiple numerical processing tasks to assess various constructs associated with quantitative knowledge. Previous studies have found conflicting support for the *representational* (defective number module and approximate number system deficit hypotheses) and *access deficit* hypotheses of DD by using numerical discriminations. In the current investigation, a variety of tasks that assess various components of numerical knowledge were administered to children with persistent DD and typically developing controls. In addition to symbolic and non-symbolic numerical discrimination, these tasks included the physical size congruity task (automatically processing symbolic numerals), the number line estimation task

(estimation of numbers on a visually presented number line), and an audio-visual matching task (integration of auditory and visually presented numerals).

Studies investigating the core deficits of numerical processing in children with DD predominantly use non-symbolic and symbolic numerical discrimination tasks, and the results of these studies provide conflicting support for the representational and access deficit hypotheses of DD. According to both representational hypotheses of DD (e.g. the approximate number system and the defective number module hypotheses), arithmetic impairments are caused by an overall deficit in processing both symbolic and non-symbolic representations of numerical magnitude. In support of this hypothesis, Mussolin and colleagues found that children with DD demonstrate significantly worse performance on both symbolic and non-symbolic numerical discrimination tasks compared to typically developing controls (2010). In contrast, the access deficit hypothesis postulates that DD is caused by a specific deficit in processing the semantic representations of symbolic numerals. Evidence supporting the access deficit hypothesis comes from studies that reveal specific impairments on symbolic numerical discrimination tasks, while children with DD show no deficits when discriminating between non-symbolic magnitudes (De Smedt & Gilmore, 2011; Rousselle & Noel, 2007). Numerical discriminations tasks are optimal for assessing the underlying representation of numerical magnitude, yet they only measure intentional processes related to discriminating between magnitudes, which is only one aspect of quantitative knowledge. Moreover, tasks that measure basic numerical magnitude processing do not necessarily assess the same numerical processes (Rubinsten, Henik, Berger, & Shahar-Shalev, 2002) but tap into distinct mechanisms that are associated with specific task demands (Bugden & Ansari, 2011).

The results of the present study suggest that symbolic number comparison and the number line estimation task demonstrate the greatest differences in performance between children with DD and typically developing peers. They are consistent with the access deficit hypothesis of DD, because children with DD performed significantly worse on the symbolic numerical discrimination task in comparison to typically developing controls. But, children with DD showed similar performance on the non-symbolic numerical

discrimination task compared to typically developing children. These results suggest that children with DD appear to have relatively intact representations of non-symbolic numerical magnitude, but demonstrate specific deficiencies in accessing the semantic meaning of symbolic numerals relative to their typically developing peers.

This deficit appears to be specific to intentional processes involved in discriminating between symbolic magnitudes, as there were no group differences found on the physical size congruity task. This suggests that automatic processes associated with the irrelevant dimension are not fundamentally different between groups. According to the access deficit hypothesis, one would expect that children with DD would have significantly faster response times during the physical size congruity task, because semantic representations of symbolic numerals would not interfere with physical size judgments. However, this was not the case in the present study, which is consistent with research conducted by Landerl and colleagues (2009; 2013). One hypothesis to account for the lack of difference in performance during the physical size congruity task is that both typical children and children with DD do not automatically process the specific magnitude of the symbolic numeral; interference and facilitation effects can be attributed to coarse classifications into small or large categories. Specifically, the irrelevant dimension of the numerical magnitude is either classified as being small (1-4) or large (6-9), where five falls under both classifications, and therefore, when these classifications conflict with the physical size, they interfere with performance. When both physical and numerical classifications are the same, facilitation effects are found (Tzelgov, Meyer, & Henik, 1992). In view of this, one might argue that although children with DD have poor performance associated with accessing the semantic meaning of numerical symbols, coarse representations (classification into small and large) remain intact, and therefore, they interact with their ability to select the physically larger stimulus. In typically developing children, performance on the physical size congruity task was not found to correlate with standardized measures of arithmetic achievement in first and second grade children (Bugden & Ansari, 2011). Additionally, the results of the present study demonstrate that automatic processes that are recruited for the physical size congruity task do not differ between individuals with DD and typically developing children. Taken together, these findings suggest that cognitive underpinnings associated with

automatically processing the irrelevant numerical dimension are not a critical skill for arithmetic performance/development.

Performance on the non-symbolic numerical discrimination task did not differentiate between children with DD and typically developing children, which is contrary to what the approximate numerical deficit hypothesis (or defective number module hypothesis) would expect (Piazza et al., 2010). According to these findings, children with DD do not demonstrate an underlying impairment in the approximate number system, but their approximate numerical abilities were relatively comparable to typically developing children. These findings are consistent with previous studies that did not find significant differences in performance during non-symbolic numerical discrimination tasks (DeSmedt & Gilmore, 2011; Rousselle & Noel, 2007). Similarly, within the typically developing literature, the relationship between non-symbolic numerical abilities and individual differences in symbolic math performance is inconsistent (for a review see: De Smedt et al., 2013). The sources of these conflicting findings in both typically and atypically developing studies remain unclear. However, recent typically developing studies have begun to reveal that differences in task construction can impact performance (Gilmore et al., 2013; Inglis & Gilmore, 2013, 2014). Specifically, Gilmore and colleagues (2013) found that the visual and perceptual properties of the dots (e.g. size, area, and density) conflict with the numerically larger dot array (incongruent trials) and appear to be driving the relationship between approximate numerical abilities and math achievement. Furthermore, inhibition skills accounted for greater unique variability in predicting math achievement than performance on the approximate numerical task. The effect that visual perceptual variables of dot stimuli has on performance during non-symbolic numerical discriminations in children with DD compared to TD children will be examined in Chapter four of the present thesis.

Children with DD demonstrated pronounced deficits in estimating the spatial location of numbers during the 0 to 1000 number line estimation task. These findings highlight an important avenue of future research into the development of the place value system for Arabic numerals. The place value system (base 10 system) refers to the positional organization of multiple digit numbers (e.g. $10 - 1 =$ tens column and $0 =$ ones

column). Previous research using double digit numerical discrimination tasks has shown that double-digit numbers are not processed holistically, but the magnitude of the numeral in the ones and tens column affects accuracy rates and response times during numerical discrimination in typically developing adults (Neurk, Weger, & Willmes, 2001). Additionally, Landerl et al. (2013) found that children with persistent DD showed greater and stable impairments in discriminating between double-digit numbers over time. The authors found that children with DD did not demonstrate a systematic pattern of responses but randomly made a response based on the size units or tens column, and therefore, it was suggested that children with DD guessed on the double-digit task. Very few studies have investigated the integrity of the place value system in children with DD and future research is required to elucidate whether numerical representational system in children with DD breaks down for multiple digit numbers.

The audio-visual matching task did not reveal significant group differences during the integration of auditory and visually presented numbers. However, there was a marginally significant trend with DD children showing worse performance compared to typical controls. Recently, Göbel and colleagues (2014) used a similar task where children had to identify Arabic numerals corresponding to verbal number words at six years of age. They found that this task was a unique predictor of arithmetic over 11 months (Göbel, Watson, Lervåg, & Hulme, 2014). These findings demonstrate that children with DD do not exhibit a deficit in matching symbolic numerals that are presented cross modally. The access deficit hypothesis purports that deficits in DD are caused by deficiencies in accessing the semantic representation of Arabic numerals, therefore, the lack of group differences found in the audio-visual matching task further support that cross modal representations (both audio and visual stimuli are symbolic representations) are not the locus of deficit, but that children with DD have greater difficulties in accessing representations across format. To the best of my knowledge, only one study has investigated the relationship between audio visual matching task and arithmetic performance in typically developing children in grades one through six (Lyons et al., 2014). They found that performance on this task did not significantly predict individual differences in arithmetic, suggesting that integrating verbal and visually

presented numbers is not a fundamental skill required for the development of basic arithmetic skills, unlike in other academic domains such as reading.

Although the present study found significant differences in performance during symbolic number comparison and number line estimation, the MANOVA only tests for differences in performance between groups, and does not reveal an interaction between task and group. Although these findings appear to be consistent with studies that have also demonstrated specific impairments on tasks that require the processing of symbolic numerals (De Smedt & Gilmore, 2011; Rousselle & Noel, 2007), it is important to note that the specificity of this impairment is yet to be determined with this analysis. Additionally, the present study cannot disentangle the relative contributions of the defective number module and the approximate number system hypotheses in predicting DD. The non-symbolic task was not designed to examine whether there are differences in performance during the discrimination of small dot arrays (e.g. exact non-symbolic processing) compared to the discrimination of large dot arrays (e.g. approximate non-symbolic processing).

Taken together, the present findings revealed that children who were identified on the basis of persistent arithmetic deficits did not exhibit numerical magnitude processing deficits across tasks that measure various constructs of quantitative knowledge. Instead, they demonstrated deficiencies in processing and representing symbolic numerical representations as evidenced by poor performance on the symbolic numerical discrimination and the 0 to 1000 number line estimation tasks relative to their typical peers. The results appear to conflict with the representational hypotheses of DD (defective number module and approximate number system hypotheses) suggesting that children with DD do not exhibit impairment in processing non-symbolic magnitudes, but show specific deficits in processing symbolic numerals. The present data provide stronger supporting evidence for the access deficit hypothesis of DD, suggesting that children with persistent DD exhibit greater difficulties in accessing the semantic representation of symbolic numerals.

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Chapter 4

4 Probing the nature of approximate numerical deficits in children with persistent DD

4.1 Introduction

Children with DD have severe difficulties executing calculation procedures and often rely on immature strategies when they cannot consolidate arithmetic facts into long-term memory (Geary, 1993). The underlying cognitive and neural mechanisms leading to poor arithmetic performance in children with DD are currently not well understood (Price & Ansari, 2013). Furthermore, gaps in our knowledge about the core deficits and characteristics of children with DD have led to inconsistent causal proposals accounting for the severe difficulties children with DD have with learning basic arithmetic.

One dominant proposal is that DD is caused by a core deficit in the so-called ‘Approximate Number System’ (ANS; Piazza et al., 2010; Piazza, 2010); a system responsible for manipulating and discriminating approximate numerical quantities (Dehaene, 1997; 2007; Wilson & Dehaene, 2007). The ANS is thought to be a phylogenetic precursor to developing exact symbolic representations (e.g. number words and Arabic numerals) that enable children to carry out basic arithmetic problems and higher order mathematics (Piazza, 2010). Consequently, deficiencies in the ANS would lead to imprecise symbolic representations and poor arithmetic knowledge.

Currently the ANS is assessed using a non-symbolic numerical discrimination task where children are asked to choose the numerically larger dot array as fast and accurately as they can without counting. Response times and accuracy measures are used as indices for the precision of the ANS. As the numerical distance/difference between the two dot arrays decrease, reaction time and error rates increase - this is referred to as the Numerical Distance Effect (NDE; Moyer & Landauer, 1967; Sekuler & Mierkiewicz, 1977). The Numerical Ratio Effect (NRE) is a complementary effect that accounts for the numerical ratio between the compared dot arrays. The NDE and the NRE have been

explained by recourse to models of numerical representation, which postulate that magnitudes are represented on a hypothetical internal mental number line. Numerical values activate a Gaussian distribution, thus creating overlapping distributions of numbers that are separated by a relatively small numerical distance/large numerical ratio (Dehaene & Cohen, 1995; Dehaene, 1997; Gallistel & Gelman, 2000). These representations are thought to be analogue and therefore imprecise. The parameters of the Gaussian distribution specify the nature and precision of numerical representations. The Weber fraction (W), which is an index of ‘number acuity’, is indicative of the standard deviations of the estimated Gaussian distributions of numerical representations in the approximate number system. It signifies the degree of precision and amount of error in one’s quantity representations (Halberda, Mazocco & Feigenson, 2008). More specifically, as W increases, the noise of the internal representations increases whereby the discrimination of numerical magnitude close to one another becomes more difficult (Dehaene, 2003; 2007). Therefore, W is a psychophysical model indexing the underlying internal representation of numerical magnitude. Better performance on the non-symbolic numerical discrimination task results in a smaller W , which is indicative of a more precise internal representation of numerical magnitude (Halberda et al., 2008). There is evidence to suggest that individual differences in W predict variability in symbolic mathematical achievement, supporting the notion that precise numerical magnitude representations are associated with higher mathematical abilities in typically developing individuals (Halberda et al., 2008; Libertus, Feigenson & Halberda, 2013).

The first evidence supporting the ANS core deficit theory in DD was obtained by Piazza et al., (2010). The authors found that school-aged children with DD demonstrated severely impaired numerical acuity (as indexed by W) on a non-symbolic numerical discrimination task in comparison to a group of typically developing peers. More specifically, children with DD obtained W scores equivalent to five year-old typically developing children suggesting that their quantity representations are severely delayed. ANS acuity deficits in children with DD were further corroborated by a number of studies (Mazocco, Feigenson & Halberda, 2011); Mussolin, Meijas & Noel, 2010; Price et al., 2007). In contrast to these findings, some researchers have failed to find performance differences on the non-symbolic numerical discrimination task between

children with DD and their typically developing peers (DeSmedt & Gilmore, 2011; Rousselle & Noel, 2007)

The finding of lower ANS acuity in individuals with DD has been understood to reflect the impairment of the internal representation of numerical magnitude (i.e. a core representational deficit). However, recent research has suggested that processes other than the internal approximate representation of numerical magnitude influence performance indicators, such as Ws on non-symbolic numerical magnitude discrimination tasks. Specifically, researchers have begun to examine how the visual properties of the dot stimuli impact numerical discriminations. During non-symbolic numerical discrimination, participants can rely on non-numerical cues such as the size of the individual dots, or the total surface area of dots to select the numerically larger dot array. Therefore, to ensure that participants do not use superficial non-numerical cues to choose the numerically larger dot array, researchers commonly use various methods to control for dot size, density and area. The most common method to control for visual parameters is to develop stimuli where the sizes of the dot arrays are either negatively or positively correlated with the larger number in the pair. This is then presented to participants with both trial types to ensure that non-numerical variables are not a reliable cue in non-symbolic numerical magnitude discrimination tasks. For example, dot pairs where the more numerous dot array also occupies a larger area, are congruent trials. Alternatively, pairs of dots where the more numerous dot array occupies a smaller area are referred to as incongruent trials. These trials are incongruent, because they force participants to ignore the visual size of the dots in order to select the numerically larger dot array. It is important to note that there is no perfect way to control for non-numerical parameters in non-symbolic numerical discrimination (Gebuis & Reynvoet, 2012). During any given trial, participants can rely on different non-numerical cues to influence their decision, more specifically, on trials where the total surface area are equated, participants can use individual item size to make a response and vice versa.

Furthermore, recent evidence has suggested that the way in which numerical and non-numerical dimensions co-vary affects the strength of the correlation between symbolic math achievement and ANS acuity in typically developing children (Gilmore et

al., 2013). Specifically, Gilmore and colleagues found that only performance on the incongruent trials (in which the less numerous dot array occupied the larger stimulus area) of the nonsymbolic numerical discrimination task was significantly related to symbolic math achievement. In other words, only when children had to resolve a conflict between number and stimulus area did performance account for individual differences in math achievement. Moreover, when non-numerical inhibition scores were controlled for, the relationship became non-significant, suggesting that incongruent trials tap into inhibitory control mechanisms which in turn are correlated with math achievement.

In other words, the findings by Gilmore et al. (2013) suggest that the commonly found relationship between math achievement and W is not specific to numerical acuity, but is driven by the relationship between performance on the incongruent trials and individual differences in inhibitory control. This conclusion is also supported by a set of findings presented by Fuhs and McNeil (2013). These authors found that ANS proficiency in preschool children during the incongruent trials (surface area was inversely related to numerical magnitude) predicted math achievement. However, consistent with the findings of Gilmore and colleagues, this association was rendered non-significant once inhibitory control was taken into account. Based on this evidence it has been contended that inhibitory control likely plays a key role in selecting the numerically larger dot array during incongruent trials and therefore, affects the relationship between ANS acuity and arithmetic achievement in typically developing populations. Furthermore, these findings suggest that performance on tasks used to index the ANS is influenced by the covariation of numerical and non-numerical dimensions. This in turn modulates the relationship between measures of ANS and math achievement.

To date, only a few studies have investigated the effect of non-numerical variables on the non-symbolic numerical magnitude processing in children with DD. In one study, Mussolin et al., 2010 found that children with DD were more sensitive to surface and density cues of stick stimuli. Specifically, these authors found a trend, whereby children with DD made more errors than their typically developing peers when the surface area was incongruent with the number of sticks. Additionally, DeFever, Reynvoet, and Gebuis (2013) found that children with and without DD made more errors

on non-symbolic numerical magnitude discrimination task trials where the surface area and density of the dots were incongruent with numerical magnitude. Against the background of these findings, the authors suggested that non-symbolic numerical discrimination does not reflect pure numerical processing, but evokes, at least in part, visual processing strategies (DeFever et al., 2013). However, from these data, it remains ambiguous what specific underlying mechanisms or strategies are employed by both typically and atypically developing populations during non-symbolic discrimination. Furthermore, it is unclear whether children with DD are more affected by the conflicts between numerical and non-numerical variables in non-symbolic numerical magnitude discrimination tasks.

In light of these findings, it remains an open question whether children with DD have a deficient approximate number system which may lead to arithmetic deficits in school. Alternatively, performance differences on non-symbolic numerical magnitude processing tasks are caused by differences in the way in which DD and TD children process numerical and non-numerical stimulus parameters.

It is evident from the above literature review that current findings regarding the ANS in the DD literature are contradictory, and there are no clear conclusions as to what causes DD. Furthermore, there is no universally agreed upon criteria for diagnosing children with DD. This causes difficulty for researchers to make conclusions about what underlying cognitive mechanisms impair their ability to learn basic arithmetic. Some studies have included samples with milder forms of math deficits (Geary, Hoard, Byrd-Craven & DeSoto, 2004; Jordan, Hanich & Kaplan, 2003), while others use more strict criteria, for example Mazzocco and colleagues limited their sample of children with below the 10th percentile on math achievement (Mazzocco & Myers, 2003; Mazzocco, Devlin & McKenney, 2008). Importantly in the context of the present investigation, it was only children with DD who met the criteria for severe and persistent math deficits that demonstrated impairments in the ANS in comparison to children who had low math achievement (e.g. 11-35th percentile on math achievement), and typically developing children. Given that mathematics abilities vary over time (Mazzocco & Myers, 2003), it has been proposed that research studies impose a stability criterion to ensure that children

with DD are demonstrating persistent arithmetic impairments reducing the number of false positives within a DD sample (Mazzocco & Rasanen, 2013). This is further supported by the recently published Diagnostic Statistical Manual-V (American Psychological Association, 2013) requiring symptoms of severe mathematical deficits to be persistent over time to meet the criteria for DD.

The aim of the current study was to investigate differences in the ANS in children with DD characterized by a stable deficit on standardized tests of math achievement compared to typically developing age matched children. In addition, the effect of the congruency of the visual perceptual and numerical parameters during a non-symbolic numerical discrimination task were examined between children with and without DD. To elucidate the underlying cognitive mechanisms engaged during non-symbolic discrimination, we explored the relationship between working memory and performance during both the incongruent and congruent trials.

The integrity of the ANS in children with and without DD was evaluated using the Panamath program (Halberda, Mazzocco & Feigenson, 2008), which is a non-symbolic numerical discrimination task developed to assess the precision of the ANS (published online for research and public use - www.panamath.org). In the Panamath program, non-numerical parameters are controlled such that in half of the trials, the average size of dots of the more numerous dot array contained smaller sized dots (incongruent trials). On the other half of the trials, the total area of each dot array was proportional to the total number of dots in the larger array (congruent trials). Previous studies have found that children with DD have imprecise approximate numerical representations compared to typically developing children when analyzing the whole nonsymbolic numerical discrimination task (both congruent and incongruent trials). Therefore, consistent with previous research (Mazzocco et al., 2011; Piazza et al., 2010), it was hypothesized that children with DD would exhibit imprecise ANS acuity as indicated by a larger W , or greater errors, compared to typically developing children.

However, as discussed above, recent findings have questioned the precise cognitive mechanisms involved in discriminating between approximate quantities during

trials where non-numerical parameters are incongruent with the larger numerosity (Gilmore et al., 2013). Given these findings, we hypothesize that if children with DD have a pure domain specific impairment in the ANS, they would demonstrate higher W and greater errors on both incongruent and congruent trials compared to typically developing children. In other words, if the Panamath non-symbolic numerical discrimination is a pure measure of approximate numerical abilities, then group differences as a function of the congruency of the visual perceptual cues and numerical dimension would not be expected. However, if deficits on the non-symbolic numerical discrimination task are driven by difficulties in processing the conflict between numerical and non-numerical stimulus attributes, we would expect to find a larger size congruity effect in children with DD compared to typically developing children.

To examine whether verbal or visuo-spatial working memory predict individual differences in ANS acuity, correlation analyses were conducted independently for children with DD and typically developing controls. These analyses were conducted separately between groups to elucidate whether children with DD recruit different cognitive processes during the discrimination of incongruent and congruent dot stimuli compared to typically developing children.

4.2 Method

4.2.1 Participants

4.2.1.1 Developmental Dyscalculia group

Fifteen children with Developmental Dyscalculia (Mean age = 12.36, $SD = 1.20$; range: 9.44 -13.68 years) were included in the present study (11 boys, 4 girls). To meet our criteria for DD, children had to demonstrate stable low math impairments on Math Fluency and Math Calculation subtests (timed and untimed tests of basic arithmetic) from the Woodcock Johnson-III standardized tests of math achievement (Woodcock, McGrew, & Mather, 2001) over four years. Children who were selected based on these criteria were recruited back for follow up testing during the spring of 2012 and fall of 2013, at which time the non-symbolic numerical discrimination task was administered. Three

children with DD, who did not participate in the spring of 2012 testing session, were included in the present study. At the time of final testing session in fall 2013, children with DD persistently performed below average on the standardized tests of math achievement. However, children with DD demonstrated variable performance on the Reading Fluency subtest, as well as verbal and visuo-spatial working memory measures during the spring testing sessions. There are five children who had a stable low reading deficit on the Reading Fluency subtest across all testing sessions, and therefore, may have comorbid Dyslexia (a specific reading learning disability). However, evidence has demonstrated that processing numerical magnitudes is not further impaired by a reading learning disability (Hanich, Jordan, Kaplan & Dick, 2001; Landerl et al., 2004) (see chapter 2 for descriptive statistics of children with DD).

4.2.1.2 Typically developing control group

The control group consisted of 15 typically developing children who were age matched to the DD group (Mean age = 11.72, $SD = .88$; range 10.32 – 13.37 years; 8 boys, 7 girls). There were no significant differences of age found between DD and typical groups, $t(28) = -1.66, p = .11$. Children were recruited to be in the typically developing group if they demonstrated persistent typical performance or above (>85 standard score) on both subtests of arithmetic achievement, as well as working memory and reading fluency and IQ during the previous testing session. There were four typically developing children who did not participate in the fourth testing session during the spring of 2012 who were included in the present study. The typically developing group demonstrated stable IQ, working memory, arithmetic, and reading achievement scores within the normal range and above throughout all testing sessions. However, during the fall of 2013, there were three typically developing children who performed just below the cut off criterion of 85 on both Math Fluency and Math Calculation subtests (see chapter 2 for descriptive statistics of typically developing sample).

4.2.2 Materials

4.2.2.1 Standardized tests of cognitive performance

During the fifth testing session, the Math Calculation and Math Fluency subtests from the Woodcock Johnson standardized tests of achievement (Woodcock, McGrew, & Mather, 2001) were administered to each participant. Additionally, the Reading Fluency subtest from the Woodcock Johnson-III (Woodcock, McGrew, & Mather, 2001) was administered to measure participants' reading abilities (see p. 50 in Chapter 2 for description of standardized measures).

4.2.2.2 Non-symbolic discrimination: Panamath

ANS acuity was assessed using the Panamath version 1.22 software (Halberda, Mazocco & Feigenson, 2008; <http://panamath.org>) available online. Panamath is a non-symbolic discrimination task where a yellow dot array and a blue dot array were presented simultaneously side-by-side on a computer screen. Participants were asked to select the numerically larger dot array as quickly and as accurately as possible by pressing the respective button on a laptop. Stimuli display times were tailored to the age of the participant. Stimuli were presented on the computer screen for 1506ms, 1382ms, 1269ms, 1165ms, or 1071ms for participants who were 9, 10, 11, 12 or 13 years of age, respectively. Each trial was followed by a backward mask of yellow and blue white noise and then a grey screen. Participants could respond during or after the presentation of the dot arrays. Following a response, a fixation cross appeared until the participant pressed the space bar to display the next trial. The level of difficulty was manipulated by varying the ratio between the left and right dot array; the ratios were 3:8, 2:3, 4:5, and 7:8. Half of the trials were congruent, meaning that both sets of colored dots were proportional to the number of dots within the array. During these trials, the area or the amount of color in the larger dot array was congruent to its numerosity. The other half of the trials was incongruent, meaning that the proportion of area occupied by each colored dot array was equal, and therefore, the amount of visual surface area was negatively correlated with numerosity. For these trials, children could not select the larger dot array

by relying on the amount of color occupying space on the computer screen (See Figure 4.1). Panamath was administered for a total of 5 minutes, and depending on each individual's speed of response, the amount of trials varied per participant. The total number of trials completed by participants ranged from 104 to 128 trials with younger participants completing fewer trials.

A weber fraction was generated by the Panamath software for each participant using the following model: $\frac{1}{2} \operatorname{erfc}\left(\frac{n_1 - n_2}{\sqrt{2w} \sqrt{n_1^2 + n_2^2}}\right)$. For each participant, this model fits the average percentage correct for each ratio bin on the numerical discrimination task, with W (weber fraction) as a free parameter (see Panamath.org; Halberda et al., 2008 for a complete description of the modeling parameters for obtaining individual weber fractions).

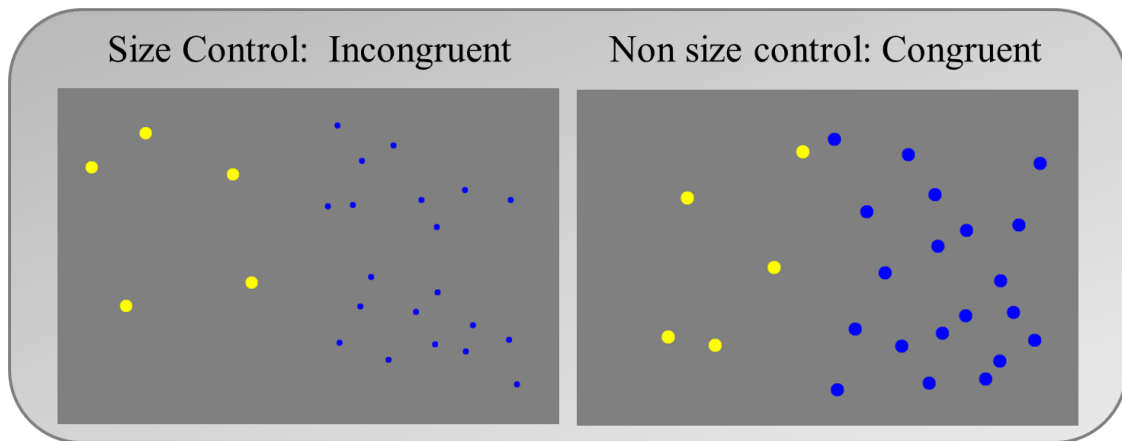


Figure 4.1: An example of incongruent and congruent stimuli administered in the Panamath task.

4.2.3 Procedure

During four previous visits each child completed the standardized battery of cognitive tests measuring math, reading, working memory skills and intelligence (see Figure 2.2 in chapter 2). During the fifth visit, children were tested individually in a quiet university

laboratory testing room where participants completed the Reading Fluency, Math Fluency and Calculation subtests from the Woodcock Johnson standardized tests of achievement (Woodcock, McGrew, & Mather, 2001). Following the standardized tests, participants completed the Panamath non-symbolic discrimination task (and other tasks not reported here) (see Figure 2.2 for a time line of testing sessions and standardized measures). This session lasted approximately one hour.

4.3 Results

4.3.1 Weber fraction (W)

To investigate whether the congruity of the dot stimuli influenced performance differently in our sample of persistent DD and typically developing children, a 2 (incongruent, congruent) x 2 (DD, Typical) mixed factorial ANOVA was conducted on W. We found a significant main effect of group, $F(1,28) = 6.24, p = .019, \eta^2 = .18$, a significant main effect of congruity, $F(1, 28) = 11.82, p = .002, \eta^2 = .23$, as well as a significant interaction between group and congruity, $F(1, 28) = 5.68, p = .02, \eta^2 = .17$ (see Figure 4.2). To further explore the locus of the interaction, independent samples t-tests were conducted on W for the incongruent and congruent trials between groups. The results from these analyses indicate that there was a significant difference between children with DD and typically developing children during the incongruent trials [$t(15.72) = -2.80, p = .013, d = 1.02$, equal variances not assumed, $F(1,28) = 10.14, p = .004$]. However, there was no significant difference between groups during the congruent trials [$t(28) = -1.64, p = .113, d = .60$ equal variances assumed, $F(1, 28) = 2.10, p = .16$]. These findings suggest that differences in ANS acuity found between groups are driven by larger W during the incongruent trials; however, there were no group differences in ANS acuity during the congruent trials. Paired samples t-tests were conducted within group to investigate the simple main effects of congruency within group. There were no significant differences in W between incongruent and congruent trials in typically developing children [$t(14) = -1.30, p = .22, d = .33$]. However, children with DD had a significantly larger W during the incongruent trials compared to congruent trials, $t(14) = -3.19, p = .007, d = .82$ (see Figure 4.2).

It has been proposed that comorbidity of dyslexia (RD) and DD results from domain general deficits in processing speed and working memory that cause greater severity in mathematical and reading performance in comparison to children with RD or DD (Wilcutt et al., 2013). We examined whether ANS acuity deficits observed during the incongruent trials are attributed to the severity of having comorbid learning disorders. Five children who demonstrated persistent impairments in reading fluency scores were removed from the analysis to examine whether the effect of having comorbid DD and RD (double deficit) are driving poor performance during the incongruent trials. The interaction between congruency of dot stimuli and group remained significant $F(1, 23) = 6.23, p < .02, \eta^2 = .21$. The interaction was driven by significant group differences during in the incongruent trials, $t(10.52) = -2.48, p < .05, d = 1.08$ equal variances not assumed, $F(1,28) = 6.35, p = .02$, but no significant differences during the congruent trials $t(23) = -1.14, p = .26, d = .47$. Additionally the effects are not altered when the three typically developing children who demonstrated low math scores during the last testing session were removed from the analysis.

4.3.2 Error rates

Although we reported W in the main analysis above, the same pattern of findings was found using error rates (see Figure 4.2b). When error rates were submitted to a 2 (incongruent, congruent) x 2 (DD, Typical) Mix Factorial ANOVA, similar to the W analysis, a significant main effect of group, $F(1,28) = 8.27, p = .008, \eta^2 = .23$, a significant main effect of Congruity $F(1,28) = 11.74, p = .002, \eta^2 = .30$, and a significant interaction between congruity and group $F(1,28) = 5.83, p = .02, \eta^2 = .17$ were found. To further explore the locus of the interaction, an independent samples *t*-test was conducted on error rates in the incongruent and congruent trials between groups. The results from these analyses indicated that there were significant differences between DD and typically developing children in error rates during the incongruent trials $t(18.65) = -3.25, p = .004, d = 1.18$, equal variances not assumed, $F(1,28) = 6.82, p = .01$; however, there were only marginally significant differences in the congruent trials $t(28) = -1.96, p = .06, d = .71$, equal variances assumed, $F(1,28) = 1.22, p = .028$. Paired samples *t*-tests were conducted within group to investigate the simple main effects of congruency within

group. There were no significant differences in error rates between incongruent and congruent trials in typically developing children, $t(14) = -.84, p = .42, d = .22$. However, children with DD had significantly greater error rates during the incongruent trials compared to congruent trials, $t(14) = -3.67, p = .003, d = .95$. In agreement with the analysis conducted on W , these findings demonstrate that children with DD had greater error rates during incongruent trials, where the surface area is incongruent with the numerical magnitude of the larger dot array, compared to performance during the congruent trials, where the surface area is congruent with the numerical magnitude of the larger dot array (see Figure 4.2).

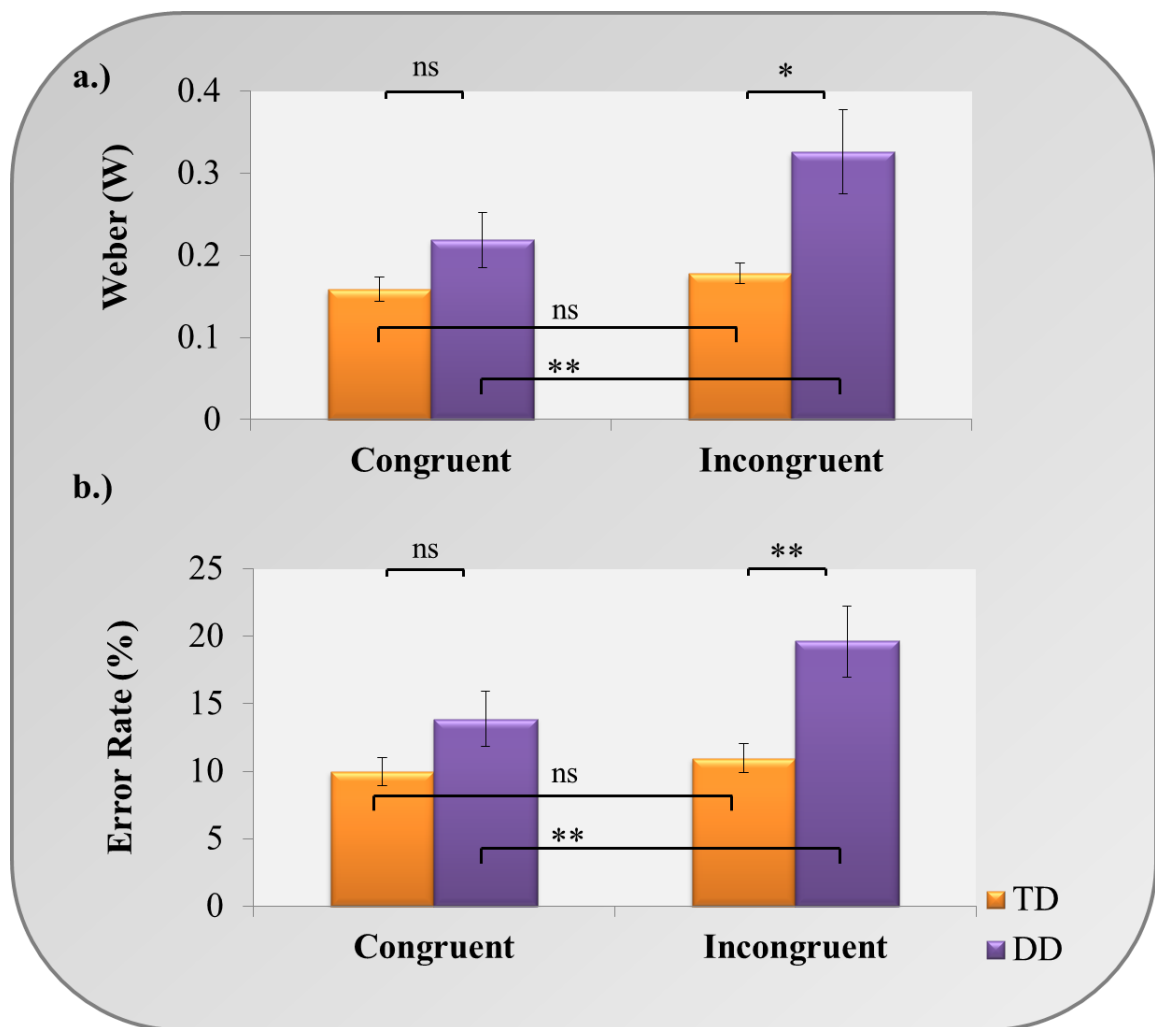


Figure 4.2: A significant interaction between group and congruency during the Panamath non-symbolic discrimination indicating children with DD were less accurate and precise at choosing the numerically larger dot array in the incongruent trials. a.) Bars represent a

larger mean W fraction in children with DD during the incongruent trials compared to typically developing children. b.) Bars represent mean error rates, with greater errors being made by children with DD during the incongruent trials in comparison to typically developing children. In both figures, error bars represent one standard error on either side of the mean.

4.3.3 Correlational analysis

To examine the role of working memory during the discrimination of congruent and incongruent trials of the Panamath task in children with DD, and typically developing children, a correlation analysis was conducted between the W on the incongruent and congruent trials and verbal and visuo-spatial working memory measures. Spearman's correlations were conducted to evaluate whether visuo-spatial working memory abilities modulate performance during non-symbolic discrimination differently in children with DD and typically developing children. Correlations were performed within groups to ensure correlations were not driven by group differences.

4.3.3.1 Developmental Dyscalculia

For children with DD, visuo-spatial working memory significantly correlated with W during incongruent trials, as well as congruent trials [$r(13) = -.52, p = .048$; $r(13) = -.54, p = .038$, respectively] (see Figure 4.3). Error rates during the incongruent trials and the congruent trials significantly correlated with visuo-spatial working memory [$r(13) = -.51, p = .05$; $r(13) = -.52, p = .05$ respectively]. There were no significant correlations between error rates and W during the incongruent and congruent trials and verbal working memory abilities (see Table 4.1 for correlation matrix).

4.3.3.2 Typically developing children

Visuo-spatial working memory did not significantly correlate with W during the incongruent, $r(13) = .02, p = .95$, and congruent trials, $r(13) = .05, p = .87$. However, W during the congruent trials marginally correlated with verbal working memory, $r(13) = -.47, p = .08$. Error rates during the incongruent trials did not significantly correlate with

visuo-spatial working memory, $r(13) = .12, p = .66$ (see Figure 4.3). Furthermore, there were no significant correlations between error rates during the congruent trials and visuo-spatial working memory or verbal working memory [$r(13) = -.03, p = .92$; $r(13) = -.44, p = .10$, respectively; see Figure 4.3].

4.3.3.3 Differences in correlation coefficients

To examine whether there is a significant difference between the correlation between incongruent W and visuo-spatial working memory in typically developing children ($r = .02$) and children with DD ($r = -.52$), a Fisher z test was conducted. A one tailed z test demonstrated that there is a marginal significant difference between the strength of the relationship between performance during the incongruent trials and visuo-spatial working memory in typically developing children and children with DD ($z = 1.46, p = .07$; two-tailed test $p = .14$). This difference is significant when correlations coefficients for the relationship between incongruent error rates and visuo-spatial working memory were submitted to a Fisher z test ($z = 1.67, p = .05$; two-tailed $p = .09$).

Table 4.1: Correlation matrix

DD	1	2	3	4	5	6
1 Incongruent W		.79**	.99**	.82**	.27	-.52*
2 Congruent W			.81**	.99**	.41	-.54*
3 Incongruent ERR				.84**	.31	-.51*
4 Congruent ERR					.34	-.52*
5 Verbal WM						-.41
6 Visuospatial WM						
TD	1	2	3	4	5	6
1 Incongruent W		.42	.99**	.41	.08	.02
2 Congruent W			.42	.99**	-.47†	.05
3 Incongruent ERR				.42	.12	-.03
4 Congruent ERR					-.44†	-.02
5 Verbal WM						.23
6 Visuospatial WM						

Note . DD = Developmental Dyscalculia; TD = Typically Developing; W = Weber fraction; ERR = Error rates; WM = Working memory.

* = $p \leq .05$; ** $p < .001$; † = $p < .10$

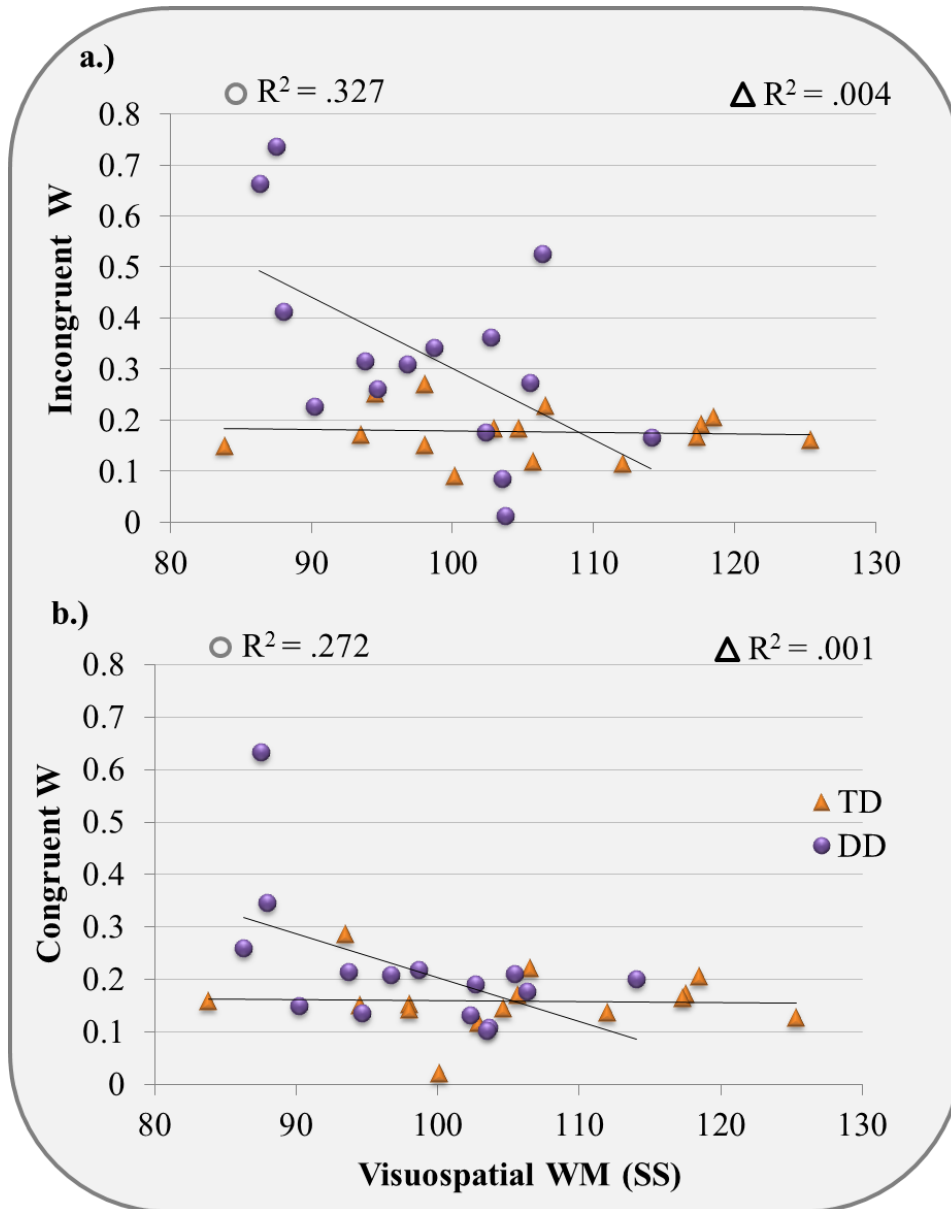


Figure 4.3. Correlational analyses. a.) The relationship between W during the incongruent trials of the Panamath task and visuo-spatial WM separately in DD and TD children. b.) The relationship between W during the congruent trials of the Panamath task and visuo-spatial WM in DD and TD children. *Note.* W = Weber fraction; WM = working memory; SS = standard score; TD = typically developing; DD = developmental dyscalculia.

4.4 Discussion

Previous studies have revealed that children with DD perform poorly on non-symbolic number discrimination tasks, such as the Panamath task (Mazzocco et al., 2011; Piazza et al., 2010). These group differences have been postulated to reflect a core representational impairment of numerical magnitude processing, or an impaired Approximate Number System (ANS) in DD. The non-symbolic numerical discrimination task has been commonly employed to measure the integrity of the ANS; however, recent research has found that measures of W and error rates collected from this task are influenced by the relationship between numerical and non-numerical parameters of non-symbolic stimuli in typically developing children (Fuhs & MacNeil, 2013; Gilmore et al., 2013). These recent data call to question whether group differences on ANS tasks can be solely attributable to an impairment of the representations that are thought to drive performance in ANS tasks. Alternatively, group differences appear to be driven by processes related to dealing with conflicting numerical and non-numerical cues in non-symbolic numerical magnitude processing tasks.

To further elucidate the role of the ANS in characterizing the cognitive deficits in children with DD, and the effect of non-numerical cues on performance, the aim of the current study was to examine whether controlling for visual perceptual parameters, such as area, of the dot stimuli alters measures of ANS acuity and differences therein between children with and without DD. To address this aim, the current study recruited a group of children with severe and persistent arithmetic difficulties from a previously conducted longitudinal screening study (Archibald et al., 2013). To ensure our typically developing control group did not have any learning disabilities, we recruited children with persistent typical performance on standardized tests of math, reading and working memory. To assess the precision of the ANS, weber fraction (W) and error rates were collected from the Panamath non-symbolic numerical discrimination task, which required children to judge the relative numerical magnitude of visually presented dot arrays (Halberda et al., 2008). The importance of scrutinizing the underlying processes employed in tasks such as the non-symbolic numerical discrimination task is critical in understanding the mechanisms that are impaired in children with DD.

Based on previous findings, we hypothesized that children with persistent DD would demonstrate greater error rates and larger W on the Panamath task compared to typically developing peers (Mazzocco et al., 2011; Piazza et al., 2010). However, given recent findings by Gilmore and colleagues (2013), we further predicted that if the approximate number system was truly impaired in children with DD, then they would have greater error rates and W regardless of the congruency of the dot stimuli compared to typically developing peers. In contrast, if domain general ancillary systems or low level visual perceptual processes are compromised in children with DD, making it difficult for them to tease apart conflicting numerical and non-numerical parameters, then performance differences would only be expected when there are conflicts between numerical and non-numerical cues. Specifically, it could be expected that children with DD would demonstrate greater error rates and imprecise W s during trials where the total area of dot stimuli is incongruent with the larger numerosity compared to congruent trials.

Consistent with previous research (Mazzocco et al., 2011; Piazza et al., 2010), we found that children with persistent DD demonstrated significantly greater error rates and W compared to typically developing children. However, in contrast to these studies, in which researchers did not examine the effect of congruency on performance, we found that differences between DD and typically developing children were driven by performance during the incongruent trials. More specifically, only children with DD demonstrated greater error rates and W during the incongruent trials, where the total area of the dot stimuli were anti-correlated with numerical magnitude, compared to their typical age matched peers. In contrast, their ability to discriminate numerical dot arrays remains intact during the congruent trials, where the total area of dot stimuli were positively correlated with numerical magnitude, in relation to their typically developing peers' performance.

These findings reveal that indices commonly used to measure the internal representation of numerical magnitude (e.g. W and error rates) are highly affected by the methods used to control for visual parameters of dot stimuli and that this affects children with DD to a greater extent than their typically developing peers. These methods are

employed to ensure that across all trials of the numerical discrimination task, participants cannot rely solely on visual cues to inform their decision, but forces participants to use numerical cues to discriminate between approximate magnitudes. However, after examining *W* and error rates separately during different trial types (incongruent and congruent trials) in children with DD, these indices of internal quantity representations clearly change as a function of the congruency of dot stimuli. In other words, having both congruent and incongruent trials does not eliminate the influence of non-numerical variables on numerical magnitude discrimination.

This is consistent with studies investigating the effect of visual perceptual cues in typically developing adults demonstrating that they *do not* extract number from non-symbolic stimuli independently of the visual perceptual cues present (Gebuis & Reynvoet, 2012; Leibovich & Henik, 2014). In the natural environment, it is often the case that individuals rely on visual cues to inform their numerical judgments (Gebuis & Reynvoet, 2012). However, in a laboratory setting, these cues are controlled to isolate numerically specific processes, but recent evidence suggests that controlling for visual cues does have an effect on performance. Specifically, individuals engage other cognitive processes and strategies across different trials types to select the numerically larger dot array (Gebuis & Reynvoet, 2012; Leibovich & Henik, 2014).

The results of the current study suggest that differences found between children with and without DD on non-symbolic numerical discrimination cannot be solely attributed to deficits of the approximate number system. The stronger effect of congruity between numerical and non-numerical variables in the DD group shows that the interaction between numerical and non-numerical variables strongly influences their performance on this task.

In addition to examining the role of congruity between numerical and non-numerical variables in non-symbolic number discrimination, we examined the role of working memory as a potential mechanistic candidate for how children with DD discriminate between non-symbolic numerical magnitudes differently from typically developing controls. In particular, we correlated measures of working memory with *W*

collected from the incongruent and congruent trials separately. Correlation analyses were conducted independently for both groups to examine whether children with DD recruited different cognitive processes during the different trial types. Although we did not administer an inhibitory control measure, we hypothesized that visuo-spatial working memory specifically would be required to disambiguate between the conflicting cues during non-symbolic numerical discrimination. Indeed, we found that visuo-spatial working memory negatively correlated with W during the incongruent trials, and marginally correlated with error rates during the congruent trials in children with DD, but not typically developing children. More specifically, children with DD who had lower visuo-spatial working memory abilities had greater difficulty discriminating between non-symbolic numerical magnitudes during the incongruent trials. These relationships were specific to visuo-spatial working memory as there were no significant correlations found between performance on Panamath and verbal working memory. These findings shed light on the qualitative differences between typically developing children and children with DD in the way in which visuo-spatial working memory abilities modulate performance during non-symbolic numerical discrimination, more so during the incongruent trials of the task.

Based on our current findings, we can offer three possible interpretations to explain why children with DD demonstrate greater error rates and imprecise W during the incongruent trials and how performance changes as a function of working memory ability in DD but not TD.

First, in light of this data, it is possible that children with DD do not necessarily suffer from an impaired ANS, but experience difficulties with inhibiting the irrelevant non-numerical dimensions during non-symbolic numerical discrimination. In other words, the deficit does not lie at the representational level, but that children with DD exhibit difficulties in accessing the numerical representation when non-numerical cues are interfering with this process. To successfully choose the numerically larger dot array during the incongruent trials (when the total area of the dots are negatively correlated with numerosity), participants are required to suppress or inhibit the conflicting visual cues of the dot stimuli in order to base their decision on numerical magnitude. This

explanation was supported by Gilmore et al. (2013) who found that inhibitory control significantly predicted performance during the incongruent trials of the nonsymbolic numerical discrimination task, and explained the relationship between non-symbolic processing and arithmetic achievement in typically developing children. Although we did not explicitly examine inhibitory control in the current study, visuo-spatial working memory and inhibitory control has been found to be severely impaired in children with DD (Szucs et al., 2013). As a result, deficits in either visuo-spatial working or inhibitory control (or both) would hinder their ability to access intact numerical representations. This notion is supported by the strong correlation between visuo-spatial working memory and performance during the incongruent trials in children with DD. Children who had greater visuo-spatial working memory difficulties, were unable to disambiguate between the non-numerical conflicting cues and numerical magnitude. To compensate for potential visuo-spatial working memory deficits (or potential inhibitory control deficits), children with DD require more time to resolve the conflict between numerical and non-numerical stimulus features to make successful non-symbolic numerical judgments.

Further support for this interpretation comes from methodological studies demonstrating that *W* is highly influenced by task construction. Specifically, in a study conducted by Inglis et al. (2013), it was demonstrated that *W* changes depending on the stimulus duration despite difference in the onset to decision latencies in typically developing adults. In other words, they found that *W* decreased when the stimulus display increased, which presumably allowed participants more time to access internal representations of quantity on more difficult trials. These findings clearly suggest that measures of ANS acuity are dependent on the time given to compare the displays of non-symbolic numerical magnitudes, thereby showing that measures like *W* are not fixed internal variables, but are strongly modulated by stimulus-dependent processing. Given these findings, we speculate that if children with DD had more time to access numerical representations during trials where visual perceptual cues are incongruent with numerical magnitude, differences between children with DD and typically developing children would diminish. Furthermore, in view of our findings we would predict that difficulties in processing rapidly presented non-symbolic stimuli would be more pronounced for children with DD who also have poor visuo-spatial working memory abilities. Given

their limited capacity to hold non-symbolic representations in working memory, shorter presentation times during incongruent trials would further augment their difficulties in choosing the numerically larger dot array.

Secondly, it is plausible that children with DD do have an impaired ANS, which forces them to compensate for numerical deficits by relying on the visual perceptual cues to perform the task. Put differently, when children with DD are unable to efficiently process numerical magnitude during dot discrimination, and they cannot rely on the visual properties of the stimuli to inform their decision during the incongruent trials, performance breaks down. However, during the congruent trials, area cues are consistent with the larger dot array and aide in the discrimination process. Therefore, it is plausible that children with DD who have ANS deficits are highly influenced by visual perceptual processes when discriminating dot arrays. Although this explanation cannot be ruled out completely, visuo-spatial working memory modulates performance during non-symbolic numerical discrimination in children with DD; and therefore, it suggests that non-symbolic numerical discrimination task is not a pure measure of numerical magnitude processing abilities. Furthermore, it highlights the role of visuo-spatial working memory during the reconciliation of visual perceptual cues and numerical magnitude whilst discriminating the incongruent dot arrays. Therefore, our data do not support the ANS hypothesis given how visuo-spatial working memory predicts ANS acuity, measured by a task that was previously assumed to measure pure numerical abilities, in children with DD.

Third, and lastly, it is conceivable that children with DD may experience both a weak ANS, and suffer from the inability to inhibit non-numerical visual cues. More specifically, both imprecise approximate numerical representations and deficiencies in visuo-spatial working memory can explain the performance differences found in the incongruent trials between children with DD and typically developing controls and its relationship to visuo-spatial working memory. Rather than focusing on one core deficit causal theory of developmental dyscalculia, Fias, Menon and Szucs (2013) proposed that developmental dyscalculia is likely a multi-deficit disorder due to its heterogeneous nature and its high comorbidity rates with other learning disorders, such as dyslexia and

ADHD (Lewis, Hitch & Walker, 1994; Shalev, Auerbach, Manor, Gross-Tsur, 2000). The ability to perform arithmetic operations hinges on the competency of a complex intricate system of cognitive processes such that it requires the ability to process and access symbolic numerical magnitudes, and it requires the temporary storage during the manipulation of symbolic magnitudes in working memory. The recruitment of similar brain regions have been implicated during basic numerical processing tasks as well as visuo-spatial working memory tasks in typically developing populations (Dumontheil & Klingberg, 2011; Zago & Tzourio-Mazoyer, 2002). Indeed these same regions show atypical activation patterns in children with DD (Rotzer,Loenneker, Kucian, Martin, Klaver & von Aster, 2009; Price et al., 2007), which can compromise the efficiency of both cognitive systems. It remains unclear the dynamic relationships between numerical magnitude representations and working memory throughout development in children with DD.

These findings have important implications for new avenues of research for investigating the core deficits of DD. For example, further research is required to understand how children with DD process conflicting non-numerical variables during dot discrimination. A closer examination into the role of visuo-spatial working memory and inhibitory control within the same sample of children with DD during the discrimination of different trial types is necessary to understand different compensatory mechanisms or strategies used by children with DD compared to typically developing children. Subsequently these findings can lead to potential implications for training children with DD to focus on numerical magnitude while ignoring the irrelevant non-numerical cues.

To summarize, the present data demonstrate that visual stimulus properties influence performance on the non-symbolic numerical discrimination task in children with persistent DD, specifically during trials where the visual perceptual cues conflicted with the numerically larger dot array. Additionally, we found that individual differences in visuo-spatial working memory in children with DD modulated performance during the non-symbolic numerical discrimination, suggesting that children with DD rely on visuo-spatial processes to facilitate discrimination –more so during the incongruent trial types. Furthermore, the current study provide support for the notion that non-symbolic

numerical discrimination tasks are unreliable measures of the integrity of numerical magnitude representations and open the questions as to what underlying cognitive processes and strategies are employed during different trial types. It is important to note that discriminating dot arrays is a complex process that does not rely solely on approximate numerical representations and future research is necessary to advance our understanding of the causal relationship between the ANS, visual perceptual cues, and visuo-spatial working memory in children with DD.

4.5 References

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Chapter 5

5 The neural correlates of symbolic and non-symbolic number processing in children with persistent DD

5.1 Introduction

Studies investigating the neural correlates of numerical magnitude processing in children with Developmental Dyscalculia (DD) are sparse; and therefore, little is known about the neurobiological sources of mathematical disabilities (for a review see: Bugden & Ansari, in press). Currently there are only a handful of neuroimaging studies investigating the core numerical deficits of DD. Therefore, there currently exists little consensus pointing to specific brain regions that show atypical activation during symbolic and non-symbolic numerical processing. The aim of the present study was to investigate the neural underpinnings of numerical magnitude processing in children who demonstrated persistent DD.

5.1.1 Functional neuroimaging methodology

Functional magnetic resonance imaging (fMRI) is a technique used to investigate brain function by measuring the physiological changes in cerebral blood flow while participants are performing various tasks. These physiological changes in response to neural activation are referred to as the hemodynamic response (HDR). The fMRI signal varies (over time) as a function of the concentration of oxygenated and deoxygenated blood in response to increased neural activation (Blood Oxygenation Level Dependent; BOLD; Ogawa, Lee, Kay & Tank, 1990). The BOLD contrast reflects changes in neural activity as a result of increased metabolic demands that results in increased levels of oxygenated blood. These contrast changes are detected when increases in oxygenated blood displaces the deoxygenated blood, which has a suppressing effect on the intensity of the fMRI signal. Thus through the increase in oxygenated blood there is an increase in the fMRI signal. A series of images are collected over the course of the task in order to detect changes in the BOLD signal as a function of specific task demands. For example, while children are performing numerical tasks during an fMRI scan, images are collected

to detect which voxels (a three dimensional pixel) of the brain are showing increases or decreases in the hemodynamic response (BOLD signal) in comparison to when they are not performing a task (e.g. rest) or in comparison to a control task (Huettel, Song, McCarthy, 2004).

5.1.2 The typically developing adult and child brain

Research studies have consistently implicated the parietal lobe, more specifically the Intraparietal Sulcus (IPS), as a key region for processing and manipulating numerical magnitude in typically developing adults (e.g. Dehaene, 1999; Pinel et al., 2001).

Researchers commonly use numerical discrimination task to investigate the neural correlates of both symbolic and non-symbolic numerical magnitude processing (see introduction and chapter 3 for a detailed review of numerical discrimination paradigms and their utility for the study of numerical cognition in both typically and atypically developing children). These studies have consistently revealed the involvement of the IPS. For example, it has been repeatedly observed that the BOLD signal in the IPS is correlated with the numerical distance between the magnitudes that are being compared (e.g. the neural distance effect), suggesting that it houses the representational system of quantity regardless of notation (e.g. dot arrays, Arabic numerals e.g. 3 and numbers words, e.g. three) (e.g. Dehaene, 1999; Pinel et al., 2001).

Comparable to the data from adults, children as young as four years of age have been found to activate the IPS during numerical tasks, but to a lesser degree (Cantlon, Brannon, Carter & Pelphey, 2006). These researchers used an fMRI adaptation paradigm to investigate changes in neural activation in response to passively viewed non-symbolic numerical stimuli. Participants viewed a continuous presentation of an array of dots that were constant in shape and quantity (standard stimulus, e.g. 16 dots). During this habituation phase the neural signal decreased (weakens) over time. Occasionally after the habituation phase, a deviant novel stimulus was presented that either differed in shape or quantity. The numerical deviant stimulus varied in ratio from the standard, and therefore the strength of signal in response to deviant stimulus is examined as a function of the ratio (refer to introduction and chapter 3 for discussion of the ratio effect). Using this paradigm, the authors revealed that adults demonstrated greater bilateral ratio

dependent activity in the IPS in response to the numerical deviant stimuli, whereas children showed some ratio-dependent activation in response to the numerical deviants in the right IPS.

In contrast to these findings, Ansari and colleagues have found that elementary school children showed greater modulation of distance (i.e. the neural distance effect) during symbolic and non-symbolic numerical discrimination tasks in prefrontal regions (Ansari & Dhital, 2006; Ansari, Garcia, Lucas, Hamon & Dhital, 2005); however, adults demonstrated greater neural distance effect in the IPS. The authors interpreted these findings of greater frontal activation in children and more modulation of the IPS in adults in the following way: they argued that children recruit prefrontal regions during numerical discrimination to compensate for imprecise and immature representations of numerical magnitude in the IPS, but as they grow older the IPS becomes functionally specialized to process numerical magnitude (for a review see: Ansari, 2008). Taken together, these findings are beginning to shed light on the ontogenetic activation differences that support increased automaticity and functional specialization of the parietal cortex for numerical magnitude processing in the brains of typically developing children.

5.1.3 The Developmental Dyscalculic brain

It is important to understand the ontogenetic processes underlying numerical abilities in typically developing children to further investigate how the typical developmental trajectory might go awry in children with DD. The findings reviewed above lead us to question whether the atypical development of brain systems underlying the numerical magnitude representations in the IPS leads to a representational impairment in children with DD. This question follows from the original definition of DD quoted on p 39. Researchers have begun to shed light on these questions using developmental cognitive neuroscience methods. For example, Price, Holloway, Rasanen, Vesterinen and Ansari

(2007)³ were the first to investigate the neural correlates of basic numerical magnitude processing using a non-symbolic numerical discrimination task in children with pure DD compared to their typically developing controls. They found that children with DD demonstrated atypical activation in the right IPS during non-symbolic discrimination. More specifically, typically developing children exhibited a stronger neural distance effect in the right IPS compared to children with DD. The lack of modulation in the right IPS found in children with DD suggests abnormal processing mechanisms in response to more difficult non-symbolic trials (e.g. close distance trials). Additionally, atypical activation was found in the left fusiform gyrus as well as the left medial prefrontal cortex. Consistent with these findings, Mussolin and colleagues (2009)⁴ found that typically developing children exhibited a larger neural distance effect in the left superior parietal lobule and the right IPS during a symbolic numerical discrimination task compared to children with DD. Additionally, Kaufmann and colleagues (2009)⁵ found atypical activation in bilateral regions of the IPS during non-symbolic numerical processing in nine-year-old children with DD. However, in contrast to previous findings, differences were driven by stronger activation in the left IPS and less pronounced deactivation in the right IPS. But in the study conducted by Kaufmann et al., typically developing children demonstrated greater deactivation in bilateral IPS. Other brain regions that showed atypical activation included the left angular gyrus, the bilateral supramarginal gyrus, left postcentral gyrus and right superior frontal gyrus. The majority of studies use arrays of dots or objects in a non-symbolic discrimination task; in the Kaufmann et al.'s study, children were instead asked to compare finger patterns. The authors interpreted greater activation in the left angular gyrus as reflecting verbally mediating counting strategies that were elicited from finger patterns in children with DD.

³ Children with DD obtained at least 1.5 standard deviations below control mean on test of arithmetic achievement, no comorbid developmental disorders, such as ADHD, dyslexia.

⁴ Children with DD had a 2 year delay on a mathematical battery, verbal and nonverbal IQ > standard score (SS) of 85, no comorbid developmental disorders, such as ADHD or dyslexia.

⁵ Children with DD were identified based on significant discrepancy (1.5 standard deviations) between average IQ (>85 SS) and below average (<40 t-score) performance on a standardized dyscalculia test (German dyscalculia test Heidelberger Rechentest/HRT).

In an attempt to ascertain whether these findings (and others) yield a consistent pattern of data, Kaufmann et al. (2011) conducted a meta-analysis synthesizing the functional neuroimaging data that have investigated the neuronal correlates of both symbolic and non-symbolic numerical magnitude processing in children with DD. They found that, when considering all available evidence and using meta-analytic analysis tools, children with DD have distinct differences in activation patterns compared to typically developing controls. For example, control children demonstrated greater activation than children with DD in the left IPS, right inferior parietal lobe, left paracentral frontal lobe, the superior frontal gyrus, the right middle frontal gyrus and the left fusiform gyrus. In contrast DD participants showed greater activation in the left postcentral gyrus, superior frontal lobe, as well as the bilateral inferior parietal regions, more specifically in the right supramarginal gyrus and the left lateral IPS. These findings demonstrate that children with DD demonstrated atypical activation in a network of regions, including the left IPS, in contrast to typically developing controls (Kaufmann et al., 2011). It is important to note that the meta-analysis only included three studies that investigated numerical processing abilities merging data from separate investigations of symbolic and non-symbolic numerical discrimination in children with DD compared to typical controls. Thus any direct, within-subjects comparisons between the formats cannot be made from this meta-analysis.

Taken together, these studies demonstrate consistent atypical recruitment of the intraparietal sulcus in children with DD, a region known to house the semantic representation of numerical magnitude in typically developing adults and children (Butterworth, 1999; 2005; Cantlon et al., 2006; Dehaene, 1992; 2003). Studies have also found atypical structural organization of bilateral regions in the IPS, specifically children with DD have decreased grey matter volume in the right IPS (Rotzer et al., 2008), as well as the left superior parietal lobule (Rykhlevskaia et al., 2009). To date, no study has investigated both symbolic and non-symbolic numerical processing abilities in the same sample of DD children and, as a result, there is no cognitive neuroscience evidence to support or refute the representational or access deficits hypotheses as the root mechanism underlying DD (see section 1.3 in Chapter for review). It is necessary to investigate these

effects using a within subjects design to make direct comparisons between the neural correlates underpinning both symbolic and non-symbolic processing in children with DD.

5.1.4 Cross format numerical discrimination/mapping abilities.

A large body of evidence has found that symbolic numerical processing skills predict mathematical abilities (see De Smedt et al., 2013 for a review), suggesting that mapping symbolic numerals to their underlying non-symbolic representations plays a key role in mathematical development (see introduction and chapter 3 for more details).

Additionally, studies investigating symbolic numerical processing skills in children with DD have found that they show a specific deficit in processing symbolic numerals, which gave rise to the ‘access deficit hypothesis’. This theory proposes that developmental dyscalculia is caused by an impairment in mapping symbolic numerals to their semantic meaning of quantity (De Smedt & Gilmore, 2011; Rousselle & Noel, 2007), rather than an impairment of foundational non-symbolic representations of numerical magnitude.

Taken together, symbolic numerical magnitude abilities are critical for the development of basic arithmetic skills; however, evidence supporting these findings comes from symbolic numerical comparison tasks. Researchers have argued that symbolic representations are acquired by attaching arbitrary numerical symbols to their corresponding approximate numerical representations (e.g. the approximate number system (ANS) – see chapter 4) (Dehaene, 1992; Dehaene, 2007; Piazza et al., 2010).

Evidence supporting this theory comes from studies that have observed signatures of the ANS in symbolic numerical discrimination tasks, specifically, symbolic numerical distance and ratio effects have been found in adults (Moyer & Landauer, 1967) and children (Holloway & Ansari, 2009). Ratio or distance dependent responses revealed in symbolic distance/ratio effects are interpreted as traces of the ANS, supporting the notion that internal representations are automatically accessed when processing symbolic numerals (Dehaene, 1992) and therefore, mapping abilities have commonly been studied indirectly using a symbolic numerical discrimination task.

More recently, researchers have begun to design cross format matching or numerical discrimination tasks to directly assess numerical mapping abilities across both symbolic and non-symbolic formats (Mundy & Gilmore, 2009; Benoit et al., 2014;

Brankaer, Ghesquière & De Smedt, 2014). In these tasks, children are presented with a target, either a dot array or a symbolic numeral, at the top of the computer screen and presented with two quantities in the opposing format as the target (e.g. symbolic target and non-symbolic choice options and vice versa). Participants are asked to pick which of the two quantities matched the target number. Research studies using this task have found that mapping between symbolic and non-symbolic representations account for greater unique variance in predicting mathematical abilities compared to same format discriminations, suggesting that mapping abilities do play a crucial role in mathematical development (Brankaer, et al., 2014; Mundy & Gilmore, 2009). However, using direct mapping tasks appears to capture mapping abilities more so than symbolic numerical discrimination tasks. Presently, there are no neuroimaging studies that investigate the direct mapping between symbolic and non-symbolic representations using these tasks in typically or atypically developing children. Therefore, it is unclear whether similar neurocognitive mechanisms involved in non-symbolic numerical and symbolic discrimination also subserve the mapping between representations.

5.1.5 The present study

The aim of the present study was to provide the first investigation of both symbolic and non-symbolic numerical processing skills in the same sample of children with persistent DD and thereby allow, for the first time, to directly address the symbol-mapping deficit hypothesis with neuroscientific data. To extend previous findings, I examined differences in mapping abilities between children with DD and typically developing controls by administering a mixed numerical discrimination task. In this task, children were presented with a dot array and a symbolic numeral simultaneously on the computer screen and asked to choose the numerically larger quantity. Therefore, children are required to compare numerical magnitudes represented by both symbolic and non-symbolic formats. The mixed numerical discrimination was adapted from Lyons et al., (2012) and selected to assess mapping abilities rather than a direct mapping task described above, because it matches the task requirements of both the symbolic and non-symbolic numerical discrimination tasks. Therefore, it allows for direct comparison between tasks and minimizes potential confounding factors influenced by different tasks

demands. This mixed numerical discrimination task was administered to assess whether the same cerebral substrates are implemented in mapping between non-symbolic and symbolic representations, as those that are recruited for symbolic numerical or non-symbolic numerical comparison independently in children with DD compared to TD children.

If DD is caused by a deficit in accessing the semantic meaning of numerical symbols (e.g. access deficit hypothesis), it is hypothesized that atypical brain activation during symbolic processing, as well as mix format comparison would be evident in brain regions specific to processing numerical magnitude (e.g. intraparietal sulcus) in children with DD compared to their typical controls. Both tasks require children with DD to process the semantic meaning of symbols during the symbolic comparison task, as well as map between symbols and non-symbolic representations in the mixed comparison task. In contrast, if DD was caused by a representational (defective number module hypothesis or ANS) deficit, it is hypothesized that children with DD would elicit atypical activation in bilateral regions of the IPS during, symbolic, non-symbolic, and mixed format numerical processing.

5.2 Method and Materials.

5.2.1 Participants

There were 15 children with DD and 22 typically developing children who were recruited from the previous behavioural studies to participate in the present neuroimaging study (see chapter 2 for participant details). Within the DD sample, there was one child who did not complete the fMRI scan because she/he was claustrophobic; there were four children, who withdrew from the fMRI session for unknown reasons, and there was one child who was excluded, because his/her head motion exceeded our minimum motion criteria. More specifically, children were excluded if head movement was greater than 3mm over the entire scan, or they had greater than 2mm jump between subsequent volumes of brain images. Within the typical sample, four children were excluded because they had too much head motion, one child did not participate in the fMRI

because she/he had braces (which can affect the detection of MRI signals), and one child opted out of participating in the fMRI session.

There were 11 children (8 male, 3 female) with DD who were included in the final data set [Mean age: 12.39 years, $SD = 1.28$ years, age range: 9.44-13.68 years]. From the final group of typically developing children, there were 11 (5 male, 6 female) typically developing children who were age-matched as best as possible to the sample of DD [Mean age: 12.03 years, $SD = .75$, age range: 10.88-13.37 years]. There were no significant differences in age between children with DD and typically developing children, $t(20) = -.79$, $p = .44$. All children were right handed and had normal or corrected to normal vision and hearing. The procedures implemented in the current study were approved by the University of Western Ontario's Health Sciences Research Ethics Board (see Appendix B).

5.2.2 Experimental design

Each child participated in a pre-scanning training session, where they were trained in the procedures associated with having an fMRI scan. During this session they had the opportunity to lie in a mock scanner that simulated the environment including the sounds of the MRI machine. This practice session gave participants the opportunity to practice lying still while being trained on the experimental tasks administered during the real fMRI scanning session. Training on the fMRI procedures took approximate 15-20 minutes per participant. Following the scanner training session, the Reading Fluency, Math Calculation and Math Fluency subtests from the Woodcock Johnson-III Standardized Tests of Achievement (Woodcock, McGrew, & Mather, 2001) were administered to each child. Standard scores from this testing session, in addition to all the previous testing sessions, were included in calculation of the math and reading composite scores for each participant (see chapter 2 for description of standardized measures and sample). The pre-training session was approximately one hour per participant.

5.2.3 Task design and stimuli

There were three experimental conditions (symbolic numerical discrimination, non-symbolic numerical discrimination and mixed format numerical discrimination), as well as two control conditions (symbolic control condition and non-symbolic control condition) that were administered to participants in the scanner (see Figure 5.1 for an example). Each condition was presented as a functional run in random order using E-prime stimulus presentation software (Psychological Software Tools, Pittsburgh, PA). An event-related fMRI design was employed in which each stimulus event can be modelled separately.

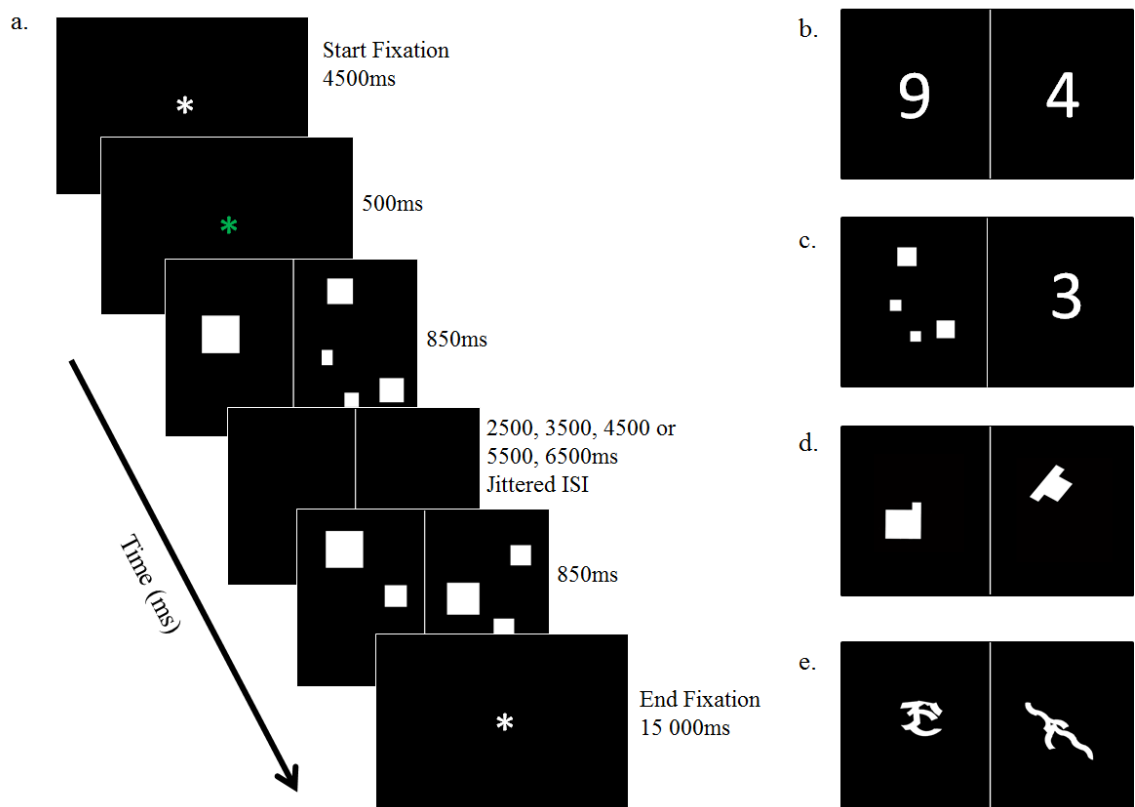


Figure 5.1: Experimental paradigms. a.) An illustration of the timing procedures of the numerical discrimination and control tasks modelled using the non-symbolic stimuli. b.) An example of the symbolic stimuli. c.) An example of the mixed stimuli. d.) An example of the non-symbolic control stimuli. e.) An example of the symbolic control stimuli.

5.2.3.1 Symbolic numerical discrimination

Participants were presented with a series of pairs of Arabic numerals and asked to choose the numerically larger number as fast as they could without making any errors. Arabic numerals ranged from one to nine and the distance between pairs ranged from one to three. The numerals pairs presented had an equal number of small and large quantities to ensure that specific numbers were not oversampled (e.g. small number pairs: 1,4; 2,3; 2;4 & large number pairs: 6,7; 7,9; 5,8). The pairs were presented in white on a black background. Each of the six pairs was administered 12 times for a total of 48 trials within the symbolic run. The task began with a fixation screen for 5000ms in order to gain a rest baseline measure. Each trial thereafter was administered for 1000ms followed by an inter-stimulus screen with a variable fixation period with an average jitter 4500ms (e.g. 2500ms, 3500ms, 4500ms, 5500ms, 6500ms). This variable ISI (jitter) is necessary in event-related fMRI studies in order to allow for the deconvolution of the BOLD response to individual trials (if trials were presented with a fixed ISI this would lead to a large temporal correlations of the BOLD signals correlated with stimulus presentation and thus an inability to extract independent parameter estimates for each event) The run ended with a 15 000ms fixation screen and was four and a half minutes in total running time (see Figure 5.1a & b).

5.2.3.2 Non-symbolic numerical discrimination

The non-symbolic discrimination task followed the same sequence and timing parameters as the symbolic comparison task. During this task, children were presented with two dot arrays simultaneously on a computer screen and were asked to select the numerically larger dot array as fast as they could without making any errors and trying their best not to count the dots. Dot arrays were created using a Python script that controlled for visual properties, such that half of the trials were controlled for total surface area and the other half of the trials were controlled for total perimeter (see: Price, Palmer, Battista, & Ansari, 2012 for the same stimulus design procedure). More specifically, when total surface area was equated across both dot arrays, the array with more dots occupied had a greater total perimeter. In contrast, during trials where the total perimeter were equated across both dot arrays, the total cumulative surface area was greater in the larger array of

dots. Trials were randomly presented in an effort to prevent children from responding based on visual properties and to rely on numerical cues (see Figure 5.1a).

5.2.3.3 Mixed numerical discrimination

In the mixed number comparison task, children were presented simultaneously with an Arabic numeral either on the right or left side of the screen as well as a dot array on the opposing side. They were asked to compare both formats and to select the larger quantity as fast as they could without making any errors. Participants were asked to not count the dots to ensure they were activating the approximate number system. The timing parameters and the stimuli pairs were matched to the non-symbolic and symbolic comparison tasks. Therefore, the mixed numerical discrimination task only differed in format of stimuli from the non-symbolic and symbolic numerical discrimination tasks. On half of the trials, the dot array occurred on the right side of the screen (see Figure 5.1c).

5.2.3.4 Control tasks

The control tasks were adapted from Holloway et al. (2010). During these tasks children were asked to judge which of the two stimuli resembled a diagonal line (see panels d & e in Figure 5.1 above). For the symbolic control task, Arabic numerals were segmented into parts, rotated and reconstructed into arbitrary shapes that either resembled a diagonal line or not. Similarly, the squares used in the non-symbolic comparison task were connected together to create arbitrary shapes including a shape that resembled a diagonal line. These tasks were developed to control for processes that are not specific to processing numerical magnitude such that both tasks require a button press and require visual perceptual processing of the same amount of white stimulus area presented on a black background.

5.2.4 Data acquisition

The fMRI sessions took place at Robarts Research Institute using a 3 T Siemens Trim Trio MRI system with a Siemens 32-channel receive-only head coil (Erlangen, Germany). An anatomical scan was performed encompassing the whole brain after the

functional runs were completed. This was achieved by collecting 192 one-mm thick slices using a 3-D T1-weighted acquisition MPRAGE sequence (1 x 1 x 1mm, T1-900ms, TE – 4.25ms, TR- 2300ms, flip angle - 9°). The in plane resolution of the anatomical scanners was 256 pixels x 256 pixels. To collect functional data, we used a T2* - weighted echo-planar imaging sequence (TE – 30.0ms, TR-2000ms, flip angle - 90°) for BOLD acquisition, the field of view was 21.1cm x 21.1cm with an in-plane matrix size of 64 pixels x 64 pixels. Each image consisted of 38 slices (voxel size – 3mm) with an inter slice time of 52ms. There were no gaps between slices and 138 volumes were collected in each run resulting in a total time of 4 minutes and 38 seconds. There were no runs discarded from the beginning of the run in addition to the two volumes removed by the scanner.

5.2.5 Image preprocessing and statistical analysis

Both structural and functional images were analyzed using Brain Voyager QX 2.8.2.2 (Brain Innovation, Maastricht, Netherlands). The functional images were preprocessed to correct for slice acquisition time, head motion, linear trends and low frequency noise. Functional images were spatially smoothed using a 6mm full width at half maximum Gaussian smoothing kernel, and were aligned to high resolution T1 3D structural images using automatic initial and fine tuning alignment algorithms, which involves using iterative techniques to maximize the overlap between spatial landmarks in the functional and anatomical images. To allow for averaging data across subjects, the realigned functional data set was normalized by transforming it into Talaraich space (Talairach & Tournoux, 1988) for statistical analysis. Transforming the data into a standard coordinate system is important for locating common brain regions across each subject, given the individual variability in brain size and shape. Therefore, each voxel is given a three dimensional spatial coordinate (x, y, z), which allows for the identification of regions using the Talaraich and Tournoux brain atlas (Talairach & Tournoux, 1988).

The functional runs were modelled using a random effects general linear model (GLM) and included all five tasks as predictors. The design matrix contained event related predictors for the symbolic, non-symbolic and mixed format conditions, as well as the symbolic and non-symbolic control conditions. To model the expected BOLD signal,

the predictors were convolved using a box-car time series with a two gamma hemodynamic response function at trial onset (Friston et al, 1998). A box-car time course can be defined by setting values throughout the time series to either “1” when the condition is ‘on’, and “0” at all other points in the time course. At the whole brain level, the GLM tests how well the model predicts the actual fMRI time course during each condition within each voxel of the brain. A beta value is then derived for each voxel to represent how well the predictor time course explains the ‘actual’ voxel time course. In other words, the beta weight represents the strength of activation (large positive beta value) or deactivation (large negative beta value) in response to the modelled condition compared to baseline (e.g. baseline is also referred to as rest, when the participant is not performing the task). Therefore, multiple whole brain contrasts were conducted to investigate how well the model for each condition fit or explained the actual activation pattern in every voxel of the brain relative to baseline.

In the interest of characterizing brain activation differences between children with DD and typically developing children as a result of processing specific formats of numerical magnitude representations, the present study did not model distance as a predictor for the following reasons. First, neural distance effects are characterized by differences in brain activation for small and large distances, and therefore, driven by the activation differences in ‘easy’ and ‘hard’ discriminations that shed light on the precision of numerical magnitude representations. The precision of the symbolic and non-symbolic numerical representations was not the focus of the present investigation, but rather the differences in brain activation involved in processing different formats of number to disambiguate the different theoretical accounts of DD. The present numerical discrimination task included trials with small distances (e.g. 1-3), in other words, the task included the most difficult trials to ensure engagement of the IPS specific to processing numerical magnitude. Second, as a follow up to the study conducted in chapter three, task/format was included as a predictor to isolate brain activation specific to discriminating numerical magnitudes represented by different formats. And lastly, when conducting fMRI experiments with children, tasks being administered in the scanner have to be short in duration. Therefore, when there are a limited number of trials, contrasts were collapsed across distances to ensure there was enough power to detect differences in

format specific brain activations if they exist. Both inaccurate and accurate behavioural responses were modelled in the brain. Errors were included in the analyses after no differences in the results with and without them included were found therefore ensuring maximum possible power.

5.3 Results

5.3.1 Behavioural data

To examine differences in reaction time and accuracy during the non-symbolic, symbolic and mixed numerical discrimination tasks, performance (p) measures were computed for each task using the same formula as described in Chapter 3 [$P = RT(1+2*\text{Mean Error Rate})$] (Lyons et al., 2014). Consistent with the analysis used for neuroimaging data, multiple t -tests were conducted to examine the differences in performance values for children with DD and typically developing (TD) during each of the comparison tasks. A Bonferroni correction was applied to decrease the probability of making a Type I error when multiple comparisons are conducted; therefore, a p -value less than .01 was considered significant.

The results of this analysis demonstrated that children with DD [$M = 1705.11$, $SD = 356.77$] had significantly lower performance values during the mixed discrimination, $t(20) = -3.32$, $p = .003$, $d = 1.41$, as well as symbolic discrimination [DD: $M = 1090.41$, $SD = 273.12$, $t(20) = -2.93$, $p = .008$, $d = 1.25$ compared to TD children [mixed discrimination: $M = 1245.25$, $SD = 290.03$; symbolic discrimination: $M = 794.18$, $SD = 194.30$]. However, there were no significant group differences in performance on the non-symbolic discrimination task, $t(20) = -1.46$, $p = .16$, $d = .62$ (Levene's test marginally significant, $F = 3.74$, $p = .067$) (see Figure 5.2).

There were no significant differences in performance between groups during both control tasks [symbolic control, $t(20) = -1.51$, $p = .15$, $d = .64$, Levene's test of equality of variance marginally significant $F = 3.89$, $p = .063$; non-symbolic control, $t(20) = -.50$, $p = .63$, $d = .21$, Levene's test of equality of variance marginally significant $F = .68$, $p = .42$].

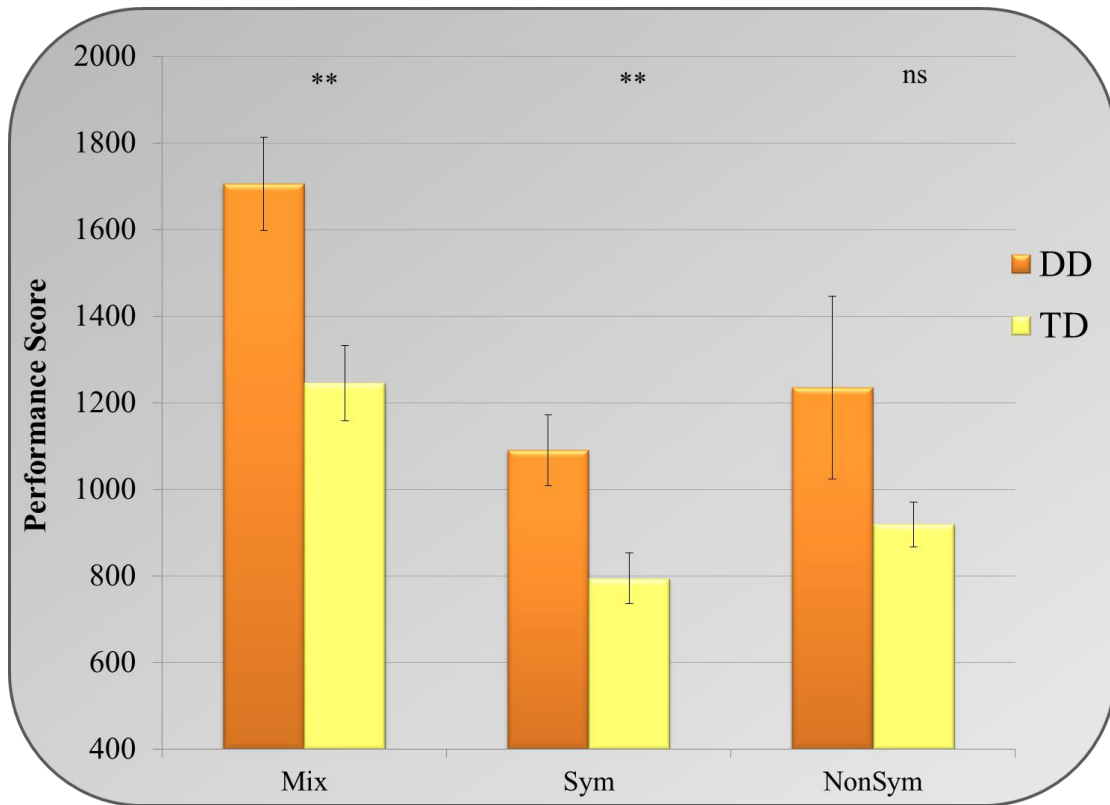


Figure 5.2: Shows performance values for all three experimental conditions for both groups. Error bars represent one standard error from the mean. DD= Developmental Dyscalculia; TD = Typically developing, Mix = Mixed numerical discrimination, Sym = Symbolic numerical discrimination, Nonsym = Non-symbolic numerical discrimination. Error bars represent one standard error on either side of the mean.

5.3.2 Neuroimaging data analysis overview

5.3.2.1 Whole brain analyses

A whole brain general linear model (GLM) analysis was conducted to identify regions that exhibited a statistical difference between format specific activation and rest between groups of participants. Specifically, three whole brain analyses were conducted separately for each numerical discrimination task to examine format specific activation differences between children with DD and TD children. These analyses allow for the investigation of both approximate number system and access deficit hypotheses of DD by examining format specific activation in DD and TD children.

For all of the whole brain analyses, the resulting statistical maps were corrected for multiple comparisons using a cluster correction thresholding method (Forma et al., 1995; Goebel et al., 2006). The initial random effects threshold was set at $p < .005$, uncorrected. The resulting maps were submitted to different correction criterion based on the estimates of the map's smoothness and on an iterative procedure (Monte Carlo Simulation) for estimating cluster-level false positive rates. After 1000 iterations, the minimum cluster size yielded a false positive rate of .05 and was used to threshold all the statistical maps.

5.3.2.2 Region of interest (ROI) analyses

Following each format specific whole brain analysis, an ROI analysis was conducted by extracting the beta values from regions that showed significant activation differences between groups at the whole brain level. The beta values within these regions were averaged across all voxels that showed significant activations within the region of interest for each condition and separately for each participant.

ROI analyses were conducted to further understand the results of the whole brain analyses for non-symbolic, symbolic and mixed numerical discrimination. First, to test the specificity of results for numerical discrimination, paired samples t-tests were conducted within each group to examine whether activation during the numerical task significantly differed from its control task.

Second, to test whether group differences found in the whole brain analysis during the numerical discrimination tasks were specific to numerical discrimination, independent samples t-tests were conducted on the control tasks to examine whether the groups differed significantly in terms of the activation of these regions during the processing of the control task. If differences in activation were found between groups during the control task, it would suggest that group differences found at the whole brain level during numerical discrimination are not specific to processing numerical magnitudes, but are common to both numerical and non-numerical processing (i.e. the control tasks).

To ensure that ROI analyses were independent (meaning that analyses conducted at the ROI level are independent from those used to identify the ROIs at the whole brain level), none of the ROI analyses involved comparing the experimental task of interest (non-symbolic, symbolic or mixed numerical discrimination) between groups (Kriegeskorte, Lindquist, Nichols, Poldrack & Vul, 2010; Vul & Pashler, 2012). The only between-group analyses were conducted on the activation related to the control tasks, which were not part of the whole brain analyses used to isolate the ROIs. All analyses were Bonferroni corrected to reduce type I error rates when conducting multiple comparisons.

5.3.3 Neuroimaging data results

5.3.3.1 Non-symbolic numerical discrimination (Non-symbolic > Baseline) - Whole brain analysis

Activation differences during the non-symbolic discrimination task against rest were examined at the whole brain level between children with DD and typically developing children. This analysis was conducted to explore whether brain activation differences are revealed in bilateral IPS to test the approximate numerical system hypothesis of DD. The minimum functional voxel size to reach statistical significance at the whole brain level was 27 voxels (725 structural voxels). The results of this analysis demonstrated that a widespread network of regions within the prefrontal cortex, as well as the right temporal lobe was found to show greater deactivation (negative beta weights) in children with DD compared to typically developing children (see Table 5.1 for cluster name and location) (see Figure 5.3 for an illustration of cluster locations in green that demonstrated significant group differences).

Table 5.1: A list of brain regions that elicited significant differences in activation between children with DD and TD children for each whole brain analysis. The statistical information, as well as the specific locations are included for the peak activation for each cluster.

Talairach Coordinates										
Analysis	Cluster label	x	y	z	Hemisphere	Lobe	Brodman Area	Size	t - value	p - value
Non-Sym > Baseline	Middle Temporal Gyrus	38	13	-18	Right	Temporal	38	2329	3.04	$p = .007$
	Superior Temporal Gyrus	53	-23	3	Right	Temporal	22	1906	-2.02	$p = .04$
	Putamen	26	-2	0	Right	Midbrain/Sub-lobar		1721	3.62	$p = .002$
	Thalamus	8	-11	-3	Right	Midbrain/Sub-lobar		1571	3.4	$p = .001$
	Medial Frontal Gyrus	-10	43	9	Left	Frontal	10	1737	3.69	$p = .001$
	Superior Temporal Gyrus	-43	-14	-6	Left	Temporal	22	942	1.95	$p = .07$
	Fusiform Gyrus	20	-59	-9	Right	Occipital	19	654	5.31	$p < .0001$
Sym > Baseline	Cingulate Gyrus	2	-14	39	Right/Left	Frontal	24	936	3.39	$p = .003$
	Caudate	11	10	12	Right	Midbrain/Sub-Lobar		2569	4.84	$p = .0001$
	Anterior Cingulate	-4	3	24	Left	Limbic		651	3.68	$p = .002$
	Superior Parietal Lobule	8	-62	48	Right	Parietal	7	910	3.43	$p = .003$
	Superior Parietal Lobule	-19	-62	39	Left	Parietal	7	1001	4.87	$p < .0001$
	Fusiform Gyrus	23	-65	-9	Right	Occipital	19	879	5.31	$p < .0001$
	Superior Parietal Lobule	-19	-62	39	Left	Parietal	7	731	4.87	$p < .0001$
Mix > Baseline	Fusiform Gyrus	20	-47	-12	Right	Occipital		2469	5.86	$p < .0001$
	Caudate	11	4	15	Right	Midbrain/Sub-Lobar		1232	4.84	$p = .0001$
	Thalamus	-19	-23	15	Left	Midbrain/Sub-Lobar		845	4.80	$p = .0001$
	Lingual	-16	-65	9	Left	Occipital	30	828	4.48	$p = .0002$
	Superior Parietal Lobule	-19	-65	39	Left	Parietal	7	985	4.87	$p < .0001$

Note. Non-Sym = Non-symbolic NC; Sym = Symbolic NC; Tal = Talairach Coordinates; Cluster labels were identified using Talairach daemon software

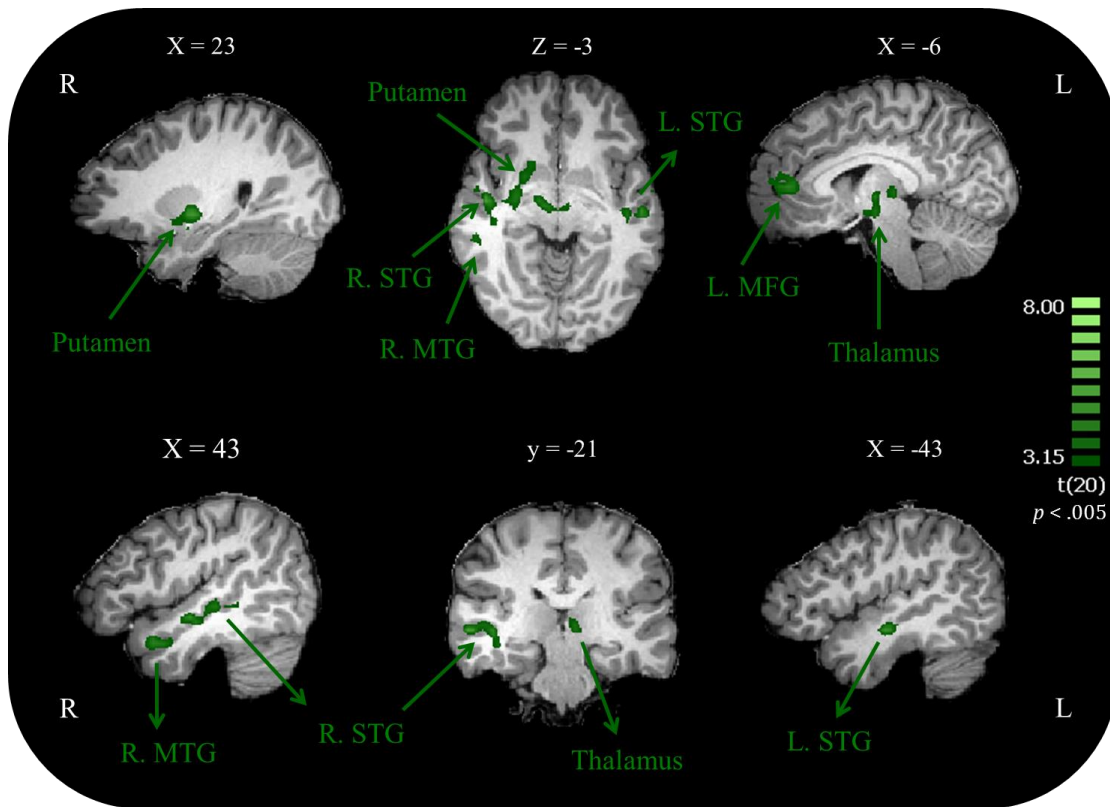


Figure 5.3: Brain regions that demonstrated significant differences between typically developing children and children with DD during the non-symbolic against rest whole brain contrast. Uncorrected $p < .005$, with cluster correction $p < .05$. R = right, L = left, STG = Superior Temporal Gyrus, MFG = Medial Frontal Gyrus, MTG = Medial Temporal Gyrus.

5.3.3.2 Non-symbolic numerical discrimination - Region of interest (ROI) analysis.

A closer examination into whether the differences in activation found in the non-symbolic discrimination task were specific to non-symbolic magnitude processing, beta weights were extracted from the regions showing greater deactivation in children with DD compared to typically developing children during the whole brain analysis. This analysis was used to establish whether the pattern of activation and deactivation during non-symbolic number processing in each group differed significantly from the activation

elicited by the non-symbolic control task (refer to Figure 5.1). Specifically, paired samples t-tests were conducted within each group between mean beta values during the non-symbolic numerical discrimination task and the non-symbolic control task. A significant effect was detected if a p value $< .008$. Within the typically developing sample, there were no significant differences between brain activation during then non-symbolic magnitude task and the control task in the right middle temporal gyrus (R. MTG), right superior temporal gyrus (R. STG), the left medial frontal gyrus (R. MFG) and the left superior temporal gyrus (L. STG), putamen and the thalamus (all p values $> .03$).

For children with DD, results from the Bonferroni corrected t-tests demonstrated that there were no significant differences in activation in all clusters between activation specific to non-symbolic magnitude discrimination and its control task ($p > .01$) (see Table 3 for mean beta weights within each group).

Additionally, independent samples t-tests were conducted to examine whether there were group differences in activation during the non-symbolic control task in the regions of interest derived from the whole brain analysis. The result of these analyses were corrected for multiple comparisons using Bonferroni method ($p < .008$ to be considered significant) and revealed no significant differences in activation during the non-symbolic control task between children with DD and typically developing children in the left medial frontal gyrus ($p = .40$), putamen ($p = .60$) as well as the thalamus ($p = .87$), the right middle and superior temporal gyri ($p = .07$). A significant group difference was found in the left superior temporal gyrus reflecting the fact that children with DD exhibited stronger deactivation during the control task compared to typically developing children ($p < .001$, $d = 1.31$) (see Table 5.2 for mean beta weights).

The results of the ROI analysis revealed that clusters found to be significantly different between DD and TD children in the non-symbolic whole brain analysis were not specific to numerical magnitude processing. There were no specific activation differences between numerical magnitude processing and the control task.

Table 5.2: Mean beta weights that were extracted from the clusters that demonstrated greater deactivation in children with DD compared to TD children for the non-symbolic numerical discrimination > baseline whole brain contrast.

Cluster	Task	TD	DD
		Mean (SD)	Mean (SD)
Right Middle Temporal Gyrus	Non-Sym NC	.85 (1.58)	-3.11 (2.30)
	Non-Sym Ctrl	-.27 (1.71)	-2.25 (3.03)
Right Superior Temporal Gyrus	Non-Sym NC	.48 (1.72)	-2.40 (.98)
	Non-Sym Ctrl	-.50 (.96)	-1.76 (1.87)
Putamen	Non-Sym NC	2.06 (1.71)	-1.33 (1.99)
	Non-Sym Ctrl	-.16 (2.61)	-.65 (1.55)
Thalamus	Non-Sym NC	1.80 (1.51)	-1.79 (1.59)
	Non-Sym Ctrl	.13 (1.47)	.23 (1.14)
Left Medial Frontal Gyrus	Non-Sym NC	.52 (2.28)	-1.63 (.82)
	Non-Sym Ctrl	-.87 (1.84)	-1.66 (2.48)
Left Superior Temporal Gyrus	Non-Sym NC	.50 (1.33)	-1.63 (.82)
	Non-Sym Ctrl	.17 (1.66)	-1.81 (1.34)

Note. TD = typically developing; DD = developmental dyscalculia; NC = number comparison; SD = standard deviation; Non-sym = Non-Symbolic; Ctrl = Control

5.3.3.3 Symbolic numerical discrimination (Symbolic > Baseline) – Whole brain analysis

A whole brain analysis was conducted to examine regions that showed activation differences during symbolic numerical magnitude processing in children with DD compared to typically developing children. Therefore, group comparisons were conducted for the symbolic numerical discrimination > baseline whole brain contrast. For this analysis, initial uncorrected threshold was set to $p < .005$, and the resulting statistical map had a false positive rate of $p < .05$, with cluster sizes that met or exceeded 24 functional voxels (623 structural voxels) once cluster correction was applied. The statistical map revealed that typically developing children demonstrated significantly greater activation in the right and left superior parietal lobules (SPL), as well as the caudate, anterior cingulate, right fusiform gyrus, and the right cingulate in comparison to children with DD (see Figure 5.4a for an illustration of cluster locations in red mapped onto an anatomical brain).

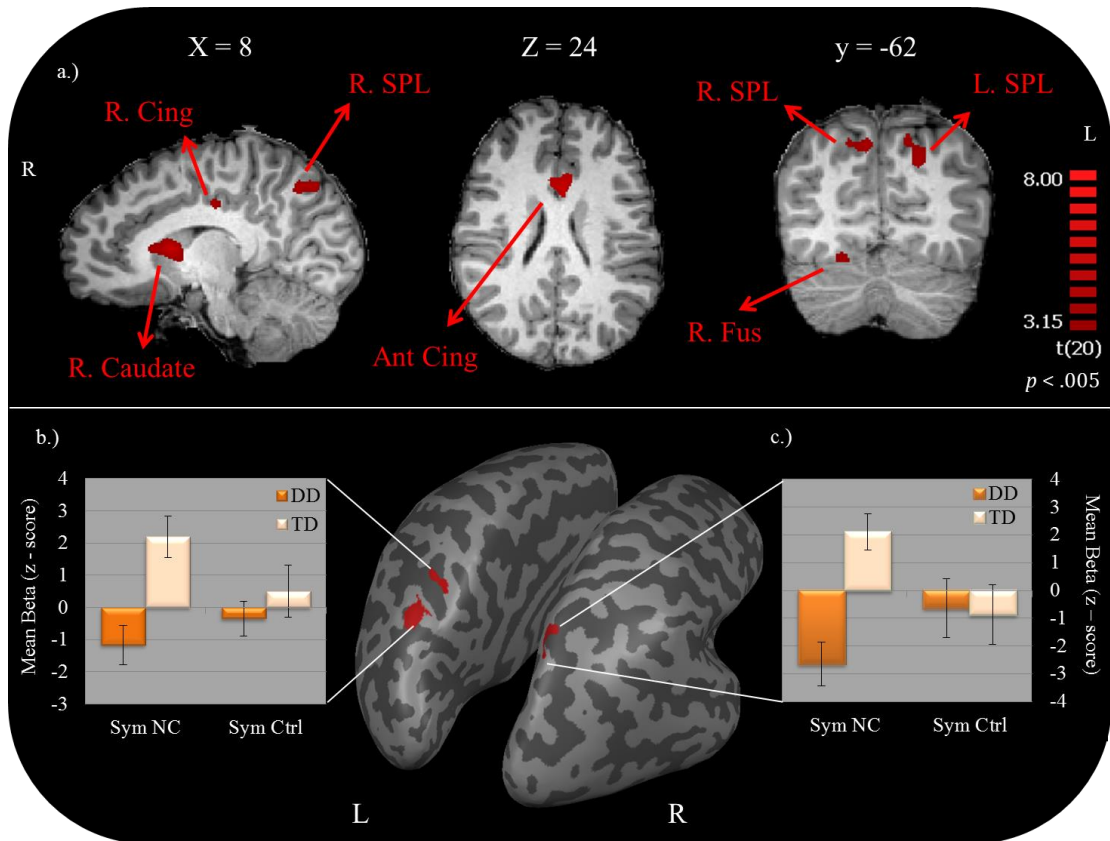


Figure 5.4: Statistical map illustrating regions where TD children demonstrated greater activation for the symbolic > baseline whole brain contrast compared to children with DD. a.) Six clusters shown on a sagittal, coronal and transverse view of a T1 anatomical brain. Uncorrected $p < .005$, with cluster correction $p < .05$. b.) The right and left parietal clusters are presented on an inflated anatomical brain, where greater activation during symbolic comparison (Sym NC) in typically developing children is represented by light yellow bars on bar charts displayed on the right and left side of the brain (representative of left (b) and right (c) parietal clusters) compared to children with DD represented by the orange bars. The mean beta weights (z-score) for the symbolic control tasks (Sym Ctrl) are represented in the bar charts revealing no differences in brain activation between groups. Error bars represent one standard error on either side of the mean. R = Right; L = Left; Cing = Cingulate; Ant Cing = Anterior cingulate; SPL = Superior parietal lobule; Fus = Fusiform.

5.3.3.4 Symbolic numerical discrimination - ROI analysis

fMRI parameter estimates for each cluster during the symbolic discrimination task was submitted to paired samples t-tests within each group to examine whether greater

activation found in the control group was specific to symbolic numerical magnitude processing compared to the symbolic control task. Bonferroni correction was applied to the following t-tests, and therefore a significant effect was detected if a p value $< .008$. Paired samples t-tests within the typically developing group demonstrated greater activation during the symbolic numerical discrimination task compared to the control task in the left anterior cingulate ($p < .004$) and the left IPS ($p < .008$). However there were no significant differences between symbolic numerical discrimination and control tasks in the remaining whole brain clusters (all p values $> .01$). In the DD group, children revealed no significant differences in activation during the symbolic numerical discrimination task and symbolic control task (all p -values $> .10$). These findings indicate that activation in the left anterior cingulate and the left SPL is specific to processing symbolic numerical magnitudes in typically developing children compared to the control tasks (see Table 4 for mean beta weights within each group).

Additionally, independent samples t-tests were conducted to examine whether there were significant group differences in activation during the symbolic control tasks. Bonferroni corrected t-tests (significant effect was detected if a p value $< .008$) revealed no significant differences in activation for the control tasks (right fusiform gyrus, $p = .25$; right cingulate, $p < .71$; caudate, $p = .56$, left anterior cingulate, $p < .60$; right inferior parietal lobule, $p = .88$; left IPS, $p = .39$) (see Table 5.3 for mean beta weights).

The results of these analyses demonstrate that activation differences found in the left anterior cingulate and the left superior parietal lobule at the whole brain level are specific to symbolic numerical magnitude processing, and not processes that are recruited in both symbolic numerical comparison and control tasks. (e.g. motor processes in button press or low level visual processes).

Table 5.3: Mean beta weights that were extracted from the clusters that demonstrated greater activation in TD children compared to children with DD for the symbolic numerical discrimination > baseline whole brain contrast in addition to the symbolic control task

Cluster	Task	TD	DD
		Mean (<i>SD</i>)	Mean (<i>SD</i>)
Right Fusiform Gyrus	Sym NC	6.31 (3.91)	1.31 (1.98)
	Sym Ctrl	3.69 (3.73)	2.09 (2.51)
Right Cingulate	Sym NC	1.70 (1.29)	-1.13 (1.09)
	Sym Ctrl	-1.12 (2.34)	-1.49 (2.25)
Caudate	Sym NC	3.10 (2.93)	-.86 (1.44)
	Sym Ctrl	-.20 (1.51)	-.70 (2.31)
Left Anterior Cingulate	Sym NC	3.39 (2.89)	-.82 (1.41)
	Sym Ctrl	-1.38 (2.50)	-2.65 (2.63)
Right SPL	Sym NC	2.11 (2.18)	-2.65 (2.63)
	Sym Ctrl	-.87 (3.55)	-.65 (3.50)
Left SPL	Sym NC	2.19 (2.15)	-1.17 (2.03)
	Sym Ctrl	.50 (2.69)	-.36 (1.81)

Note . TD = typically developing; DD = developmental dyscalculia; NC = number comparison/discrimination; SD = standard deviation; Sym = Symbolic; Ctrl = Control; SPL = Superior parietal lobule.

5.3.3.5 Mixed numerical discrimination (Mixed > Baseline) - Whole brain analysis

To test whether typically developing children exhibited significantly different brain activation patterns during mapping between non-symbolic and symbolic formats of discrimination, a whole brain analysis was conducted. This analysis was used to identify voxels that showed differences in activation from the mixed numerical discrimination task greater than baseline in children with DD compared to typically developing children. For this analysis, initial uncorrected threshold was set to $p < .005$, and the resulting statistical map, which had a false positive rate of .05, had cluster sizes that met or exceeded 23 functional voxels (587 structural voxels) once cluster correction was applied. The results of this analysis revealed two clusters that demonstrated significant differences between typically developing children and children with DD (see Figure 5.5a for an illustration of cluster locations in blue mapped onto an anatomical brain). Specifically, greater activation was found in the left SPL and the right fusiform gyrus in typically developing children relative to children with DD (see Figure 5.5b).

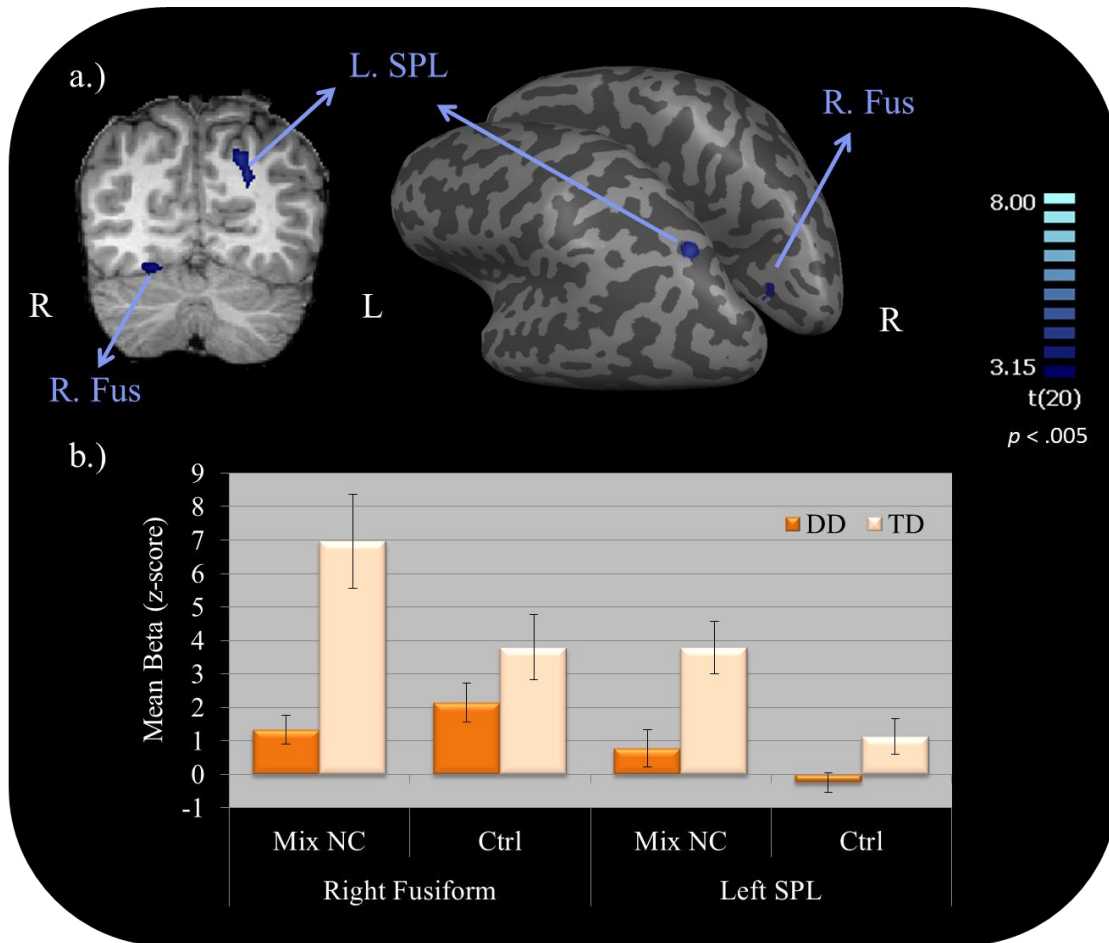


Figure 5.5: Statistical map illustrating regions in blue where TD children demonstrated greater activation in the Mixed condition > baseline (Mixed NC) whole brain contrast compared to children with DD. a.) Two clusters shown on the coronal view of a T1 anatomical brain (on the left) as well as an inflated anatomical brain (on the right). b.) The mean beta weights (z-score) for the mixed numerical discrimination and the mean of both symbolic and non-symbolic control tasks (Ctrl) are plotted for both typically developing children (light yellow bars) and children with DD (dark orange bars). Error bars represent one standard error on either side of the mean. IPS = intraparietal sulcus; Fus = Fusiform; L = left; R = right; Ctrl = Control; NC = number comparison.

5.3.3.6 Mixed numerical discrimination ROI analysis

Paired samples t-tests were conducted within groups to examine whether activations found within group were specific to discriminating between mixed formats compared to the mean beta values extracted from the symbolic and non-symbolic control tasks. The combination (mean) of both symbolic and non-symbolic control tasks was used to control for non-numerical processes that are required to complete the fMRI tasks. Both control tasks were used to control for dot configurations, as well as the numerals administered during the mixed condition. Bonferroni correction was applied to the following t-tests, and therefore a significant effect was detected if a p value $< .01$. Greater activation was found during mixed numerical discrimination compared to the mean beta weights for both symbolic and non-symbolic control tasks ($p < .005$) in the right fusiform gyrus in typically developing children. Furthermore, typically developing children recruited the left SPL to a greater extent during mixed discrimination relative to mean of symbolic and non-symbolic control tasks ($p < .004$). However, children with DD did not exhibit significant differences in activation during the mixed discrimination compared to the mean beta values for both control tasks in the right fusiform gyrus ($p > .32$) and the left SPL ($p > .17$) (see Table 5.4 for mean beta weights).

Additionally, independent samples t-tests were conducted to examine whether there were significant group differences in activation during the non-symbolic and symbolic control tasks. For an effect to be significant, a Bonferroni corrected p -value $< .02$ must be reached. There were no group differences in the mean activation during both symbolic and non-symbolic control tasks in the right fusiform gyrus ($p > .10$) and a marginally significant difference between groups in the left SPL ($p < .035$) (see Table 5.4 for mean beta weights). The ROI analyses revealed that stronger activation during the mixed numerical discrimination was specific to numerical mapping rather than low level processes common in both numerical discrimination and control tasks.

Table 5.4: Mean beta weights that were extracted from the clusters that demonstrated greater activation in TD children compared to children with DD for the mix numerical discrimination > baseline whole brain contrast, in addition to the non-symbolic and symbolic control tasks

Cluster	Task	TD	DD
		Mean (<i>SD</i>)	Mean (<i>SD</i>)
Right Fusiform Gyrus	Mixed NC	6.97 (4.67)	1.34 (1.40)
	Control	3.80 (3.23)	2.14 (1.95)
Left SPL	Mixed NC	3.79 (2.62)	.77 (1.83)
	Control	1.14 (1.77)	-.24 (.98)

Note. TD = Typically developing; DD = developmental dyscalculia; SD = standard deviation; NC = number comparison/discrimination; SPL = Superior Parietal Lobule.

5.3.3.7 Conjunction analysis (Mixed \cap Symbolic > Baseline)

Both the mixed and symbolic numerical discrimination whole brain analyses independently revealed common group differences in activation. Therefore, a conjunction of both mixed and symbolic formats were analyzed between groups to examine whether there are regions that differ both for the mixed and symbolic conditions between the children with and without DD. To undertake this analysis, first individual statistical maps were calculated for each participant estimating the conjunction of mixed and symbolic processing. Then, the individual conjunction maps were averaged across each group so that we could compare the activation that was common to both mapping and symbolic numerical processing between children with DD and TD children. The initial uncorrected threshold was set to $p < .005$, and the resulting statistical map, which had a

false positive rate of $p < .05$, had cluster sizes that met or exceeded 9 functional voxels (243 structural voxels) once cluster correction was applied.

This analysis revealed that children with DD atypically recruited a region in the left SPL, right fusiform gyrus, as well as lingual gyrus, thalamus and right Caudate (see Figure 7a for an illustration of cluster locations in purple showing significant differences) in comparison to typically developing children during both mix and symbolic comparison. Specifically, stronger activation in all regions was found for typically developing children in comparison to children with DD.

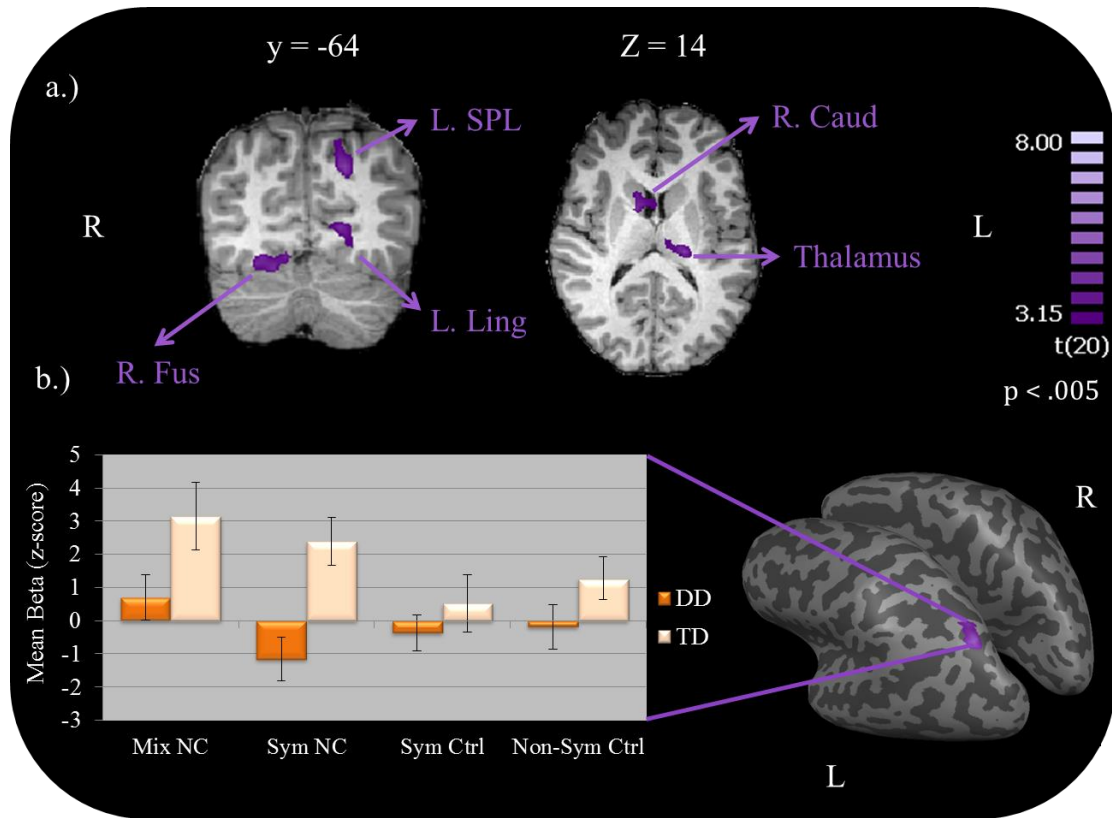


Figure 5.6: Statistical map illustrating regions in purple where TD children demonstrated greater activation from the mixed \cap symbolic $>$ baseline whole brain contrast compared to children with DD. a.) Five clusters shown on the coronal and transverse views of a T1 anatomical brain b.) The mean beta weights (z-score) extracted from the left SPL for the mix and symbolic numerical discrimination, as well as both symbolic and non-symbolic control tasks are plotted for both typically developing children and children with DD on the left. The left SPL is mapped onto an inflated anatomical brain on the right. Error bars represent one standard error on either side of the mean. L = left; R = right; IPS = Intraparietal sulcus; Fus = Fusiform; Ling = Lingual gyrus; Caud = Caudate; Ctrl = Control; NC = number comparison/discrimination.

5.3.3.8 Conjunction ROI analysis

Beta weights were extracted from clusters that demonstrated differential activation patterns in the mixed and symbolic conjunction analysis between children with DD and typically developing children. Paired samples t-tests were conducted within groups to examine whether activations found within groups were specific to discriminating between

mixed and symbolic formats compared to both the symbolic and non-symbolic control tasks. For this analysis, Bonferroni corrected p values need to be less than .005 to remain significant. Typically developing children demonstrated significantly greater activation during the conjunction of both mixed and symbolic numerical discrimination tasks in the right fusiform gyrus ($p < .002$) and marginally significant greater activation in the left SPL ($p < .006$). However, none of the other t -tests remained significant once the Bonferroni correction was applied (right caudate, $p < .05$; left thalamus $p < .03$; left lingual gyrus, $p < .03$).

Within the DD group, paired samples t -tests revealed that there were no significant differences between the mean beta values during the conjunction of mix and symbolic numerical tasks and the mean beta values during the control tasks ($p > .40$).

Independent samples t -tests investigating the differences between typically developing children and children with DD during the control tasks revealed no significant group differences in any of the clusters (all p -values $> .12$). These findings suggest that group differences in the activation during the conjunction of mixed and symbolic numerical discrimination tasks are associated with processes involved in mapping between non-symbolic and symbolic formats and symbolic numerical processing rather than processes common across both control and numerical tasks.

Table 5.5: Mean beta weights that were extracted from the clusters that demonstrated greater activation in TD children compared to children with DD for the conjunction of mixed and symbolic numerical discrimination > baseline whole brain contrast, in addition to the non-symbolic and symbolic control tasks.

Cluster	Task	TD	DD
		Mean (<i>SD</i>)	Mean (<i>SD</i>)
Right Fusiform Gyrus	Sym-Mixed NC	5.85 (3.19)	1.81 (.97)
	Control	3.77 (2.81)	2.22 (1.73)
Right Caudate	Sym-Mixed NC	2.31 (2.25)	-.67 (1.35)
	Control	-.22 (2.34)	-.58 (1.91)
Left Thalamus	Sym-Mixed NC	1.90 (1.41)	.15 (.72)
	Control	.52 (.62)	.12 (1.31)
Left Lingual Gyrus	Sym-Mixed NC	4.95 (2.85)	1.39 (1.71)
	Control	2.77 (2.38)	1.38 (1.87)
Left SPL	Sym-Mixed NC	2.96 (2.64)	-.23 (1.90)
	Control	.90 (2.04)	-.27 (1.27)

Note . TD = Typically developing; DD = developmental dyscalculia; SD = standard deviation; NC = number comparison/discrimination; Sym = Symbolic; SPL = Superior Parietal Lobule.

5.4 Discussion

A limited number of studies have examined the neurocognitive mechanisms associated with processing both symbolic and non-symbolic numerical magnitudes in children with Developmental Dyscalculia (DD). The few studies that have been published only examined the neural correlates of one format of representation (either symbolic or non-symbolic) resulting in no studies to date that have examined whether children with DD exhibit differences in brain activation for both symbolic and non-symbolic numerical

processing within the same sample of children. Moreover, no investigation has examined whether children with DD exhibit atypical brain activation while mapping between symbolic and non-symbolic numerical representations. Therefore, there is no cognitive neuroscience evidence to support or refute either the representational hypothesis or the access deficit hypotheses of DD. Thus the aim of the current study was to elucidate the neurocognitive underpinnings of symbolic and non-symbolic magnitude processing in children with DD to shed light on the efficacy of the ‘representational’ and ‘access deficit’ hypotheses of DD.

Converging evidence from functional neuroimaging studies in typically developing populations has revealed the intraparietal sulcus (IPS) as a key region for representing and processing numerical magnitude (Dehaene et al., 2003; Nieder & Dehaene, 2009). Thus abnormalities in the bilateral IPS would lead to deficits in the foundational competencies required to perform basic arithmetic operations in children with DD. Based on previous behavioural and neuroimaging evidence, researchers postulate that severe arithmetic difficulties manifested in children with DD are caused by a core ‘representational’ deficit in representing numerical magnitude (Dehaene et al., 2003). In contrast, recent behavioural studies have found that children with DD exhibit selective deficits in symbolic numerical comparison tasks while processing non-symbolic magnitude remains intact. These findings have led to the formulation of the ‘access deficit’ hypothesis which posits that DD is caused by a deficit in accessing the semantic representation of symbolic numerals (Rousselle & Noel, 2007; DeSmedt & Gilmore, 2011).

In light of the above, the present study aimed to address the gaps in the current literature by investigating the neural correlates of symbolic and non-symbolic numerical processing in children with and without DD. In addition, the present study investigated the neural processes associated with mapping between both formats in children with persistent DD compared to typically developing controls. Whole brain contrasts were conducted independently for each numerical task to directly test the ‘representational’ and the ‘access deficit’ hypotheses of DD.

At the behavioural level, our findings point toward a specific deficit in processing the semantic properties of symbolic numerals as evidenced by poor performance on both the symbolic and mixed numerical discrimination tasks. Children with DD had greater difficulties in discriminating between numerical magnitudes in both tasks that involved processing an Arabic digit. In contrast, comparable performance was observed in both groups during the non-symbolic numerical discrimination task suggesting that children with DD do not suffer from an impaired ability to discriminate between sets of squares. Although it appears that children with DD had poor performance during the non-symbolic discrimination task (see Figure 5.2), a null result could be attributed to greater variability in performance in the dyscalculia group.

The behavioural findings appear to support the ‘access deficit’ hypothesis of DD suggesting that mapping symbolic numerals to their quantity representations is impaired. The neural data yield similar results; specifically, children with DD demonstrated abnormal activation in the left IPS during symbolic and mixed numerical discriminations. However, group differences during the discrimination of non-symbolic numerical quantities demonstrated differential engagement of a network of regions in the prefrontal cortex, as well as the temporal lobes. Discriminating between non-symbolic representations did not reveal a divergent pattern of activation between groups in bilateral regions of the IPS.

Converging evidence from functional neuroimaging studies support the crucial role bilateral regions of the IPS play in processing the semantic representations of numerical magnitude; therefore, the present evidence suggests that children with DD do not present with a domain specific functional impairment in processing non-symbolic quantities in the bilateral IPS. In contrast, atypical activation of the IPS was found during the comparison of two symbolic numerals, or the mapping of symbolic numerals to their representations. Therefore, the present findings do not lend support for the existence of a core deficit in processing numerical magnitude across different formats. Instead, the present data suggest that symbolic representations of numerical magnitude in the brain are atypical in DD. These findings are consistent with the predictions of the ‘access

deficit' hypothesis suggesting that children with DD have deficits in accessing the semantic meaning of symbolic numerical representations in the IPS.

In contrast to the non-symbolic task, children with DD produced a weak neural response in the bilateral regions of the IPS during the discrimination of symbolic numerical representations compared to typically developing children. ROI analyses revealed that typically developing children demonstrated stronger activation during symbolic numerical discrimination compared to the control task in the left IPS. Aside from the left anterior cingulate, typically developing children did not show greater activation during symbolic comparison in the remaining clusters from the whole brain analysis compared to the control task. Therefore, left anterior cingulate, as well as the left IPS showed greater activity during symbolic discrimination compared to control task in typically developing children, suggesting that greater activation found in these regions are specific to processing numerical magnitudes. Additionally, there were no significant group differences in activation in the left IPS during the control task, supporting the specificity of the deficit in left IPS during symbolic numerical discrimination. Using a within-subjects design, this is the first study demonstrating atypical activation in the left IPS during symbolic comparison for children with DD compared to the brain network involved in discriminating between non-symbolic quantities. Consistent with behavioural studies demonstrating weaker performance during symbolic tasks compared to TD children, while performance in non-symbolic tasks remain intact, the present findings support a specific deficit in the neurocognitive mechanisms underpinning symbolic numerical discriminations.

Additional support for the existence of atypical processing of numerical symbols in the IPS comes from the finding of atypical activation in the same, as demonstrated by the conjunction analysis, left IPS cluster during mixed numerical discrimination in children with DD compared to typically developing children. Therefore weak activation during symbolic and mixed numerical discrimination in children with DD is suggestive of specific impairment in mapping between symbolic numerals and their semantic representations. Activation in the left IPS was found to be specifically related to numerical processing as opposed to general task processes, in view of the finding that

there was greater activation during symbolic and mixed format discriminations compared to the control tasks in typically developing children. Left IPS dysfunction, in the same overlapping region, has been associated with the atypical processing of symbolic numerals in children with DD (Mussolin et al., 2010). Specifically, Mussolin et al., found weaker distance dependent modulation in the left IPS in children with DD compared to TD controls. The left IPS is in close proximity to the left precuneus identified in the meta-analysis showing atypical distance effects merged across both symbolic and non-symbolic numerical discrimination (Kaufmann et al., 2011, Talarach coordinates: -22, -62, 50). Additionally, structural investigations using voxel-based morphometry have revealed reduced grey matter volume in regions around the bilateral IPS (Rotzer et al., 2008; Rhysklevnia et al., 2009). In view of this, structural and functional deficiencies in the left IPS might be neural substrate for impaired symbolic processing in children with DD.

A large body of evidence has implicated the left IPS in processing symbolic representations compared to non-symbolic representations, suggesting hemispheric differences in the right and left IPS in the development and engagement of symbolic numerical representations. Adult studies have found that the left IPS to be more engaged and fine-tuned to processing symbolic numbers compared to non-symbolic quantities (Piazza et al., 2007). Developmental studies have shown age related changes in the left IPS (Ansari & Dhital, 2006), as well as an increased left IPS activity over time as a function of numerical acuity (Cantlon & Emerson, 2014). Additionally, activation in the left IPS during symbolic numerical discrimination also predicts individual differences in standardized tests of arithmetic achievement (Bugden et al., 2012). The present data provide neurocognitive evidence supporting a deficit in processing symbolic numerical representations, with stronger evidence suggesting a specific mapping hypothesis in children with DD.

Thus far it has been argued that the present data provide supporting evidence for the 'access deficit' hypothesis of DD; however, an alternate explanation of these data can be put forward which leads to a different hypothesis regarding the nature of symbolic number processing deficits in DD. Specifically, until recently, researchers have not

directly tested the hypothesis that symbolic representations are acquired through the automatic association and consistent pairing of arbitrary symbols with non-symbolic, approximate numerical representations. However, recent studies have provided both behavioural (Lyons et al., 2012) and neural (Lyons et al., 2014) evidence to suggest that the underlying structure of the symbolic representational system is qualitatively different from approximate non-symbolic representations, thereby challenging the commonly held belief that symbolic representations are automatically mapped to non-symbolic quantities. If both formats of numerical magnitude are represented by fundamentally different representational systems, it is unclear from the current findings whether atypical activation in the left IPS is driven by a deficit in associating symbolic numerals to their respective quantities or whether it is driven by a specific deficit in processing symbolic numerical magnitudes. The mixed numerical discrimination requires children to compare both a symbolic and non-symbolic format, but neural correlates recruited during this task could be attributed to processing a symbolic numeral. It can be postulated that if symbolic and non-symbolic representations are processed in fundamentally different ways, the present data also supports a specific deficit in processing symbolic numerals. Thus, DD maybe caused by a deficit in processing symbolic numerals in the left IPS, rather than the specific process of mapping them to their respective non-symbolic approximate representations. The present study provides new avenues for future studies to test this hypothesis using a direct mapping task discussed in the introduction where participants have to match a specific number to its cross format counterpart, rather than discriminating between two different formats. Different cognitive processes may subserve a direct mapping task and a cross format (mixed) numerical discrimination task.

The present study also revealed that the right fusiform gyrus located in the occipital lobe exhibited differential activation that is numerically specific during the mixed numerical discrimination task and the conjunction of both mixed and symbolic discrimination. Children with DD showed reduced activation in this region during the processing of symbolic numerals. It has been postulated in the 'Triple Code Model' that the fusiform gyrus houses the asemantic coding of Arabic numerals. It has been implicated in the identification of Arabic numerals both in the left and right hemisphere. This region has been referred to as 'visual number form area' and hypothesized to be

associated with sending information about the identified digit to the parietal lobes for processing (Cohen & Dehaene, 1995; Holloway, Battista, Vogel & Ansari, 2013; Pinel et al., 2001; Shum et al., 2013; see Price & Ansari, 2011 for conflicting findings). Atypical activation found in the present study may be associated with differential visual coding of symbolic numerals in children with DD in addition to their parietally-mediated semantic representation.

The non-symbolic discrimination task produced differential networks of regions in children with DD that lie specifically in the bilateral superior temporal gyrus as well as the medial frontal gyrus, thalamus, putamen and left middle temporal gyrus. Previous research has not implicated these brain regions in processing numerical magnitude; furthermore, group differences were characterized by greater deactivation in children with DD relative to typical controls. Subsequent region of interest analyses revealed no significant differences in recruiting these regions of interest during non-symbolic discrimination and control tasks in both groups. Similar patterns of brain activation found during both non-symbolic discrimination and control tasks suggest that group differences are driven by domain general processes or strategies that are similarly recruited for the execution of both tasks.

The recruitment of prefrontal regions has been associated with domain general processes such as attention and working memory that support discrimination of numerical quantities (Ansari & Dhital, 2006). The recruitment of regions in the prefrontal cortex in young children has been interpreted as reflecting effortful and less automatic processes that are compensating for an imprecise (not yet developed) representation of numerical magnitude in the IPS that is continually undergoing developmental specialization (for a review see: Ansari, 2008). It is plausible that differential activation in the medial prefrontal cortex found between children with DD and typically developing controls is associated with domain general processes such as working memory and attention required to make a response during both non-symbolic and control tasks. It could be argued that differential recruitment of prefrontal regions is associated with less specialized IPS for discriminating between non-symbolic quantities. However, no differences were found in the IPS between groups, moreover, differences in activation

found between groups were not specific to the non-symbolic discrimination task as there were no differences found between the experimental and control conditions.

Group differences found in the prefrontal cortex may be associated with domain general cognitive processes recruited to reconcile between incongruent and congruent stimuli of the non-symbolic discrimination task. Indeed, the results from chapter four suggest that different cognitive strategies and processes are employed across different non-symbolic trial types (e.g. congruent and incongruent); therefore, it is plausible that differential activation in the prefrontal cortex is associated with executive functioning during the discrimination of incongruent and congruent trials. Future studies are required to tease apart different neurocognitive mechanisms underlying the discrimination of congruent and incongruent visual perceptual cues that has been found to affect performance in the behavioural literature (Fuhs & McNeil, 2013; Gebuis & Reynvoet, 2012; Gilmore et al., 2013; DeFever, Reynvoet, & Gebuis, 2013).

The differences in activation during the non-symbolic task were characterized by greater deactivation in the sample of DD compared to typically developing children. This finding is consistent with the study conducted by Price et al. (2007) who found that children with DD had greater deactivation during close distance pairs in the medial prefrontal cortex during non-symbolic numerical discrimination compared to typically developing controls. This region found in Price et al. was located in close proximity to the region found in the present study (MPFC: -13, 54, -2). These findings were associated with greater deactivation of the default mode network in response to task difficulty (Gusnard & Raichle, 2001). Taken together, these findings suggest that reduced deactivation in the prefrontal cortex for typically developing children are associated with similar domain general processes during both non-symbolic discrimination and control tasks. These domain general processes could be related to executive processes, such as working memory or decision related processes, and thus it is difficult to draw any conclusions that are specific to group differences in the neuronal processing non-symbolic numerical magnitude.

Differential recruitment in regions located in the STG and MTG during non-symbolic numerical discrimination was less expected as they are commonly associated with speech perception and language abilities (for a review see: Leonard & Chang, 2014). Previous DD neuroimaging studies investigating non-symbolic numerical discrimination have not found differences in activation in regions located in the temporal lobe; however, it is speculated that greater activation in the STG in typically developing children in the present study is associated with using verbal strategies. In a study conducted by Venkatraman, Ansari & Chee (2005), they found that typically developing adults recruited the bilateral insula (which is located in close proximity to the left STG in the present study) during an approximate addition task. During this task, participants added sets of dots and estimated the correct answer by selecting from two symbolic numerals. It was suggested that the insula was involved in the internal recitation of number words (Venkatraman et al.). It is plausible that typically developing children relied on similar verbal strategies such as internally reciting strategies during task responses in both non-symbolic and control tasks. However it remains unclear specifically what is driving greater deactivation in these regions in children with DD compared to typically developing children and these speculations are based on reverse inference. However, the fact that no differences were found between activation during the non-symbolic numerical discrimination task and the control task in the prefrontal and temporal regions indicates that group differences were not specific to discriminating between non-symbolic magnitudes, but to processes recruited for the execution of both tasks.

Our pattern of findings are inconsistent with those presented in Price et al. (2007), in that we did not find atypical activation in the right IPS for non-symbolic processing in children with DD. There are a few explanations to account for the disparate findings between the current study and Price et al., (2007). First, in contrast to Price et al.'s investigation, the present study examined format specific activation differences in symbolic, non-symbolic and mixed numerical discrimination; and therefore, numerical distance was not examined in the present study. Second, children with DD in the present study were identified based on persistent impairments in arithmetic abilities and therefore both studies could include qualitatively different samples of children with arithmetic deficits.

The aim of the present study was to examine differences in brain activation specific to each format in children with DD compared to their controls. From the current design, it is unclear whether differences in activation found in the left IPS during symbolic and mixed comparisons were significantly greater than the null result found for the non-symbolic comparison (e.g. no interaction tested). Although the differences in activation during the symbolic and mixed conditions appear to be greater than the non-symbolic condition, this has yet to be tested with the present analysis.

In conclusion, the present study was the first to investigate the neural correlates of symbolic, non-symbolic and mixed format numerical processing in a group of children with DD identified as having severe and persistent impairments in speeded and unspeeded measures of arithmetic performance. Using a within subjects design, the data are the first to demonstrate the existence of functional impairments associated with processing both symbolic and mixed format representations in the left IPS in children with DD compared to their typically developing controls. These results are the first to associate mapping between symbolic and non-symbolic formats in the left IPS and provide supporting evidence for deficiencies of accessing the semantic meaning of numerical symbols in children who present with persistent impairments of arithmetic.

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Chapter 6

6 General discussion

Developmental dyscalculia (DD) is a specific learning disorder that impairs the acquisition of basic arithmetic skills. Relative to the field of dyslexia (a specific reading disorder), research investigating the core deficits of DD is in its infancy (Murphy et al., 2007). Consequently, the cognitive and neurological origins of severe arithmetic impairments in children with DD remain unclear. This is problematic, as DD has a prevalence rates equal to dyslexia (5-7% of school age children) and is associated with poor social and emotional outcomes (Shalev et al., 2000; Shalev, 2004). Some studies have found that children with DD exhibit difficulties in semantic memory and working memory systems that lead to problems with arithmetic (Geary, 1993; Geary, 2004; McLean & Hitch, 1999). In contrast, other studies have not revealed such differences between children with and without DD (Landerl et al., 2004), but instead have demonstrated specific impairments in representing and processing numerical information that may cause deficiencies in arithmetic performance (Landerl et al., 2004; 2013; for a review see: Butterworth, 2010). Furthermore, little consensus has been reached within the field of general learning disabilities as to the best method to operationally define a specific LD. Within the DD literature, researchers have used a wide variety of operational definitions and divergent sets of selection criteria to identify children with DD (see Table in Chapter 2). This heterogeneity in definitional criteria has hindered efforts to understand the root causes of DD. To address the inconsistencies within the field of DD, in the present thesis, I reported a series of studies examining both the neurological and cognitive characteristics in a sample of DD who were identified as having persistent arithmetic deficits.

It is generally agreed upon that children with DD have severe difficulties learning arithmetic facts and often rely on immature calculation strategies rather than retrieving answers to calculation problems from memory (Geary, 2013). Researchers are still attempting to uncover what neurological and cognitive mechanisms contribute to the

inability to learn basic arithmetic. Historically, researchers have argued that DD is caused by a deficit in domain general systems such as working memory, which lead to difficulties in storing and retrieving arithmetic facts (Geary, 1993). Studies supporting the domain general account of DD do not include tasks that measure numerical or math related skills; therefore, based on these studies alone it is difficult to make strong conclusions about domain general processes being the sole or most important contributor of DD. More recently, researchers have been focusing on early basic numerical skills, such as representing numerical magnitude. In this vein, Butterworth and colleagues (1999, 2005) have proposed the ‘*defective number module*’ hypothesis wherein DD is caused by a domain specific impairment in the core capacity to represent and manipulate discrete numerical quantities (Butterworth, 1999, 2005; Iuculano et al., 2008). According to this theory children with DD are thought to demonstrate specific impairments in tasks that require discrete numerical processes such as object enumeration, processing and discriminating between symbolic numerals, and counting. Furthermore, other researchers have found that children with DD demonstrate deficiencies in approximating between large non-symbolic magnitudes (e.g., dot arrays; Mazzocco, Feigenson & Halberda, 2011; Mussolin, Meijas & Noel, 2010; Piazza et al., 2010). Against this background, it has been proposed that DD is caused by deficits in the *approximate number system* (ANS), which has been theorized as a phylogenetic precursor to representing both non-symbolic and symbolic numerical representations (for a review see: Dehaene, 2007). According to this hypothesis, children with DD exhibit severe difficulties in discriminating between and manipulating approximate non-symbolic magnitudes. In addition, this theory posits that children with DD would also exhibit difficulties in processing symbolic numerals (e.g., non-symbolic and symbolic numerical discrimination tasks), because symbolic representations are grounded in the ANS. In contrast to both of these representational hypotheses of DD (defective number module and impaired ANS), studies have revealed that children with DD do not only demonstrate impairments in processing symbolic numerical magnitudes, but demonstrate typical performance on approximate numerical tasks (De Smedt & Gilmore, 2011; Rouselle & Noël, 2007). As a result of these findings, Rouselle and Noël (2007) speculate that the deficit is not with the representation of numerical magnitude, but in the connections

between number symbols (e.g., Arabic numerals - 3 or, number words - three) and their respective magnitude meaning.

Evidence supporting each of these causal theories of DD comes from behavioural studies that use symbolic and/or non-symbolic numerical discrimination tasks. In only a handful of studies that examine the neurocognitive mechanisms associated with DD (using methods such as functional Magnetic Resonance Imaging of the brain), researchers have only employed either the symbolic or non-symbolic numerical discrimination tasks. Their results suggest that a dysfunction of areas in the parietal cortex may underlie reduced capability in processing non-symbolic or symbolic numerical magnitudes in children with DD. Specifically, in a study that used a non-symbolic discrimination task, children with DD exhibited reduced activation in the right IPS compared to their typical controls (Price et al., 2007). Similarly, Mussolin and colleagues (2010) found atypical activation in the left IPS during symbolic numerical discrimination in children with DD compared to typically developing children. In both studies, a widespread network of regions was found to have atypical activation in children with DD. However, there is converging evidence from adult and developmental studies to suggest that the IPS is critical for representing and manipulating numerical magnitudes (for a review see: Dehaene et al., 2003). Thus, the IPS is likely the most important brain region associated with numerical magnitude processing. To date there are no functional neuroimaging studies that administer both symbolic and non-symbolic discrimination tasks in the same sample of children with DD, and as a result, there is no neuroimaging evidence to specifically support or refute the representational (Defective number module and Approximate number system) or access deficit hypotheses of DD at the brain level of analysis.

It is evident that current findings supporting the causal hypotheses of DD are contradictory, and that there exists no clear conclusions as to what causes DD and no universally agreed upon criteria for diagnosing DD (Mazzocco & Myers, 2003). As a result, it is difficult for researchers to make conclusions about what underlying cognitive mechanisms impair children's ability to learn basic arithmetic. The present thesis aimed to address inconsistencies in definitional criteria of DD by selecting children who

previously participated in a longitudinal screening study (Archibald et al., 2014) and demonstrated persistent impairments on speeded and un-speeded standardized measures of arithmetic achievement. By examining a group of children who demonstrated persistent impairments in arithmetic performance (in accordance with the recently published DSM-V criteria; APA 2013), I aimed to examine the veracity of the domain specific causal hypotheses of DD by investigating the behavioural and neurocognitive mechanisms associated with symbolic and non-symbolic numerical processing.

First, to assess the definitional criteria implemented in the present thesis, I examined differences in performance on a domain specific numerical magnitude processing task, which was not used in the selection of samples (Chapter 2). This task was a paper and pencil version of the numerical discrimination task, where children had to select the numerically larger number or dot array by making a mark on the page corresponding to the larger quantity as fast as they could (Nosworthy et al., 2013). The findings from the analyses demonstrated that children with persistent DD performed significantly worse on the numerical discrimination task compared to children with inconsistent math performance and typically developing children. Therefore, these data revealed qualitative differences in numerical magnitude processing deficits in children who demonstrated persistent deficits in arithmetic skills compared to children who exhibited inconsistent performance over time and persistent typically developing children. This finding highlights the importance of incorporating a stability criterion in identifying children with DD as children who would have been identified as having DD after one testing session (inconsistent DD group) did not demonstrate differences in performance compared to TD children. Therefore, the DD and TD samples recruited for the subsequent investigations (Chapters 3-5) were optimal for examining core deficits in numerical magnitude processing by reducing or even eliminating any children who would have been mistakenly identified as having DD (false positive).

In the following year, a behavioural investigation examining differences in processing symbolic and non-symbolic numerical magnitudes between children with persistent DD and their typical controls was conducted using a wide array of numerical tasks (Chapter 3). Numerical discrimination tasks (i.e., judging which of two numerical

magnitudes is numerically larger) are most commonly used to assess symbolic and non-symbolic processing abilities as they are thought to reveal indices about the integrity of their underlying representational system. The nature of specific numerical processing deficits (to either support or refute the causal theories) of DD were examined using tasks that are commonly employed with typically developing samples (e.g., Physical size congruity task, Number line estimation tasks, Numerical discrimination tasks), as well as a fairly novel task – an Audio-visual matching task.

The results from this study (Chapter 3) provided support for the access deficit hypothesis as children with DD only demonstrated significantly worse performance on symbolic numerical discrimination and the 0-to-1000 number line estimation tasks. No other significant differences were found in tasks that assess the automaticity in processing symbolic numerals, approximating between non-symbolic magnitudes and integrating auditory and visually presented symbolic numerals. Children with DD demonstrated a specific deficit in tasks that required intentional manipulation of symbolic numerals. The behavioural findings contradict the approximate numerical deficit as well as the number module hypotheses since children with DD exhibited performance similar to the typically developing group on the non-symbolic numerical discrimination task.

Recently, studies conducted with typically developing participants have challenged the reliability of non-symbolic numerical magnitude tasks (Inglis & Gilmore, 2013; 2014; Gilmore et al., 2013). In a study conducted by Gilmore et al. (2013), they investigated whether participants' response patterns were altered by methods used to control for the effect of visual perceptual cues of the non-symbolic dot stimuli on performance (relying on size or area to inform judgments rather than numerical magnitude). These control parameters result in the size and area of the dots either being correlated (congruent trials) or anti-correlated (incongruent trials) with the larger dot array. They found that performance on the incongruent trials significantly correlated with mathematical achievement, but no longer predicted math achievement once inhibitory control abilities were accounted for. This study revealed that performance on the non-symbolic numerical discrimination task in typically developing children is not specific to domain specific numerical processes. Instead, in order to make a response

based on quantity during the incongruent trials, children recruit domain general cognitive processes such as inhibitory control to inhibit the task irrelevant cues (such as area or size of the dot stimuli). Therefore, differences found in studies that examine the non-symbolic discrimination task may be a product of variability in the task construction, and/or differences in domain general cognitive processes recruited during the discrimination of different trials types (see below for a more thorough discussion).

In view of these data, I sought to probe the nature of the approximate numerical deficit in children with persistent DD. In particular, I examined whether visual perceptual cues inherent in the dot stimuli affected performance differently in children with DD and typically developing children. The integrity of the ANS was measured using the widely-used Panamath (www.panamath.org) non-symbolic numerical discrimination test, which has been published online (Halberda, Mazocco & Feigenson, 2008). ANS acuity was indexed by calculating a Weber fraction (W) for each participant. W theoretically reflects the size of the standard deviation of the Gaussian distributions representing numerical magnitudes (Piazza et al., 2010; Piazza, 2010). This analysis revealed that differences in W were only found between DD and TD children on the incongruent trials (where numerical and non-numerical cues conflict). Additionally, visuo-spatial working memory strongly predicted individual differences in ANS acuity (W) during the incongruent trials in children with DD but not in the typically developing controls. Thus the purported ANS deficit in DD can be explained by a difficulty in extracting number from an array of dots specifically when area is anti-correlated with number. These data highlight the role of visuo-spatial working memory during the extraction of numerically specific information when visual perceptual cues are incongruent with numerical magnitude. Previous studies supporting an ANS deficit in children with DD, did not examine the effect of visual perceptual variables on performance to disentangle whether other domain general cognitive processes as well as low level visual processes influence performance differently across trials (Mussolin, Meijas & Noel, 2010; Piazza et al., 2010; Price et al., 2007). The findings from the study conducted in chapter 4 demonstrate that close attention needs to be paid to perceptual processes invoked by tasks purported to represent measures of the ANS.

In the final study of my thesis (Chapter 5), I tested the veracity of the access deficit and approximate numerical deficit hypotheses using neuroscientific data. Specifically, symbolic and non-symbolic discrimination tasks, as well as a cross format discrimination task were administered in an fMRI scanner to assess the neural correlates associated with mapping within and between formats. The results from this study were the first to demonstrate neurocognitive evidence supporting the access deficit hypothesis. Specifically, children with DD demonstrated atypical activation in the left IPS during the symbolic and mixed numerical discrimination tasks compared to their typical controls. In contrast, children with DD did not demonstrate functional impairments in the IPS during non-symbolic discrimination. Instead, children with DD demonstrated greater deactivation in regions in the prefrontal and temporal lobes that have not been previously associated with the semantic processing of numerical magnitudes. These findings are consistent with previously conducted fMRI studies that have revealed atypical activation during either symbolic or non-symbolic magnitude processing in the left IPS (Mussolin et al., 2010; Kaufmann et al., 2011). Furthermore, structural studies have found reduced grey matter volume in the same overlapping cluster (Rykhlevskaia et al., 2009). Therefore, consistent with previous studies, I found that the left IPS may be the neural substrate underlying symbolic number skills as well as mapping skills in children with DD. However, in contrast to previous studies, I was able to show, using a within-subject design, that unlike non-symbolic number discrimination, symbolic number discrimination and mapping tasks are associated with atypical parietal activation in children with DD.

6.1 Evidence supporting the ‘Access Deficit’ hypothesis

Taken together, the behavioural and neurocognitive data in the present thesis provide converging evidence to support the access deficit hypothesis in children with DD. In accordance with previous studies supporting the access deficit hypothesis (De Smedt & Gilmore, 2011; Rouselle & Noel, 2007), the findings from the present thesis suggest that children with DD demonstrate greater difficulties in accessing the semantic representations of symbolic numerals in tasks that require children to intentionally access their corresponding representations. Deficits in processing symbolic numerals and

mapping them to their corresponding quantities are associated with functional impairments in the neurological substrate that has been implicated in processing symbolic numerical magnitudes in typically developing populations – the left IPS (for a review see: Ansari, 2008).

The results of these studies contradict the commonly held and dominant theory that DD is caused by a deficiency in the development of approximate numerical representations (Dehaene et al., 2003; Piazza, 2010). In all three studies conducted in this thesis, children with DD did not demonstrate poor performance on non-symbolic discrimination tasks, and as revealed in chapter 4, if differences were found, they could be attributed to processes related to disentangling numerical and non-numerical dimensions of non-symbolic stimuli, rather than a core deficit in processing non-symbolic numerical magnitudes. Therefore, in a sample of children who demonstrated stable arithmetic impairments across four years of testing, approximate numerical representations were found to be intact.

Previous studies have demonstrated significant differences in performance on approximate numerical discrimination tasks (Mussolin, Meijas & Noël, 2010; Piazza et al., 2010; Price et al., 2007). In these studies, the effect that visual perceptual cues have on performance was not examined. In the present thesis, I demonstrated for the first time, that children with DD only exhibited significantly worse ANS acuity in trials where the size of the dots are incongruent with the larger dot array. No differences in performance were found during the congruent trials. These findings suggest that the non-symbolic numerical discrimination task is not a pure measure of approximate numerical representations, but also requires domain general processes such as inhibitory control (Gilmore et al., 2013) and/or visuo-spatial working memory. It is unclear whether previous studies that have found ANS deficits in children with DD can be attributed to poor performance on incongruent trials. Future research is clearly needed to tease apart the precise cognitive mechanisms involved in the discrimination of differently constructed dot stimuli to understand what this task is assessing.

It is possible that the lack of activation differences found in bilateral regions of the IPS, as well as the lack of group differences in behavioural correlates of ANS acuity can be attributed to compensatory mechanisms that children in this age group have developed through instruction and experience. Children who participated in the present studies were between the ages 9-13 years during the final testing session (fMRI study); therefore, with 6-9 years of formal schooling. Hence, children with DD could have developed a more precise representation of non-symbolic magnitudes. Previous research has found that ANS acuity measured in infants predicts mathematical achievement in preschool. These findings suggest that the preverbal ANS plays a fundamental role in the development of early math skills (Starr, Libertus & Brannon, 2013). Therefore, ANS may play a greater role in developing symbolic numerical representations and is more strongly related to individual differences in arithmetic achievement early in development. It is plausible that differences in brain networks involved in discriminating between approximate numerical quantities when children are first learning formal mathematics would be more pronounced in children with DD during early school years. Children who were tested in the present study already had developed a fully intact approximate numerical representational system in the bilateral regions of the IPS, yet they demonstrated greater atypical activation during symbolic numerical tasks. Children with DD may experience different profiles of difficulties at different time points over the course of development. Future longitudinal studies are necessary to investigate the developmental trajectories of both approximate and symbolic numerical systems.

Notwithstanding the above, the data in the present thesis provide stronger support for the access deficit hypothesis that postulates a specific deficit in connecting symbols to their corresponding quantities. However, recent studies have proposed that symbolic and non-symbolic representations have a qualitatively distinct structural system, suggesting that non-symbolic and symbolic representations are not as tightly linked as previously believed (Lyons et al., 2012; 2014). If symbolic and non-symbolic formats are represented by fundamentally different systems, then the present data provide support for an alternate hypothesis regarding the nature of symbolic number processing deficits in DD. Specifically, children with DD may experience deficits in processing symbolic numerical magnitudes, rather than in associating them with their corresponding

approximate numerical representations. This notion is supported in typically developing children (Gobel, Watson, Lervag & Hulme, 2014). This alternate hypothesis leads to open empirical questions about the nature of symbolic and non-symbolic numerical representations both in typically developing children and children with DD. Future studies using direct mapping tasks (Mundy & Gilmore, 2009; see chapter 5 for description) are needed to elucidate whether children with DD do indeed have a mapping deficit or a difficulty in processing symbols independently of their semantic referents.

6.2 Domain general cognitive deficits in DD

The studies conducted in the present thesis focused on examining the core deficits of numerical processing skills in children with persistent DD. In other words, I did not examine the relationship between numerical processing deficits and working memory abilities in children with persistent DD. Children with persistent DD in the present study demonstrated variable but weak verbal and visuo-spatial working memory abilities, with an overall greater impairment in verbal working memory. Previous research investigating various components of working memory reveal a contradictory picture with respect to domain-general deficits in DD, with some studies suggesting that working memory is associated with DD (Geary, 1993), and others finding no significant differences (Landerl et al., 2004). In the current study, I found that visuo-spatial working memory was more impaired in children who demonstrated a greater impairment in arithmetic achievement (see chapter 2). This finding is consistent with a study conducted by Passolunghi and Mammarella (2012) who found that only children with severe mathematical learning disabilities, compared to children with low mathematical achievement, demonstrated poor performance on a spatial working memory. Recently, researchers have suggested that visuo-spatial working memory specifically plays a greater role in poor arithmetic abilities in children with DD (Swanson, 2006; Szucs et al., 2013). Additionally a recent meta-analysis was conducted to synthesize the present data examining working memory abilities in children with reading and mathematical learning disabilities. Specifically, Peng and Fuchs (2014) found that children with DD showed more severe deficits in specific numerical working memory tasks (e.g., backwards digit recall or counting span tasks) compared to verbal working memory tasks that did not

involve number as stimuli, such as listening recall. Therefore, it is plausible that children with DD do not demonstrate a global working memory deficit, but exhibit difficulties when they are reaching their limits and capacities in areas related to arithmetic and numerical processing.

Additionally, functional neuroimaging studies have found that children with DD elicited weaker activation in the right IPS, right insula and the right inferior frontal gyrus during a visuospatial working memory task (Klingberg et al., 2002). Furthermore, these findings give rise to the hypothesis that spatial working memory abilities are related to building a numerical representational system. Therefore, deficits in spatial working memory may lead to numeracy (Price et al., 2007) and arithmetic impairments. This was further supported by a study conducted by Dumontheil and Klingberg (2011), who found that activation in the left IPS during a visuospatial working memory task, relative to the rest of the brain, predicts arithmetic performance two years later in 6-16 year old participants. The results from these studies are inconsistent with the notion that the IPS is involved in the domain-specific representation of numerical magnitude (the quantity code of the triple-code model) and instead suggest that the IPS is associated with individual differences in working memory. Activation differences found in the IPS among children with DD may reflect impairment in working memory circuitry rather than the domain-specific representation of numerical magnitude. These findings emphasize the need for future studies to examine the interaction of brain circuits involved in working memory and numerical magnitude processing within the same group of children with DD to uncover the nature of the relationships between working memory abilities and mathematical tasks in children with DD.

6.3 Heterogeneity of DD

Mathematics is a complex academic subject that is cumulative in nature. The mastery of specific mathematical processes such as quantitative knowledge and symbolic decoding are required for the development of more complex skills. In addition to numerical knowledge, arithmetic performance depends on the integrity of multiple cognitive systems. For example, working memory, semantic memory and attention are

domain general cognitive processes involved in the execution of calculation procedures as well as the storage of arithmetic facts (Geary, 1993; Geary, 2013). Current research has focused on seeking to identify a single core deficit in numerical magnitude processing that results from a biological abnormality found in the IPS (the neural substrate involved in numerical magnitude processing). However, the behavioural and cognitive deficits found in children with DD are heterogeneous (Bartelet, Ansari, Vaessen, & Blomert, 2014; Fias, Menon & Szucs, 2013; Rubinsten & Henik, 2009) and it has been proposed that DD is better characterized by a multiple deficit model. Therefore, DD may not necessarily originate from a single cause. Instead, impairments in single or multiple brain regions (functional or structural impairments) alter the integrity of a complex neural system involved in calculation and arithmetic fact retrieval (Fias et al., 2013). In the present thesis, children with DD had a deficit in processing and accessing the semantic representations of symbolic numerals. According to a recent study conducted by Bartelet et al., (2014) there exist multiple subtypes of children with DD who are characterized by different strengths and weaknesses using different numerical and domain general measures. It is plausible that the current group of children with DD represent a specific subtype of children with DD who have symbolic numerical deficits. The deficits exhibited by children with DD are diverse and can stem from different origins. Therefore, future multidisciplinary research is needed to investigate the interactions among various numerical and domain general processes in both brain and behaviour.

6.4 Future directions

In future research it will be important to explore how numerical representations change throughout development. For instance, symbolic numerals (e.g., Arabic numerals) are cultural inventions that require explicit instruction to learn. Therefore, understanding how children map symbolic numerals to their iconic semantic referents can only be explained with a developmental approach. Developmental studies should investigate how symbolic representations emerge in children with DD and whether they are qualitatively different from typical controls at a young age. To reiterate this point, developmental studies are necessary to elucidate the role the approximate number system

has in the development of formal mathematical abilities. These studies will further our understanding of the causal relationship between learning symbolic numerals, non-symbolic representations and later arithmetic difficulties. Moreover, using developmental neuroimaging studies, researchers can investigate compensatory mechanisms and pathways that children with DD employ during non-symbolic and symbolic processing.

Using different neuroimaging analyses and methods, researchers can begin to uncover qualitative differences in the underlying neuronal mechanisms that underpin symbolic and non-symbolic numerical representations. Conventional statistical analyses of fMRI, such as the ones I employed in this thesis (Chapter 5) use a univariate statistical method to locate macroscopic brain regions involved in specific numerical tasks. These analyses characterize functional brain regions based on activity that is averaged across multiple voxels (three-dimensional pixels). Recently, there has been growing interest in moving beyond investigating average brain activity of particular regions, towards an exploration of activity pattern differences in specific brain regions by taking into account variability in the activation of individual voxels within areas of interest. Multivariate pattern analysis (MVPA) is an optimal approach to investigate the representation of numeracy in specific brain regions. This is because it uses a more fine-grained measure of patterns of activity within the brain that allows researchers to draw inferences about the representational content (Mur, Bandettini, & Kriegeskorte, 2009). Using these statistical techniques, future research should examine whether patterns of activity are significantly different between symbolic and non-symbolic representations in children with DD compared to representational systems in typically developing children. These studies can elucidate the integrity of the underlying representational systems in children with DD compared to typically developing children. Additionally, they can be informative about whether atypical numerical processing is caused by a qualitative difference in the symbolic and non-symbolic representational systems, or by a delay in accessing and processing the semantic properties of numbers.

Furthermore, an unexplored avenue of research involves understanding the social and emotional factors that accompany having DD. Math anxiety is characterized by

feelings of worry or stress in response to math related situations (Ashcraft & Krause, 2007). Presently it is unknown whether a) children with DD experience math anxiety, and b) whether math anxiety uniformly impacts arithmetic difficulties in DD or if the impact of math anxiety on performance differs as a function of the calculation task examined.

6.5 Educational and clinical implications of definitional criteria

The present findings have important educational and clinical implications. It should be mentioned that although the present thesis implemented a stringent set of criteria for identifying children with persistent DD, it is not clinically appropriate to ensure that children's arithmetic deficits persist for four years before they receive a diagnosis and special education services. Using data collected across two different time points as suggested in the DSM-V (APA, 2013) is sufficient to ensure arithmetic deficits are specific to having DD. However, implementing such stringent criteria in the present study allows for a thorough investigation into the core deficits that accompany arithmetic impairments in a sample of children with a true disorder. Therefore, it is unlikely that children in the present study were mistakenly identified as having DD. The present thesis shed light on deficits that should be targeted for training and intervention studies. These studies should investigate whether arithmetic deficits can be alleviated if children with DD receive training in connecting symbolic numbers to their corresponding quantities. And lastly, these data can inform the development of assessment tools that could be used to identify children who are at risk for developing DD at a young age.

6.6 The integration of Mind Brain and Education

In the current thesis, I conducted multidisciplinary studies using both behavioural and fMRI methods to understand the core numerical deficits in children with persistent DD. The integration of both neuroscience and behavioural methods to understand cognitive processes involved in numerical and mathematical development can generate findings that are applicable to education. The present thesis provides converging evidence to support a deficit both at the neural and behavioural level for processing and accessing the

semantic representations of numerical symbols. Using functional brain imaging techniques in addition to behavioural research are optimal in elucidating the mechanisms that subservise multiple cognitive processes associated with mathematical development. The results from the present thesis demonstrated qualitatively different brain networks engaged in non-symbolic and symbolic numerical discrimination between children with DD and typically developing peers. Similarly, in the field of Dyslexia, neuroimaging research has proven fruitful for understanding the mechanisms underlying phonological impairments in children with Dyslexia.

Additionally, interdisciplinary research is advantageous for understanding the effects of training and remediation on the brain. For example, there are many studies that have been conducted to understand the neurobiological consequences of structured reading remediation programs (Meyler, Keller, Cherkassky, Gabrieli & Just, 2008; Temple et al., 2003). These studies have revealed that remediation is associated with both normalization of activation and the engagement of neuronal circuits that are not typically associated with reading. These findings have been interpreted as reflecting the engagement of compensatory mechanisms. Similar studies should be conducted with DD children to understand the extent and limits of neuronal plasticity associated with attempts to remediate the behavioral consequences of DD.

6.7 Limitations

There are some limitations that should be mentioned and explored in future studies. First, the present thesis investigated the core deficits associated with severe and persistent arithmetic deficits and did not include a non-math impaired group such as a group of children who had persistent reading or working memory disabilities. Given that a few of the children with DD tested in the present thesis also demonstrated poor reading abilities, a persistent Dyslexia control group would elucidate the whether the symbolic numerical deficits are specific to children with pure Dyscalculia. Domain general processes such as executive attention and working memory play an important role in the acquisition of arithmetic fact retrieval (Geary, 1993; LeFevre et al., 2013). Moreover, they have been found to be associated with arithmetic and numerical magnitude deficits in children with

DD. Therefore, to understand the nature of working memory deficits in children with pure DD, including a non-math impaired control group with working memory deficits would allow for the investigation of group differences in both numerical processing and working memory tasks. Additionally, the functional neuroimaging chapter only provided an investigation of the neural correlates of numerical processing skills. Including a working memory control condition would have clarified whether activation found in the left IPS was specific to symbolic numerical processing abilities or involvement of working memory.

Second, the present study had relatively small sample sizes. A larger sample would increase the power of the present findings reported in the thesis. It is also possible that a larger sample size would reveal significant differences in tasks, where there were no significant differences initially found.

Third, children with DD were selected if they obtained below one standard deviation of the mean on standardized tests of arithmetic achievement. This criterion can be considered relatively lenient in comparison to studies that have used a three standard deviation cut off point. Although the majority of children with DD in the present studies performed well below the cut-off criteria used (e.g. greater than 1 SD below the mean), the effects of arithmetic severity in children identified using different cut-off criteria is important for future investigations.

Fourth, it should be noted that the concept of DD or any disorder where classification is dependent on a score falling below a specific cut-off point along a distribution has been challenged (Branum-Martin, Fletcher, & Stuebing, 2012). Therefore, it is unclear whether DD reflects a qualitatively different disorder as opposed to individuals who score lower on a distribution of scores.

Fifth, the current study did not examine differences in socio-economic status and the effect of home environment on numeracy skills. Recent evidence has demonstrated a relationship between parent number talk and home activities on the development of numeracy and reading skills (Gunderson & Levine, 2011; Skwarchuk, Sowinski, &

LeFevre, 2014). Future research is necessary to examine whether home environments can mitigate arithmetic achievement in children with DD.

Sixth, the studies presented in the thesis were unable to assess whether children with DD exhibit deficits in processing exact non-symbolic quantities (e.g. 1-4 objects). The defective number module hypothesized that DD is caused by a deficit in processing exact non-symbolic quantities. Previous research has found that children with DD demonstrate impairments in enumerating small sets of objects compared to typically developing children (Landerl et al., 2013). However, the non-symbolic tasks used in the present studies did not examine differences in processing large approximate quantities to small exact quantities in children with DD. Future studies should explore the differences in the approximate number system and the defective number module hypotheses using designs that control for exact and approximate numerical processes.

Lastly, it is unclear from the present fMRI study whether differences in brain activation are attributed to poor performance in the scanner, poor arithmetic achievement or specific neural deficits associated with having DD. Hoeft and colleagues (2006) administered a rhyme judging task to participants with Dyslexia and two control groups: reading level-matched and age-matched. They found that reduced activation found in reading-related brain areas was specific to having dyslexia and was not attributed to differences in reading level or scanner performance. Future studies should investigate the neural correlates of numerical magnitude processing using a similar research design to confirm that activation deficits are specific to having DD.

6.8 Conclusion

Taking a multidisciplinary approach, I presented a series of behavioural and functional neuroimaging studies in an effort to constrain our understanding of the core numerical deficits of children who exhibit stable arithmetic deficits over time. By incorporating a stability criterion in the identification of children with DD, the chances of including false positive cases in the present sample are reduced. Therefore, the results provide strong and convincing evidence towards the access deficit hypothesis of children with DD.

Specifically, abnormal recruitment in numerically specific brain regions, as well as behavioural difficulties were more pronounced during symbolic and mixed format tasks that required children to access the semantic representations of symbolic numerals. These findings lead to important educational and clinical implications for assessment and intervention tools targeting specific skills in children who experience severe symbolic deficits. Additionally, this work opens important questions about the interaction between the development of symbolic and non-symbolic numerical representations, and domain general processes, such as working memory, in different subgroups of children with persistent DD.

6.9 References

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Appendices

Appendix A: Ethics approval from the University of Western Ontario Human Participants ethics board for studies conducted in chapters 2-3.



Use of Human Participants - Ethics Approval Notice

Principal Investigator: Prof. Daniel Ansari
Review Number: 13502S
Review Level: Delegated
Approved Local Adult Participants: 450
Approved Local Minor Participants: 0
Protocol Title: Behavioral Studies of Numerical and Mathematical Skill Development
Department & Institution: Social Science\Psychology, University of Western Ontario
Sponsor: Natural Sciences and Engineering Research Council

Ethics Approval Date: March 07, 2012 **Expiry Date:** May 31, 2013

Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Revised Western University Protocol	The age range for participants has changed from 5-10 to 5-15. The Automated Working Memory Assessment has been added along with 5 additional tasks.	
Change in Study Personnel	Ian Holloway and Lucia van Eimeren will be replaced by Stephanie Bugden and Nadia Nosworthy.	
Revised Study End Date	The study end date was revised to May 31, 2013.	
Revised Letter of Information & Consent		2012/01/25

This is to notify you that The University of Western Ontario Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the applicable laws and regulations of Ontario has granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above.

This approval shall remain valid until the expiry date noted above assuming timely and acceptable responses to the NMREB's periodic requests for surveillance and monitoring information.

Members of the NMREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussions related to, nor vote on, such studies when they are presented to the NMREB.

The Chair of the NMREB is Dr. Riley Hinson. The UWO NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Signature _____ ✓

Ethics Officer to Contact for Further Information

This is an official document. Please retain the original in your files.

Appendix B: Ethics approval from the University of Western Ontario Health Science Research Ethic Board for studies conducted in chapters 4-5.



**Western
Research**

Research Ethics

**Western University Health Science Research Ethics Board
HSREB Amendment Approval Notice**

Principal Investigator: Prof. Daniel Ansari
Department & Institution: Social Science\Psychology, Western University

HSREB File Number: 6455
Study Title: The Neural Correlates of symbolic number processing in children - 16400
Sponsor: Canadian Institutes of Health Research

HSREB Amendment Approval Date: October 03, 2014
HSREB Expiry Date: December 31, 2017

Documents Approved and/or Received for Information:

Document Name	Comments	Version Date
Revised Study End Date		

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the amendment to the above named study, as of the HSREB Amendment Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review. If an Updated Approval Notice is required prior to the HSREB Expiry Date, the Principal Investigator is responsible for completing and submitting an HSREB Updated Approval Form in a timely fashion.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Ethics Officer, on behalf of Dr. Joseph Gilbert, HSREB Chair

Ethics Officer to Contact for Further Information

This is an official document. Please retain the original in your files.

Curriculum Vitae

Department of Psychology
 Brain and Mind Institute
 University of Western Ontario
 Westminster Hall, Room 215
 361 Windermere Rd.
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Education

The University of Western Ontario,
 PhD. Candidate in Psychology
Sept 2010 - Present

The University of Western Ontario,
Sept 2008 – August 2010
 M.Ed, Special Education and Educational Psychology

The University of Western Ontario,
Sept 2004 – April 2008
 BA, Honours in Psychology

Awards

Dr. Benjamin Goldberg Research Award
June 2013

Developmental Disabilities Division
 The University of Western Ontario
 Amount: \$2 525

Awarded to fund a graduate student who demonstrates exceptional research skills to conduct a research project in the field of developmental disabilities.

Marilyn (Pack) McClelland Award in Psychology
Feb 2012

The University of Western Ontario
 Amount: \$550

Awarded to a graduate student who demonstrates high academic achievement, research productivity and quality publications.

Student Appointments

International Mind Brain and Education

May 2014-May 2015

Student representative on the Board of Directors

Scholarships

Ontario Graduate Scholarship

2011, 2012, 2013

External Government Grant

Amount: \$15 000

Recipient of Reginald K. Groome Memorial Scholarship, Scouts Canada

2006 – 2007

Scouts Canada Foundation

1345 Baseline Rd., Ottawa, ON., K2C 0A7

Amount: \$1000

Publications

Bugden, S. & Ansari, D. (2014). Why your brain can't do $2 + 2$: A case of developmental dyscalculia. *Frontiers for Young Minds*, 2(8). doi: 10.3389/frym.2014.00008

Nosworthy, N., **Bugden, S.**, Archibald, L., Evans, B., & Ansari, D. (2013). A two-minute paper and pencil test of symbolic and nonsymbolic numerical magnitude processing explains variability in primary school children's arithmetic competence. *Plos One*, 8(7), e67918.

Bugden, S., Price., G., McLean, A., & Ansari, D. (2012). The left intraparietal sulcus mediates the relationship between symbolic number processing and children's arithmetic competence, *Developmental Cognitive Neuroscience*, 118(1), 32-44.

Bugden, S., & Ansari, D. (2011). Individual differences in children's mathematical competence are related to intentional but not automatic processing of Arabic numerals. *Cognition*, 118, 32-44.

Publications in preparation

Bugden, S., & Ansari, D. (submitted). Probing the nature of deficits in the ‘Approximate Number System’ in children with persistent Developmental Dyscalculia.

Bugden, S., Merkely, R., Scerif, G., & Ansari, D. (in preparation). The effect of subitizing in mapping between symbolic and nonsymbolic number representations in 4-6 year old children.

Book Chapters

Bugden, S., & Ansari, D. (in press). How can cognitive developmental neuroscience constrain our understanding of developmental dyscalculia? In Chinn, S. (Ed.) *The Routledge International Handbook of Dyscalculia and Mathematical Learning Difficulties*. Routledge

Workshops Attended

The 4th Latin American School for Education, Cognitive and Neural Sciences
 March 10-22, 2014

Punta del Este, Uruguay

One of fifty international applicants to receive a fully funded scholarship to attend a conference focusing on applying cognitive and neural science research to educational practice.

Mortimer D. Sackler, M.D. Summer Institute
 July 22- 26, 2013

Developmental Psychobiology, NY, New York

Competitive scholarship to attend an internationally renowned training program to learn and develop collaborative relationships with distinguished researchers in the field of developmental, affective and cognitive neuroscience.

Oral Presentations

Bugden, S. & Ansari, D. (Nov, 2014). The neural correlates of numerical magnitude processing in children with Developmental Dyscalculia. *Invited symposium presenter at the International Mind Brain and Education Society, Fort Worth, Texas, U.S.*

Bugden, S. (May 9, 2013). The effect of subitizing in mapping symbolic and nonsymbolic number representations in 4-6-year-old children. *Numerical Cognition Workshop, The University of Waterloo, Waterloo, Canada.*

Bugden, S. (April 4, 2013). The importance of early numeracy skills: Evidence from typically developing and atypically developing children. *Invited talk for the Student Librarians Association for Child and Youth Services, The University of Western Ontario, London, Canada*

Bugden, S., Price, G., & Ansari, D. (2011). The left intraparietal sulcus mediates the relationship between symbolic number processing and children's arithmetic competence. *Oral symposium presentation at the biennial meeting of Society of Research in Child Development, Montreal, QC, Canada.*

Bugden, S., & Ansari, D. (2009). Individual differences in children's math competence are related to intentional but not automatic processing of Arabic numerals. *Cognitive Development Laboratory Research Retreat, Department of Psychology, University of Western Ontario.*

Bugden, S., & Ansari, D. (2008). Basic numerical processing and mathematical competence in six to eight-year-old children. *The University of Western Ontario, Psychology undergraduate thesis presentation.*

Poster Presentations

Bugden, S. & Ansari, D. (May 19, 2014). Probing the nature of deficits in the 'Approximate Number System' in children with persistent Developmental Dyscalculia. *Received a merit award funded by NIH to cover all expenses to present a poster at the Math Cognition and Learning Conference, Washington D.C., U.S.*

Bugden, S. & Ansari, D. (May 3, 2014). Probing the nature of deficits in the 'Approximate Number System' in children with persistent Developmental Dyscalculia. *Accepted poster at the annual meeting of the Banff annual seminar in cognitive science (BASICS), Banff, Alberta, Canada.*

Bugden, S. & Ansari, D. (June 2014). Probing the nature of deficits in the 'Approximate Number System' in children with persistent Developmental Dyscalculia. *Accepted poster at the biennial meeting of the EARLI Sig 22: Education and Neuroscience, Gottingen, Germany.*

Bugden, S., Archibald, L., & Ansari, D. (April 18, 2013). The effect of symbolic and non-symbolic priming on magnitude processing in children with developmental dyscalculia. *Poster at the biennial meeting of Society of Research in Child Development, Seattle, Washington, U.S.*

Bugden, S., Nosworthy, N., Archibald, L., & Ansari D. (May 2012). A longitudinal investigation of the stability of cognitive profiles in children with developmental dyscalculia. *Poster at the biennial meeting of the EARLI Sig 22: Education and Neuroscience, London, England.*

Nosworthy, N., **Bugden, S.**, Archibald, L., & Ansari, D. (May, 2012). The relationship between symbolic and non-symbolic numerical magnitude processing and arithmetic achievement in primary school: Evidence from a paper and pencil test. *Poster at the annual meeting of the Canadian Society for the Study of Education, Waterloo, ON, Canada*

Nosworthy, N., **Bugden, S.**, Archibald, L., & Ansari, D. (February, 2012). The relationship between symbolic and non-symbolic numerical magnitude processing and arithmetic achievement in primary school: Evidence from a paper and pencil test. *Poster at the annual meeting of the Lake Ontario Visionary Establishment, Niagara Falls, ON, Canada.*

Bugden, S., Price, G., McLean, A., & Ansari, D. (June 2011). Parietal brain activation during number processing predicts children's arithmetic achievement. *Poster at the annual meeting of the Organization on Human Brain Mapping, Quebec, QC, Canada*

Research Job History

Teaching Assistant, Lab Coordinator

April 2012 – Aug 2012

Teaching Assistant, Lab Instructor

Sept 2010 – April 2013

The University of Western Ontario, Research Assistant

Sept 2008 – April 2009

The Department of Education, Part- time

The University of Western Ontario, Research Assistant

Sept 2008 – Aug 2009

Supervision and Mentorships

Undergraduate Student Research Supervision

Meghan Reid (BA completed 2010)

Chelsea DeGuzman (BSc. completed 2013)

Adam Dharsee (Presently completing undergraduate thesis research project in neuroimaging)

Taylor Annett (Presently completing undergraduate thesis research project)

Jenna Horwitz (Presently completing undergraduate thesis research project)

Dominik Raabe (Visiting Scholar from Germany completing an independent neuroimaging research project)