CHAPTER 3

Developmental dyscalculia

In this chapter, we review the definition, prevalence, criteria, and characteristics of developmental dyscalculia. The potential cause(s) of this learning deficit are described and discussed in light of recent behavioural experiments. While earlier hypotheses pointed out problems with a general cognitive system, current theories focus on more specific processes which could be impaired in dyscalculia. A broad section is dedicated to a possible deficit of the number magnitude representation. We explore performances of participants with and without MD during number processing, and investigate potential group differences in the speed of comparing symbolic and non-symbolic quantities, as well as in the slope of effects supposed to depend on the number magnitude representation. The chapter ends with the contribution of neuroimaging on developmental dyscalculia.

1. Overview

Developmental dyscalculia is traditionally defined as a disorder of numerical competence and arithmetical skills which is manifest in children who fail to achieve adequate proficiency in this cognitive domain despite normal intelligence, proper schooling, emotional stability, adequate social environment, and motivation (APA, 1994; Shalev, Manor, & Gross-Tsur, 1997; Temple, 1992). Since the introduction of the term "developmental dyscalculia" by the psychologist Ladislav Kosc in 1974, other terminology has been used to refer to deficit in numeracy acquisition, such as arithmetic learning disabilities (Koontz & Berch, 1996), mathematical disabilities (Jordan, Hanich, & Kaplan, 2003b), or specific arithmetic learning difficulties (McLean & Hitch, 1999). To be consistent throughout this thesis, we refer to children with mathematical disabilities (MD) irrespective of selection criteria, except for our own experiments in which participants are referenced as children with developmental dyscalculia (DD) or children with poor arithmetic facts abilities (PoorAF) depending on the selection criteria.

Epidemiological studies conducted in several countries showed that this learning deficit is as widespread as reading disorders and affects approximately 6% of school-aged children (Badian, 1983; Gross-Tsur, Manor, & Shalev, 1996; Kosc, 1974; Koumoula et al., 2004; Lewis, Hitch, & Walker, 1994; Shalev, 2004). Moreover, mathematical disabilities often persist through childhood (Shalev, Manor, Auerbach, & Gross-Tsur, 1998) and even adulthood (Dockrell & McShane, 1993). It was also reported a high co-morbidity between numeracy and other learning disabilities. Prevalence estimates indicate that 25% of MD children exhibit attention deficit hyperactivity disorder (ADHD, Gross-Tsur et al., 1996). Moreover, around 40-60% of MD children suffer from reading difficulties (Badian, 1983; Lewis et al., 1994), but the reason for why this is the case is not clear. Language is relatively independent from the number system even if it plays a role in a range of numerical and arithmetical competencies. A recent theory proposes that weak phonological processing abilities could be the common factor underlying the learning difficulties of children with both reading and mathematical disabilities, while children with MD only might be characterised by a weak number sense (Robinson, Menchetti, & Torgesen, 2002). Up to now, however, there is no qualitative or quantitative difference between the two disabled groups, except for some language-based tasks such as problem solving (Hanich, Jordan, Kaplan, & Dick, 2001; Jordan et al., 2003b; Landerl, Bevan, & Butterworth, 2004).

1.1. Diagnosis of developmental dyscalculia

A major concern in research on mathematical disabilities is the heterogeneity in criteria and tests for assigning children to the category (see Table 3-1). To be considered as dyscalculic, a child must show arithmetical performance on a standardised test that is substantially below the level expected by the age, education and intelligence, and he or she must experience disruption of academic achievement or daily living (DSM-IV, 1994). While prevalence estimates suggest that only 5-7% of children could be classified as having dyscalculia, several studies used 20^{th} to 35^{th} percentiles of mathematical tests to select their participants. Are these criteria sufficiently rigorous for contributing to the understanding of developmental dyscalculia? For instance, the 35^{th} percentile implies that children with the best performance will be about 0.39 standard deviations below the mean, and that most children so classified will be better than two standard deviations below the mean.

Table 3-1. Criteria and selection tests used in the different studies on mathematical disabilities

Study	Criterion	Classification test	Label
Hanich et al. 2001)	35th percentile	Mathematics Composites from the Woodcock–Johnson Psycho-Educational Battery-Revised	Mathematics difficulties
Jordan et al. (2002)	35th percentile	Mathematics Composites from the Woodcock–Johnson Psycho-Educational Battery-Revised	Mathematics difficulties
Jordan et al. (2003)	35th percentile	Mathematics Composites from the Woodcock–Johnson Psycho-Educational Battery-Revised	Mathematics difficulties
Geary et al. (2000)	35th percentile	Mathematics Reasoning subtest of the Wechsler Individual Achievement Test	Mathematics disabilities
Geary et al. (1999)	30th percentile	Mathematics Reasoning subtest of the Wechsler Individual Achievement Test	Mathematics disabilities
Siegel & Ryan (1989)	25th percentile	Arithmetic subtests of the Wide Range Achievement Test	Arithmetic disabilities
Koontz & Berch (1996)	25th percentile	Iowa Test of Basic Skills	Arithmetic learning disabilities
McLean & Hitch (1999)	25th percentile	Graded Arithmetic-Mathematics Test	Specific arithmetic learning difficulties
Rousselle & Noël (2006)	15th percentile	A numerical and arithmetical tests battery	Mathematical disabilities
Geary et al. (2007)	15th percentile 23th < score < 39th	Numerical Operations subtest of Wechsler Achievement battery	Mathematical learning disabilities Low achieving children
Geary et al. (2008)	11th percentile 11th < score < 25th	Numerical Operations subtest of Wechsler Achievement battery	Mathematical learning disabilities Low achieving children
Bull & Johnston (1997)	Below the mean score	Group Mathematics Test	Low-ability in mathematics
Temple & Sherwood (2002)	1 year below the chronological age	Wechsler Objective Numerical Dimensions (WOND)	Number fact disorder
Price et al. (2007)	1.5 SD below the mean score	Standardised arithmetical test (RMAT)	Developmental dyscalculia
Shalev et al. (1997)	2 years below grade level	Standardised arithmetical battery	Developmental dyscalculia
Landerl et al. (2004)	3 SDs below the mean score	A timed arithmetical test	Developmental dyscalculia
Rubinsten et al. (2005)	No criteria[a]	Standardised arithmetical battery	Developmental dyscalculia
Bachot et al. (2005)	No criteria[b]	Battery including timed and untimed arithmetical tasks	Visuospatial disabilities
Kucian et al. (2006)	No criteria[c]	Standardised mathematical battery (ZAREKI)	Developmental dyscalculia
Rotzer et al. (2008)	No criteria[c]	Standardised mathematical battery (ZAREKI)	Developmental dyscalculia
Soltész et al. (2007)	No criteria[d]	Standardised arithmetical battery	Developmental dyscalculia

[a] Participants were diagnosed at least once in their past as having dyscalculia

[b] Participants were diagnosed by a clinician as having learning disorders including dyscalculia

[c] The diagnosis was based on the discrepancy between the individual's general intelligence and his or her mathematical performance

[d] Participants had been diagnosed with MD more than 2 years ago and must have participated in mathematical therapy for at least 2 years

In the present thesis, our participants were classified as dyscalculic children if they showed performances more than two years below what is expected based on their chronological age, or as children with MD (or PoorAF) if they scored below the 15th percentile on an arithmetical test. A cutoff of the 15th percentile is more stringent than is normally used in research on learning disabilities, but is higher than the earlier reported estimation that between 5 and 7% of children have some form of MD. However, such a criterion is necessary to ensure adequate sample sizes, and to avoid children with comorbid difficulties in reading or attention. As pointed out by some researchers (Ansari & Karmiloff-Smith, 2002; Landerl et al., 2004), another problem concerns the tests that are used to select participants with MD. The diagnosis of mathematical deficit is generally derived from batteries requiring paper-and-pencil tasks. However, an approach derived from cognitive psychology paradigms that systematically assess both processing speed and accuracy seems to be more appropriate. As dyscalculic children may perform as well as controls in untimed conditions (e.g., Jordan & Montani, 1997). Therefore, the children taking part in our experiments were mainly selected using timed arithmetical tests.

1.2. Characteristics of developmental dyscalculia

Researchers generally agree about the main behavioural features of developmental dyscalculia. The most consistent finding in the literature is that children with MD have difficulty in learning and remembering basic arithmetic facts (Barrouillet, Fayol, & Lathulière, 1997; Garnett & Fleischner, 1983; Geary, 1990, 1993; Ostad, 1997, 2000). Moreover, the ability to retrieve arithmetic facts from long-term memory apparently does not substantively improve across the elementary-school years for most children with MD, suggesting a persistent cognitive deficit rather than a delayed development (Geary, 1993). As described in Chapter 1, the typical learning of simple calculation involves a gradual shift from the frequent use of (verbal or finger) counting procedures to more efficient memory-based strategies. Several studies indicate that MD children do not show this change, and persist in using immature procedures (Geary, Brown, & Samaranayake, 1991; Geary, Hoard, & Hamson, 1999; Hanich et al., 2001; Jordan & Hanich, 2003; Jordan, Hanich, & Kaplan, 2003a; Ostad, 1998). Moreover, children with MD have problems with knowledge of facts, but also with the execution of arithmetical procedures (Russell & Ginsburg, 1984).

A second characteristic is related to the acquisition of verbal counting. Children with MD do not fully master the sequence of number words. Compared to age-matched controls, children with MD are slower in counting from 45 to 65, from 2 to 20 in twos, and from 20 to 1 backwards (Landerl et al., 2004). They also exhibit difficulties in objects enumeration. The slope of their latencies in counting dot patterns is steeper than controls one, but not significantly. Moreover, weak counting skills have been found in children with moderate mathematical disabilities at the age of 8 which persisted one year later (Jordan & Hanich, 2003; Jordan et al., 2003b). Finally, children with MD do not grasp the inherent principles of counting (Gelman & Gallistel, 1978). When they have to assess the correctness of a puppet's counting of poker chips of two colours, they erroneously consider as wrong the counting first based on one colour and continued with the other colour (Geary, Hamson, & Hoard, 2000). This suggests that children with MD do not understand the order irrelevance principle, and believe that adjacency is an essential feature of counting (Briars & Siegler, 1984).

1.3. Is there a genetic basis in dyscalculia?

A few studies examine the role of heredity in dyscalculia, as originally proposed by Kosc (1974). The co-occurrence of dyscalculia was analysed in twins when one of the members had mathematical difficulties (Alarcon, Defries, Gillis Light, & Pennington, 1997). It was reported that 58% of monozygotic twins and 39% of dizygotic twins had developmental dyscalculia. The concordance rates were higher for monozygotic (0.73) than for dizygotic twins (0.56), but this difference was not significant. It has been also demonstrated that approximately half of all siblings of children with developmental dyscalculia are also dyscalculic at a criterion of 25^{th} percentile, the risk being 5-10 times greater than for the general population (Shalev, 2001). These findings could be taken as evidence for a genetic basis of dyscalculia, and could account for the high prevalence of numeracy deficits in a variety of genetic disorders, such as Spina Bifida (Barnes, Smith-Clant, & Landry, 2005), velo-cardio-facial syndrome (De Smedt et al., 2007; Eliez et al., 2001), Turner syndrome (Bruandet, Molko, Cohen, & Dehaene, 2004; Rovet, Szekely, & Hockenberry, 1994), Fragile X syndrome (Mazzocco, 2001), Down's syndrome (Paterson, 2001), and Williams syndrome (Udwin, Davies, & Howlin, 1996). However, although these data favour a possible heredity of dyscalculia, they will have to await further investigation.

2. Possible origin(s) of developmental dyscalculia

2.1. A deficit of general cognitive systems

Several hypotheses have been proposed to account for the difficulties encountered by MD children. Early research focused on general cognitive functions such as processing speed (Bull & Johnston, 1997), working memory (e.g., Bull & Scerif, 2001), retrieval of information from long-term memory (Geary et al., 2000), visuospatial abilities (Rourke, 1993; Rourke & Conway, 1997), and finger gnosia (Fayol, Barrouillet, & Marinthe, 1998). We discuss each of these proposals in light of recent data, ranging from less to more number-related processes.

2.1.1. Speed of processing

Processing speed plays a crucial role in verbal (Kail, 1997a) or visuospatial short-term memory (Kail, 1997b), in reading (Kail & Salthouse, 1994), and in intellectual changes (Case, 1985). This led Bull and Johnston (1997) to investigate the relationship between processing speed and arithmetical performances. Children of 7 years old were categorised as presenting high- or low-ability according to their scores in a standardised mathematics test (Young, 1970). Performances on short-term memory, naming and ordering sequences (letters and numbers) ability, and processing speed (i.e., visual number matching and perceptual motor speed) were assessed. Results showed that children in the low-ability group were significantly worse than children in the high-ability group on measures of speed of number identification, processing speed, one-syllable speech rate, and sequencing ability, even when difference between the groups was controlled for reading ability. Regression analyses, however, revealed that processing speed was the best predictor of mathematical abilities, though it accounted for 8% of variance only. Moreover, there are only few investigations of this hypothesis. Children with MD were found to be slower than control children in naming letters and numbers measured at kindergarten and first grade (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007), but the group differences disappeared one year later (Geary, Hoard, Nugent, & Byrd-Craven, 2008). By contrast, other studies reported similar latencies for MD and control children during non-numerical processing (e.g., Landerl et al., 2004).

2.1.2. Working memory

Working memory corresponds to the ability to explicitly maintain a mental representation of some amount of information for a certain time. Three main subsystems have been identified. The *phonological loop* is used for maintaining and rehearsing verbal information (Baddeley, Lewis, & Vallar, 1984). The *visuospatial sketchpad* serves for holding and manipulating visual and spatial material (Della Sala et al., 1999). Finally, the *central executive* is an attentional controlling system involved in the coordination of performance on separate tasks, selective attention, set shifting, and inhibition (Baddeley, 1996). In adults, working memory is related to arithmetical performance (Fürst & Hitch, 2000; Heathcote, 1994; Kyoung-Min & So-Young, 2002; Logie, Gilhooly, & Wynn, 1994), mathematics problem solving (Cary & Carlson, 2001), and even mathematics anxiety (Ashcraft & Kirk, 2001). More importantly, working memory plays an important role in mathematical achievement, especially in executing calculation procedures and learning arithmetic facts (e.g., DeStefano & LeFevre, 2004; Noël, Seron, & Trovarelli, 2004). This led Geary (1993) to postulate a link between mathematical difficulties and working memory impairment. However, current findings provide no consensus about the possible causal relationship between dyscalculia and working memory measures. This is partially due to the variety of tasks used for assessing the three components of working memory as well as mathematical abilities.

Several studies have shown that children with MD had a weaker phonological loop relative to controls, as reflected in a reduction in the verbal forward span (Geary et al., 1991; Hitch & McAuley, 1991; Koontz & Berch, 1996), but these differences were not found when children were controlled for reading ability (Geary et al., 1999; Passolunghi & Siegel, 2001, 2004). Moreover, poor performances on digit span have been reported in MD children, but not on non-numerical tasks (McLean & Hitch, 1999; Siegel & Ryan, 1989). This led some authors to postulate a working memory specialised for numerical information, which could be deficient in dyscalculia (Siegel & Ryan, 1989). Similarly, a reduced visuospatial span, as measured by Corsi blocks has sometimes been observed (McLean & Hitch, 1999) in children with MD, but in other experiments this relationship has not been detected (Bull, Johnston, & Roy, 1999). Recently, it has been shown that the Corsi span was the best predictor in performances on nonverbal arithmetic problems for preschool children, but not for first-grade children (Rasmussen & Bisanz, 2005).

Several findings suggest an impairment of the central executive in MD children, as generally reflected by a weak backward span (Geary et al., 1991; Geary et al., 1999; Passolunghi & Siegel, 2004). This system was a significant mediator of group differences between MD and control children in error detection on the counting knowledge task and the number of retrieval errors in simple addition (Geary et al., 2007). This factor was also associated with poorer performances in estimating the position of Arabic numbers on a physical number line (Geary et al., 2008). Various measures of executive functions predicted arithmetical performance in 7-year-old children, with the counting span being the unique predictor of variance after controlled for other variables (Bull & Scerif, 2001). However, some other studies have not reported any deficit of the central executive in dyscalculic children (Landerl et al., 2004; Schuchardt, Maehler, & Hasselhorn, 2008; Siegel & Ryan, 1989).

2.1.3. Retrieval from long-term memory

Learning and remembering of simple arithmetic problems constitutes a major trouble encountered in children with MD (e.g., Barrouillet et al., 1997). Geary and his colleague (Geary, 1993; Geary & Hoard, 2001) proposed that difficulties in representing and/or accessing information from semantic memory might account for the weakness in retrieving arithmetic facts in children with MD. This could also explain the high co-occurrence of mathematical and reading disorders (Badian, 1983; Lewis et al., 1994). However, there is little empirical evidence for a non-numerical semantic deficit in MD children. It was found that children with both mathematical and reading difficulties were slow to articulate familiar words, although their performance with non-words was unimpaired (Geary et al., 2000). This suggests poor activation of phonological or semantic representations. In another study (Temple & Sherwood, 2002), children with MD were slower than control children in a task involving the retrieval of arithmetic facts, as well as in naming line drawings of objects and the colours of patches. However, there were only four participants in this study, which prevents any strong conclusion being drawn.

2.1.4. Spatial abilities

Numbers are often proposed to be represented spatially along a mental number line oriented from left to right. Support for this hypothesis comes from the SNARC effect in healthy adults during number comparison (Dehaene et al., 1993). This was also confirmed by neuropsychological studies of patients with left neglect, a disorder of spatial attention impairing awareness of the left side of space following right brain damage (for a review, see Halligan, Fink, Marshall, & Vallar, 2003). These patients showed a bias towards the right not only in physical space, but also when they had to bisect a numerical interval (Priftis et al., 2006; Zorzi, Priftis, & Umiltà, 2002). For instance, when asked what number was halfway between 1 and 9, left neglect patients consistently reported a number larger than the expected response, such as 7, shifting the response towards the right end of the mental number line. Importantly, such bias do not occur when patients bisected other types of ordinal sequences such as months and letters (Zorzi et al., 2006), suggesting a specific contribution to numerical processing.

While there is clear evidence for interactions between numbers and space in adults, the hypothesis of a spatial deficit in dyscalculia has received little attention. Rourke and his collaborator (Rourke, 1993; Rourke & Conway, 1997) postulated a lateralised hemispheric dysfunction in MD depending on the presence or absence of comorbid reading disabilities. They found that children with MD only had problems in non-verbal tasks involving visuospatial or psychomotor abilities while children with better arithmetical than reading scores were impaired in verbal tasks. These findings were interpreted as reflecting a left-hemisphere dysfunction in children with both mathematical and reading difficulties, while specific problems with mathematics may stem from a right-hemisphere dysfunction. However, more recent studies failed to find any difference between children with both mathematical and reading disabilities, and children with MD only, except on problem-solving tasks which involved verbal comprehension (Hanich et al., 2001; Jordan et al., 2003b).

In another study (Bachot, Gevers, Fias, & Roeyers, 2005), it was found that, compared to age-matched controls, children with both mathematical and visuospatial disabilities did not show the classic association between space and size of numbers (Dehaene et al., 1993). However, it is not clear whether the lack of SNARC effect comes from spatial difficulties or reflects an alteration of the number magnitude representation.

2.1.5. Finger gnosia

In adults, lesions to the dominant parietal lobe can produce the Gerstmann's syndrome which consists of the co-occurrence of acalculia, left/right disorientation, finger agnosia, and agraphia (Gerstmann, 1940). The constellation of the four features has been taken as evidence for the crucial role of finger movements in number manipulation (Butterworth, 1999b). Indeed, fingers are used to point to objects during counting, to represent the number of items in a set, and to support simple calculation. Alternatively, other researchers stress the proximity in brain regions dedicated to number representation and finger movements (Benton, 1961; Dehaene, 1997). The fact that the four symptoms can appear individually and are frequently associated with alexia makes the legacy of this syndrome controversial (Benton, 1961; Geschwind & Strubb, 1975; Poeck & Orgass, 1966; Strub & Geschwind, 1974). Gerstmann's syndrome has been more rarely reported in children (Benson & Geschwind, 1970; Kinsbourne & Warrington, 1963), and was often associated with mild-to-moderate dyslexia and constructional apraxia (Suresh & Sebastian, 2000).

Further support for the role of finger abilities in number development was provided by investigation on healthy children. Fayol, Barrouillet, and Marinthe (1998) found that measures of finger gnosia, graphisthesia and simultagnosia[4] at the age of 5 predicted a significant proportion of the variance in arithmetical tests administered to the same children one year later. A follow-up to this study showed that these measures still predicted mathematical performance at the age of 8, but not scores on reading and writing achievement tests (Marinthe, Fayol, & Barrouillet, 2001). However, these findings did not allow extracting a specific role of finger gnosia in number manipulation.

Noël (2005) investigated whether finger gnosia assessed at first grade could be a better predictor of numerical abilities than general developmental factors or other symptoms of Gerstmann's syndrome one year later. Finger gnosia correlated significantly with an overall numerical score computed on different tasks (symbolic and non-symbolic comparison, subitizing, number writing, simple addition problems, finger counting), but not with word reading abilities. Regarding the relation with finger gnosia, there was no clear distinction between numerical tasks that were supposed to rely on finger representation,

[4] Simultagnosia is an inability to grasp the meaning of an overall complex scene, although the different isolated elements that constitute it are well recognised.

and those that were postulated to depend on the number magnitude representation. Moreover, none of the developmental variables like processing speed and hand preference could predict numerical abilities.

Another study (Gracia-Baffaluy & Noël, 2008) compared two groups of children with poor finger gnosia on numerical skills, who received training in either finger differentiation or story comprehension. While no difference was found between the two groups before the training, the children who were trained in finger differentiation had higher post-intervention scores on finger gnosis than the children who had been trained in story comprehension. Moreover, they performed better on three numerical tasks: the subitizing task involving the presentation of sets of 2-6 items to be counted; the "how many fingers" task in which the children were presented with photographs of hands and had to identify the number of fingers raised; and the order task in which they had to judge whether pairs of Arabic numerals were or were not in increasing order. Together, these findings indicate a link between finger gnosia and numerical abilities. However, more investigation is needed in both healthy and mathematically disabled children to establish a causal relationship between poor finger gnosia and dyscalculia. It could be interesting to examine differences in the way of children use them in counting during typical and atypical development.

In summary, it is generally agreed that working memory, visuospatial ability, finger gnosis, retrieval from long-term memory, and more generally, processing speed are engaged and contribute to the development of numerical competencies. Up to now, there is however no convincing evidence that these cognitive factors are specifically related to dyscalculia. It is also very unlikely that poor abilities in processing speed, working memory, or in retrieving information from long-term memory can lead to a deficit restricted to number processing and calculation. Finger gnosia and spatial abilities could be good candidates for some difficulties encountered by MD children, as they share neural mechanisms with numbers, and influence the learning of numerical abilities. Yet, these hypotheses need further investigation to clarify the impact of finger manipulation and spatial orientation on numerical performances. In Chapter 4, we present an original study that aims at further determining the specificity of deficit in dyscalculia. More precisely, we test whether or not difficulties in solving simple calculation encountered by children with MD reflect a more general inability to retrieve semantic or verbal knowledge from long-term memory.

2.2. A specific deficit of the number magnitude representation in dyscalculia

The studies described above have examined the possibility that dyscalculia is secondary to more general cognitive dysfunctions. However, a large body of evidence indicates that the semantic system for numbers is dissociable from language (Cohen et al., 2000), from general semantic memory (Cappelletti, Butterworth, & Kopelman, 2001; Thioux et al., 2005; Zamarian, Karner, Benke, Donnemiller, & Delazer, 2006), and from working memory (Butterworth, Cipolotti, & Warrington, 1996). Consequently, it has been suggested that dyscalculic children could have a very specific deficit of a core number system. While early classifications of developmental dyscalculia distinguish difficulties in number processing (number alexia or agraphia) from those in calculation (Badian, 1983; Kosc, 1974; Temple, 1992), current theories focus on a basic inability to represent and manipulate numbers (Butterworth, 1999b; Dehaene, 1997). Here under, we explore behavioural data favouring a specific deficit in dyscalculia, especially an impairment of the number magnitude representation. We will review the different psychophysical effects underlying this approximate system, as well as experiments which compared them in participants with and without MD.

2.2.1. The number defective module hypothesis

Butterworth (1999b) argues that human beings are born with an innate capacity to recognise and mentally manipulate numerosities, and that this capacity is embodied in specialised neural circuits within the parietal lobes. He proposes that MD children might suffer from a "number defective module" induced by a highly selective impairment of the capacity to understand numbers which in turn leads to a range of difficulties in learning about arithmetic. A similar hypothesis is formulated by Dehaene (1997) who postulates a deficit in "number sense" in developmental dyscalculia which underlies our ability to quickly understand, approximate and manipulate numerical quantities non-verbally.

The hypothesis of the number defective module was originally based on the case of Charles (Butterworth, 1999b), a psychology graduate who suffered from persistent difficulties with mathematics in his daily life. Although he had normal intellectual abilities, he relied on his fingers to solve simple arithmetical problems and was unable to cope with complex calculations. His RTs in a magnitude comparison task were four times longer than normally expected and showed a reversed distance effect because he counted on his fingers to compare Arabic numerals. In a numerical Stroop-like task, Charles did not seem to be able to access magnitude from Arabic numerals automatically, while most children could do it from the end of first grade (Rubinsten et al., 2002). A similar pattern was reported in Y.K., a 11-year-old boy who suffered from a profound dyscalculia in the context of a Gerstmann's syndrome (Ta'ir, Brezner, & Ariel, 1997). He had strong difficulties or was unable to count in one-to-one correspondence and to manipulate number magnitudes above quantities 10-15 depending on the task. Together, Charles and Y.K. did not understand the meaning of number concepts and had a basic deficiency in numerical semantic representations. However, they cannot be considered as a representative sample of dyscalculic children, as their performances are exceptional.

A more convincing evidence for the defective number module hypothesis comes from the comparison between pure dyscalculic children of 8-9 years and age-matched controls (Landerl et al., 2004). It was found that dyscalculic children showed consistent deficits in numerical tasks including symbolic quantities. Compared to controls, they were slower at two- or three-digit number naming (even after controlling for colour naming), in the numerical comparison task, and in reciting number sequences from different bounds. By contrast, dyscalculic children without reading disability were in the normal range or above average on tasks involving phonological working memory, accessing non-numerical verbal information, non-verbal intelligence, language abilities, and psychomotor abilities.

These findings suggest that developmental dyscalculia affects not only the learning and remembering of arithmetic facts, but also very basic tasks such as counting or number magnitude comparisons. However, beyond these data, there is only little support for a basic numerical deficit in dyscalculia. A few studies investigated performances of children with MD relative to age-matched controls in identifying, estimating, or comparing symbolic and non-symbolic numbers. In the next sections, the findings are discussed with respect to these tasks which tap a fundamental aspect of children's understanding of number magnitude.

2.2.2. Numerosity identification

The very basic capacity to rapidly apprehend small numerosities, or subitizing, (Mandler & Shebo, 1982), which plays an important role for more elaborate numerical competencies, could be impaired in developmental dyscalculia. In a matching task, 10-year-old MD and control children had to judge whether or not two numerical quantities presented as Arabic numerals or dot patterns had the same name or physical identity (Koontz & Berch, 1996). The three types of pairs were physically different, name different (e.g., 2 3); physically different, name same (e.g., 2 ••); and physically same, name same (e.g., 2 2). A similar matching task was also used with letters. When controlling for the time required for physical identity, children with MD were not slower than their peers in judging differences in identity on numerals or letters. Yet, when judging name identity for physically same pairs, children with MD did not use the efficient strategy of just basing their decision on physical similarity, as control children did. In particular, differences between name and physical identity judgments in pairs of dot patterns were greater for three-dot than two-dot trials[5]. These data were interpreted as a dysfunctional subitizing in children with MD.

2.2.3. Number estimation

A few studies analysed estimation abilities in the context of mathematical difficulties. It was found that children with MD had problems in estimating the answer of simple addition and subtraction problems (Hanich et al., 2001; Jordan, Hanich, & Kaplan, 2003c). When presented with two erroneous answers, they tended to select the more distant one more frequently than did their control peers. However, it is not clear whether the performance of the MD children was influenced by a potential deficit in inherent number magnitude processing or rather by poor arithmetical skills.

Two recent experiments analysed differences between MD and control children in estimation abilities using a “physical number line task”. Participants had to estimate the position of Arabic numbers on physical number lines ranging from 0 to 100 or from 0 to 1000. Typically, children resorted to different strategies depending on their age. There was a shift during the development from logarithmic-based estimations, supposed to depend on

[5] Differences were also observed in Arabic numerals pairs, but in the opposite direction (i.e., greater differences for the numerical value 2 than 3).

the number magnitude representation, to linear-based estimations learned during schooling. This change arises between 6 and 8 years for 0 to 100 numbers (Siegler & Booth, 2004), and between 8 and 11 years for 0 to 1000 numbers (Siegler & Opfer, 2003).

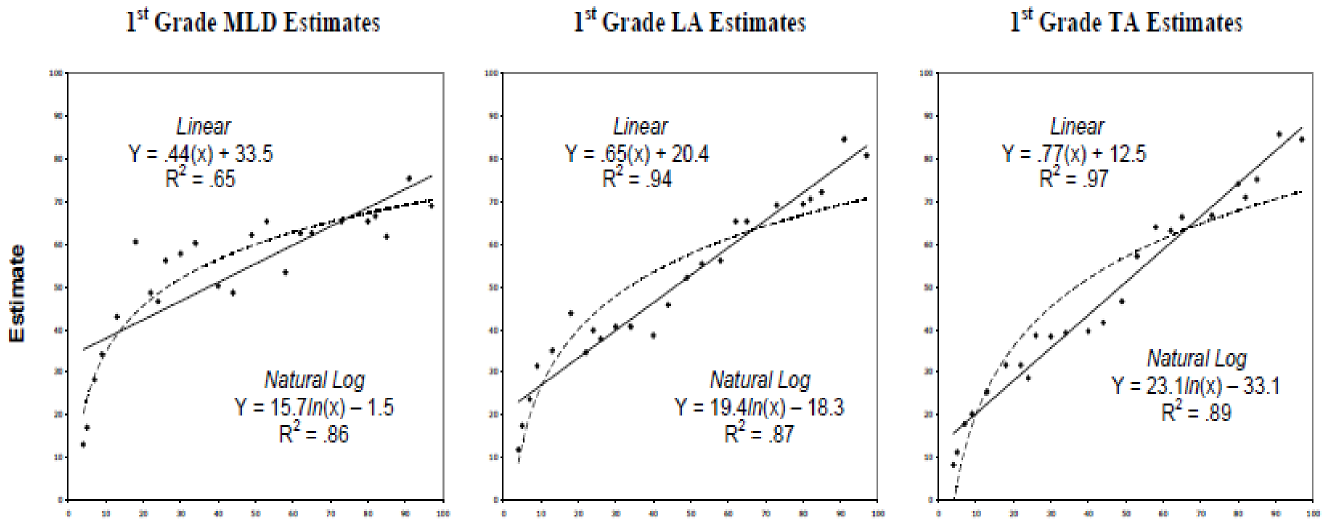

Figure 3-1. Performance in number line placements in mathematically learning disabled (MLD), low achieving (LA), and typically achieving (TA) children of first grade (adapted from Geary et al., 2008).

Children with MD were less accurate than children with low mathematical achievement (LA) and controls in kindergarten and first grade (Geary et al., 2007). Compared to control children, both disabled groups used more often logarithmic strategy and less often linear strategy. The same results were obtained one year later in a follow-up of this study (Geary et al., 2008). Children with MD were less accurate than other children irrespective of whether the quantity was smaller or larger than 50. Moreover, while the performance of control and low achieving groups was better explained by a linear than a logarithmic model, the reverse pattern was observed in the MD group (see Fig. 3-1). The analysis of trial-by-trial strategy revealed that the children with MD resorted less frequently to linear model than controls in first and second grade, and less frequently than low achieving children in second grade. Moreover, the central executive score evaluated by three measures (listening recall, counting recall, and backward digit span) was associated with the overall error estimation, but less strongly than IQ scores which emerged as the only significant mediator for group differences.

2.2.4. Number/numerosity comparison

Current research mainly focuses on a possible deficit in developmental dyscalculia during number/numerosity comparisons. As previously discussed, performance in this task mainly depends on the number magnitude representation, and is reflected by different psychophysical effects in both children and adults (see Chapter 1). Therefore, the potential difficulties of children with MD could have an impact on their speed of processing in comparing numbers, but also on the slope of the effects related to the number magnitude representation. Very few studies have examined these effects in the context of mathematical disabilities. Most of them focused on the numerical distance effect during symbolic and non-symbolic number comparison tasks. The other effects of size, SNARC, and size congruity have given rise to less investigation.

Up to now, there is no consensus about a possible impairment of the numerical distance in dyscalculia. Some studies report that, compared to age-matched controls, children with MD show a more pronounced slope of the numerical distance effect. This result seems to depend on the format of numbers to be compared, as a steeper numerical distance is often found in comparing Arabic numerals, but more rarely in comparing non-symbolic numbers.

In a pilot study (Noël, 2002), MD and control children differed neither in accuracy nor in latencies when they had to compare two sets of objects. By contrast, MD children committed more errors than controls in comparing Arabic numerals, especially for pairs of large size and small numerical distance. Moreover, although the MD children were as fast as control children, they exhibited a steeper numerical distance effect. Further support for a lack of typical numerical distance during symbolic comparisons was observed in children with MD following a genetic disturbance (De Smedt et al., 2008; De Smedt et al., 2007). Children with velo-cardio-facial syndrome (VCFS)[6] were as fast as controls in reading or writing Arabic numbers. Yet, although both groups showed typical distance and size effects in comparing pairs of Arabic numbers, children with VCFS were slower than controls when the distance between numbers was small (even after controlling for IQ differences).

[6] Velo-cardio-facial syndrome (Shprintzen et al., 1978) is genetic syndrome caused by a microdeletion in chromosome 22q11, with an incidence of 1 in 4000 live births (Scambler, 2000). Against the major characteristics of the syndrome (for a review, see Swillen, Vogels, Devriendt, & Fryns, 2000), children with VCFS have consistent deficits in mathematics while they show unimpaired reading abilities (Moss et al., 1999; Woodin et al., 2001).

Alternatively, other studies found a reduction in the slope of numerical distance in dyscalculia. Rousselle and Noël (2007) investigated the performance of MD children (with and without additional difficulties in reading) and control children during number comparison tasks on Arabic numerals and collections of sticks. While MD children were as fast as controls in the non-symbolic number comparisons, they were significantly slower in comparing symbolic numbers. Moreover, children with MD showed a weaker distance effect than controls with Arabic numerals. A similar pattern was reported for the size effect. More precisely, six of the 29 MD children showed a reversed distance effect, and 9 MD children exhibited an inverted size effect. This finding was interpreted by the authors as reflecting the use of peculiar strategies by some MD children in symbolic comparisons, especially verbal or finger counting as observed in the case of Charles (Butterworth, 1999b), to compensate for their difficulty in activating specific number magnitudes. The participants also performed a numerical Stroop-like task in which they had to judge the physical size of Arabic numerals varying in their numerical value. To control for the possible influence of the speed of processing, the physical size difference between the numerals only appeared after a variable SOA (i.e., Stimulus Onset Asynchrony), adapted to each child. Both groups showed similar latencies and size congruity effects, but MD children needed longer SOAs than controls. Together, these results were taken as evidence that MD children had difficulty in accessing the mental number line from the symbolic format, rather than in the internal representation of numbers *per se*. Similar findings were observed in adolescents with MD when they had to judge whether Arabic numerals were smaller or larger than the standard 5 (Soltész, Szucs, Dékány, Márkus, & Csépe, 2007). Although MD adolescents were as fast as age-matched controls, they showed a reverse size effect corresponding to slower latencies for small than for large numerals. Moreover, compared to controls, the slope of their numerical distance effect was less steep.

With regard to non-symbolic processing, the aforementioned studies reported an unimpaired numerical distance effect in children with MD (Noël, 2002; Rousselle & Noël, 2007). By contrast, a fMRI experiment showed that MD children had greater difficulty than controls in comparing two sets of squares separated by a small distance, even though increasing error rates rather than slowing down their latencies (Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007).

Beyond the numerical distance, the other effects related to the number magnitude representation have been investigated in dyscalculia. In a numerical Stroop paradigm, adults with MD did not present the classic size congruity effect when they had to judge perceptual characteristics (greyness, height, or physical size) of Arabic numerals (Rubinsten & Henik, 2005). Unlike the controls, the MD group showed no congruity effect in the greyness task, and an interference component but no facilitation in the height and physical size tasks. However, another study using a similar paradigm failed to find any difference between dyscalculic and control children (Landerl et al., 2004). Indeed, no congruity effect was found in any group when comparing the physical size of the numerals. By contrast, dyscalculic children were slower than controls when comparing the magnitude of the numerals. Finally, no SNARC effect was observed in children with both arithmetical and visuospatial problems during a number comparison task (Bachot et al., 2005). This result could reflect an abnormal representation of number magnitude on the left-to-right oriented mental number line.

In summary, although research on dyscalculia mainly reports difficulties related to the exact number system like in counting or calculation, recent investigation suggests that the number magnitude representation underlying the “number sense” could be less precise in dyscalculic children. Compared to age-matched controls, children with MD had poorer performances in identifying small numerosities, and in estimating the result of approximate arithmetical problems or the position of Arabic numbers on a physical number line. Moreover, children with MD had also difficulties in comparing number/numerosity magnitudes, but the findings were less clear. As reported in Table 3-2, what emerges from the above experiments is that children with MD were always slower to compare numbers, whether presented as symbols or not. However, the slowdown strongly varied across studies, ranging from 30 ms to more than 300 ms, and this variability could in turn explain why sometimes significant differences were observed between MD children and age-matched controls, and sometimes not. Regarding the nature of the psychophysical effects, it seems that the discrepancy between participants with MD and controls depended on whether numbers were presented as symbols or non-symbolic displays. In most of the cases, comparing Arabic numerals was associated with an impairment of numerical distance (e.g., Noël, 2002; Rousselle & Noël, 2007), size (Soltész et al., 2007), SNARC (Bachot et al., 2005), and size congruity (Rubinsten & Henik, 2005) effects in dyscalculia, irrespective of age. The processing of non-symbolic numbers was more rarely investigated in MD participants, and resulted sometimes in group differences related to numerical distance (Price et al., 2007) but sometimes not (Noël, 2002; Rousselle & Noël, 2007). Furthermore, it should be noted that, depending on the study, the slope of the numerical distance effect showed either a reduction or an accentuation in dyscalculia relative to normal development.

Table 3-2. Performances of MD and age-matched control participants on symbolic and non-symbolic number comparisons

Study	Age	Material	MD	Control		Effect		
			RTs	*RTs*	*Sig.*		*Sig.*	*Slope*
Rousselle & Noël (2007)	7.3	Arabic numerals	1156 (157)	970 (151)	Yes	Distance (1 vs. 3-4)	Yes	Less steep
Noël (2002)	8.3	Arabic numerals	1169 (214)	1069 (237)	No	Distance (1-2 vs. 3-4)	Yes	More steep
Landerl et al. (2005)	8-9	Arabic numerals[a]	±1500 ±700	±1150 ±680	Yes No	Distance (1 vs. 5) Not tested	No -	- -
Bachot et al. (2005)	9.3	Arabic numerals	1112	871	Yes	Distance (1-4)	Yes[b]	More steep
De Smedt et al. (2008)[c]	9.8	Arabic numerals	1057	874	Yes	Distance (1-8) Size (<5 vs. >5)	Yes No	More steep -
De Smedt et al. (2007)[c]	11.5	Arabic numerals	910 (240)	740 (140)	No	Distance (1-8) Size (<5 vs. >5)	Yes No	More steep -
Soltész et al. (2007)	16-17	Arabic numerals	503 (37)	471 (79)	No	Distance (1-4) Size (<5 vs. >5)[d]	Yes Yes	Less steep Reverse
Rubinsten et al. (2005)	24	Arabic numerals	779 (163)	596 (112)	Yes	Size congruity	Yes	More steep
Rousselle & Noël (2007)	7.3	Sticks patterns	892 (129)	847 (119)	No	Ratio (1:2 vs. 2:3)	No	-
Noël (2002)	8.3	Set of dots	1337 (401)	1131 (309)	No	Distance (1-2 vs. 3-4)	No	-
Kucian et al. (2006)	9-10	Set of objects	964 (228)	931 (254)	No	Not tested	-	-
	12	Set of objects	827 (189)	702 (176)	No	Not tested	-	-
Price et al. (2007)	12	Set of squares	678	637	No	Distance (1-3 vs. 5-8)	No[e]	-

Note. Age is expressed in years, means and standard deviations (SD) are reported in milliseconds (ms)
[a] Comparisons based on the numerical value or the physical size of numerals
[b] Marginal difference ($p < .08$)
[c] Children with velo-cardio-facial syndrome
[d] This effect is based on the size of the smaller numeral of each pair
[e] Group differences related to numerical distance were found in error rates but not in latencies

How can such heterogeneity in the results be explained? First, there is a high interindividual variability in children' performances, particularly in the context of learning disabilities. A second possibility refers to the criteria for selecting participants, and the presence or not of comorbid difficulties. While most of current experiments tended to assess pure dyscalculia, some of them are based on children with spatial and arithmetical difficulties (Bachot et al., 2005), on children with number deficit following genetic syndrome (De Smedt et al., 2008; De Smedt et al., 2007), or on children with both reading and mathematical disabilities (Rousselle & Noël, 2007). Moreover, some selection batteries already included a number comparison task, which could yield a bias in the results. Third, the numerical tasks differed on the nature and the presentation of stimuli. For symbolic numbers, instructions required comparing two Arabic numerals presented simultaneously, or comparing one centrally presented number to a fixed standard. These two tasks do not result in the same recruitment of working memory which could be impaired in dyscalculia. For non-symbolic numbers, participants had to select the larger of two visually presented sets of objects. These patterns were not always controlled for all perceptual dimensions like density or surface area that are confounded with the numerosity. Therefore, performances did not necessarily reflect number sensitivity. Concerning the time of presentation, the numbers/numerosities commonly remained visible until participants responded. On the contrary, some studies restricted the time of stimuli presentation which prevented the children resorting to immature strategies such as (overt or covert) verbal counting. Moreover, there was no consensus about the measurement of the numerical distance. In general, this effect is computed by subtracting performances on small distance from large distance ones, but there is no agreement in the choice of distance to be contrasted (1 versus 5, 1-2 versus 3-4). Alternatively, recent studies assess the slope of the numerical distance as a gradual effect (from 1 to 4 or from 1 to 8) using variance or regression analyses.

In Chapter 5, we conduct a study that addresses these issues. The purpose of that experiment is to investigate performances of MD and control children during symbolic and non-symbolic number comparisons. In order to clarify the role of the format in potential group differences, participants had to compare the magnitude of quantities presented as Arabic numerals, number words, canonical dot patterns, non-canonical dot patterns, or stick patterns. Considering that the same pairs of stimuli appeared in all formats, our paradigm allowed us to discard some of the earlier bias.

3. Brain-imaging contribution to developmental dyscalculia

Very little is known about potential cerebral correlates of developmental dyscalculia. A few neuroimaging experiments have investigated differences between participants with MD and age-matched controls either in brain structure and grey matter density, or in brain activation during number comparison and calculation. While the first neuroimaging contribution was based on adults or adolescents with MD following prematurity or genetic origin, more recent studies focused on children with pure dyscalculia.

3.1. Morphometric experiments

Considering populations which exhibit calculation difficulties in the context of genetic trouble or preterm birth, the findings suggest structural abnormalities in the IPS as compared to healthy populations (see Fig. 3-2). The analysis of sulcal morphometry revealed a decrease in the maximal depth as well as a trend toward a reduced length in the right IPS in adults with Turner syndrome[7] (TS) relative to controls (Molko et al., 2003). Qualitative differences were also reported in the configuration of the right IPS, reflected by aberrant branches, abnormal interruption, or unusual orientation in most of the TS participants. Using voxel-based morphometry, a small and marginally significant decrease in grey matter density was found in TS participants in the depth of the right IPS.

Structural brain differences in the IPS but lateralised in the left hemisphere were also observed in adolescents of 15-16 years who had been very low birth weight infants (Isaacs, Edmonds, Lucas, & Gadian, 2001). Adolescents were assigned to two groups on the basis of their performances on a numerical and an IQ tests (Wechsler, 1996). One group performed more poorly on arithmetic than expected by their IQ, and the other group had scores on mathematical reasoning (e.g., problem solving, number concepts) below the level predicted by their IQ. Compared to controls matched on age and IQ, adolescents with impaired calculation ability had less grey matter in a region in the left IPS. Interestingly, the morphological analysis failed to find difference between adolescents with mathematical reasoning disability in any cerebral region.

[7] This genetic disorder, resulting from a partial or complete absence of one of the two X chromosome in a phenotypic female, is typically characterised by visuospatial and number processing deficits (Bruandet et al., 2004; Rovet et al., 1994) in the absence of mental retardation and verbal disability (Ross, Zinn, & McCauley, 2000).

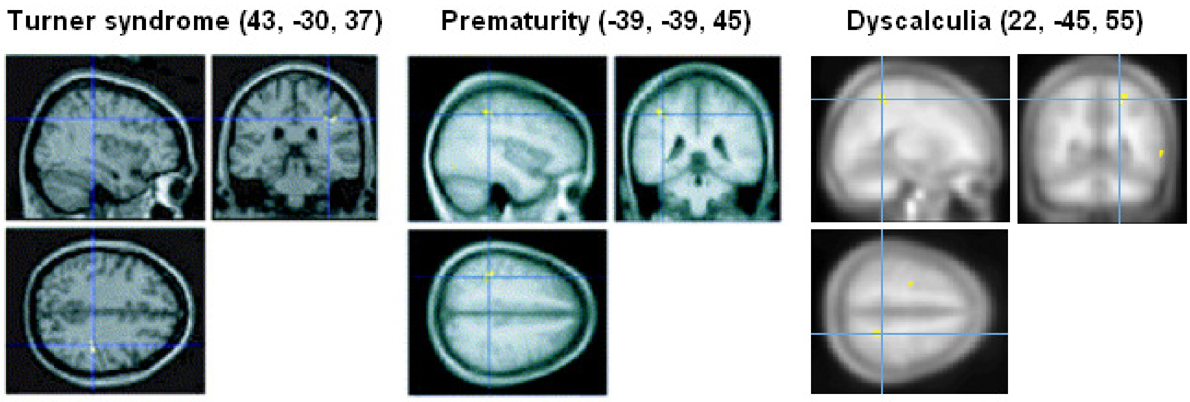

Figure 3-2. Areas in the IPS showing less grey matter in adults with Turner syndrome (Molko et al., 2003), in adolescents with very low birth weight (Isaacs et al., 2001), or in children with pure dyscalculia (Rotzer et al., 2008) relative to respective control populations.

More recently, a MRI study investigated potential differences in cerebral grey and white matter between children with pure dyscalculia (mean age of 9 years) and age-matched control children (Rotzer et al., 2008). Compared to controls, dyscalculic children showed reduced grey matter volume in the right IPS, and several frontal regions including the bilateral anterior cingulum and middle frontal gyrus, as well as the left inferior frontal gyrus. White matter comparison also revealed clusters with less volume in a left frontal area and in the right parahippocampal gyrus in dyscalculic group. These regions which seem not fully developed in these children could represent the neural substrate of impaired arithmetical abilities in dyscalculia. However, it could be questioned whether these fronto-parietal areas are engaged in specific-number processing or in more domain-general factors, such as working memory and attention (e.g., Shulman, d'Avossa, Tansy, & Corbetta, 2002). Similarly, the parahippocampal gyrus is implicated in the encoding of novel objects (Stern et al., 1996), but it is not clear whether a part of this region is specifically related to the storage or the retrieval of arithmetic facts.

3.2. Functional experiments

Other brain-imaging studies have examined differences in cerebral activity between participants with MD and controls while they performed numerical tasks like numerosity comparisons or symbolic calculation. In a first experiment, brain activation was analysed in adults with Turner syndrome and in healthy females during exact and approximate addition problems (Molko et al., 2003). In controls, a number size effect on brain activation was found in the left and right IPS, as well as in the right precuneus during exact calculation. By contrast, number size had no impact on activation pattern in participants with Turner syndrome. Moreover, while controls showed greater activation during approximate relative to exact calculation in the left and right IPS when restricted to small numbers, no differences in the cerebral networks activated in both calculation tasks were observed in participants with Turner syndrome.

A weak modulation of parietal activity was also reported in dyscalculic participants while they compared Arabic numerals to the reference standard 5 (Soltész et al., 2007). In particular, the time course related to the numerical distance slightly differed between female adolescents with dyscalculia (mean age of 17 years) and age-matched or adult groups without MD. During early window interval (about 210-300 ms), the topography of the distance effect was similar between control and dyscalculic adolescents. By contrast, ERP of the distance effect differed over the left hemisphere between adults and dyscalculic adolescents during later interval (about 340-430 ms). Similarly, there was a distance effect on right-parietal electrodes in controls, but not in the dyscalculic group. Combined with the less steep slope of the behavioural distance effect in dyscalculic adolescents than in adults, these ERP differences could reflect an abnormal processing of the magnitude of single-digit numbers. Alternatively, compared to controls, dyscalculic participants were also impaired in other tasks like mental finger rotation, finger knowledge, and tactile performance. This pattern might be interpreted as reflecting a slight functional disruption of the angular gyrus, leading to some of the symptoms which have been often observed in Gerstmann's syndrome (e.g., Kinsbourne & Warrington, 1963).

The earlier results indicated some functional differences in the context of MD. Yet, they were obtained in young adults who could have compensated for their difficulties during the development. Of particular interest were two fMRI experiments which investigated number-related neural correlates in children with pure dyscalculia. Brain activation in dyscalculic children (mean age of 10 years) and age-matched control children was compared during approximate calculation, exact calculation, and non-symbolic magnitude comparison (Kucian et al., 2006). In general, similar frontal-parietal network was activated in the two groups of children. No differences in cerebral activity were observed during exact calculation and non-symbolic comparison while brain activation during approximate calculation was slightly weaker in right insula and parahippocampal gyrus for the dyscalculic group. Subsequent ROIs analyses revealed significantly weaker activation for children with dyscalculia than for control children during approximate calculation in the left and right IPS, as well as in the inferior and middle frontal gyrus. The weaker IPS activation during approximate calculation in dyscalculic children was interpreted as an impairment in the construction or the activation of the number magnitude representation. However, this hypothesis did not account for the lack of group differences in IPS activation during non-symbolic comparison. This apparent conflict in the results could be due to the impact of perceptual variables that co-varied with the numerosity like density or total area.

Using patterns controlled for the possible confound of these factors, it was found that dyscalculic children had also difficulties in comparing non-symbolic numerosities (Price et al., 2007). Brain activation of children (mean age of 11 years) diagnosed as dyscalculic and control children of the same age was analysed while they compared two simultaneously presented sets of squares[8], separated by either a close or a far distance. The control group showed a stronger distance effect than the MD group in the right IPS and in the left fusiform gyrus. The lack of IPS modulation during non-symbolic comparison in MD children was interpreted as either a weakened parietal representation of number magnitude in dyscalculia, or a reduced ability to access numerical quantities. Nevertheless, the screening assessment revealed that control and dyscalculic children significantly differed on standard mathematical scores, but also the IQ subtest of block design (WISC-III) which could account for some of the differences in brain activation.

[8] To control for the possible confound of continuous variables, the density, individual square size, and total area of each array was systematically varied across trials.

Finally, a recent TMS study examined the impact of a temporary IPS dysfunction on number processing in adults without any mathematical difficulties (Kadosh, Kadosh, Schuhmann et al., 2007). Although the results were not based on participants with MD, they were important with respect to the causal relationship between IPS activation and the possible deficit of the number magnitude representation. Healthy adults performed a numerical Stroop-like task while TMS was (or not) applied to the left or the right IPS[9]. They had to decide which of two Arabic numerals, varying along the numerical and the physical dimensions (e.g., 2 3) was the numerically or physically larger. Both sham and left IPS stimulation led to significant facilitation and interference effects on latencies whereas the right IPS stimulation resulted in an interference component only. Interestingly, the dysfunction of the right IPS mimicked the behavioural performances of dyscalculic adults who showed a congruency effect composed by a significant interference component but no facilitation (see also, Rubinsten & Henik, 2005). This result supports the importance of the integrity of the IPS in processing automatic and intentional number magnitudes, and offered a potential locus for developmental dyscalculia.

In summary, morphometric studies indicated structural abnormalities in the IPS in participants with MD following genetic disturbance (Molko et al., 2003) or prematurity (Isaacs et al., 2001). More interestingly, similar findings were obtained in children with pure dyscalculia. However, it was not clear whether these anatomical differences really reflected an atypical development of numerical abilities. Functional experiments revealed that, compared to respective control groups, parietal regions in adolescents (Soltész et al., 2007) and adults (Molko et al., 2003) with MD showed weak or no modulation by numerical distance or problem size effects. These findings suggested an important role of areas around the IPS for the development of numerical abilities. However, there was no consensus in the findings resulting from children's investigations. Only weak differences between dyscalculic and non-dyscalculic children were observed during symbolic approximate calculation, but not during symbolic exact calculation (Kucian et al., 2006). Furthermore, although these data were interpreted as impairments of dyscalculic children in tasks requiring an understanding of number magnitudes, it should be noted that no group differences were found in brain

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9 The precise localisation was based on fMRI-guided results for each individual during the same task.

activation during magnitude comparisons on sets of objects. By contrast, a weak involvement of the IPS in dyscalculic children was reported when non-symbolic patterns were controlled for perceptual variables like density or total surface (Price et al., 2007). Compared to controls, they showed a lesser modulation of brain activation in the right IPS by the numerical distance. Together, while clear differences in brain activation were found between dyscalculic and control children during non-symbolic number comparisons when participants could not based their decision on non-numerical dimensions, current findings did not show such evidence during symbolic number processing. One possibility is that exact and approximate calculation tasks were too difficult to point out differences between dyscalculic and control children, as suggested by the high error rates. Second, it may be that the deficit in dyscalculia was closely related to the manipulation of the numerical distance as shown in non-symbolic number comparisons. Yet, the impact of the numerical distance on the modulation of brain activation during symbolic number comparisons was not tested. Finally, the participants were not assessed on non-numerical cognitive factors like working memory which could influence performances on number processing. In Chapter 7, we conduct an fMRI study that addresses these issues. The goal of this experiment is to further investigate differences in brain activation between dyscalculic and control children during symbolic number comparisons. Further details concerning this study are provided in the subsequent section.