CHAPTER 8

General discussion

Absence of evidence is not evidence of absence.

Carl Sagan, US astronomer (1934-1996)

The present thesis focused on the hypothesis of a deficit of the number magnitude representation in developmental dyscalculia. Four main questions were investigated regarding the typical and atypical development of numerical abilities. Experiment 1 tested whether poor arithmetical performances of MD children could reflect a more general deficit in retrieving information from long-term memory. In Experiment 2, we investigated differences between children with MD and controls in comparing symbolic and non-symbolic numbers. The two subsequent studies were dedicated to the neural correlates of number processing in children with and without MD. Experiment 3 examined number-related changes in brain activation between healthy children and adults. Finally, Experiment 4 analysed brain activation in children with pure dyscalculia and controls while they compared the magnitude of Arabic numerals, or the colour of non-numerical symbols. In the ensuing sections, we present an overview of the results reported in the aforementioned studies, as well as their theoretical and practical implications. Our findings are also confronted with other possible interpretations. This thesis ends with some suggestions for future research.

1. Overview of findings

In Chapter 4, we showed that difficulties encountered by children with MD (characterised by poor arithmetical abilities) were specific to the numerical domain (Experiment 1). These children were as fast as controls in retrieving information related to words (when controlled for the speed of reading), object pictures, country-city associations, or verbal proverbs from long-term memory. These results did not support the hypothesis of a general deficit in remembering information from semantic memory (e.g., Geary, 1993), nor the hypothesis of a general deficit in retrieving information by verbal routines (inspired by the double dissociation reported in Dehaene & Cohen, 1997). Moreover, while all tasks involved comparing two responses and selecting the correct one, children with PoorAF were slower than controls in the multiplication task only. This did not support a potential impairment in the process of response selection itself. Our findings demonstrated that poor arithmetical abilities were not necessarily associated with a global low processing speed. Similar latencies were found in children with PoorAF and controls when they performed a perceptual matching task. Rather, these data favoured a specific deficit for remembering or encoding arithmetic facts.

In Chapter 5, we tested more directly a potential link between weak performances in basic numerical abilities and an impairment of more elaborate mathematical competencies. Experiment 2 investigated (1) a possible slowdown in children with MD relative to controls while they compared number magnitudes; (2) whether or not a different slope of the distance effect related to number magnitude representation could appear in dyscalculia; and (3) the role of number format in potential differences between MD and control children of 10-11 years. Concerning the first point, the results indicated that MD children were not significantly slower (or less accurate) than their control peers in comparing symbolic or non-symbolic number quantities. This was in line with previous data reporting similar latencies in MD and control children during non-symbolic comparisons (e.g., Noël, 2002; Price et al., 2007). Regarding Arabic numbers processing, the age of the participants might play an important role in the presence or absence of a significant slowdown in dyscalculia. While young children of 7-9 years differed from age-matched controls (Bachot et al., 2005; Landerl et al., 2004; Rousselle & Noël, 2007), no such difference was found in older children (Kucian et al., 2006; Soltész et al., 2007). A plausible interpretation was that abilities in manipulating number magnitudes or Arabic numbers improved with age in typical children but also in children with MD, reducing the opportunity to observe group differences.

With respect to numerical distance, children with MD showed a steeper effect than controls irrespective of number formats. They mainly had difficulties when comparing numerical quantities that were close together. A similar pattern was previously observed in the context of MD (Bachot et al., 2005; Price et al., 2007). Another study reported a weaker distance effect in MD relative to control groups, resulting from the presence of a reversed distance effect in some MD children (Rousselle & Noël, 2007). Although the authors interpreted this atypical effect as reflecting the use of peculiar strategies resulting from an access deficit, it could be that a less precise representation of number magnitudes produced the same pattern (the case of Charles, Butterworth, 1999b). As previously reported, other effects depending on the number magnitude representation were impaired in dyscalculia. Compared to controls, participants with MD did not show the SNARC effect in comparing the magnitude of Arabic numerals (Bachot et al., 2005) nor the classic size congruity effect in judging the physical attributes of Arabic numerals (Rubinsten & Henik, 2005).

The role of number format was assessed using various symbolic and non-symbolic number quantities. Crucially, our findings indicated a steeper distance effect in MD children relative to controls irrespective of the number format, suggesting that they exhibited a stronger sensitivity to numerical distance not only in symbolic but also in non-symbolic comparisons. Moreover, the format influenced the latencies of both groups equally, leading to the absence of any slowdown in MD children regardless of whether numbers were presented as either symbolic or non-symbolic quantities. Together, these findings suggest that the number magnitude representation is less precise (more imprecise) in dyscalculia, leading to greater difficulties in activating a specific magnitude especially when comparing close numbers. In subsequent sections, we confront our results with other interpretations about the impairment in dyscalculia. In particular, potential discrepancies between the predictions of access and representation deficits are examined. We also discuss the extent to which a less precise representation of number magnitudes could account for poor performances in calculation. This point also refers to the question of the causality between a deficit in number magnitude representation and dyscalculia.

Beside behavioural investigations, we conducted two fMRI studies that aimed to determine neural correlates of symbolic number processing in children with and without dyscalculia. In Chapter 6, we examined differences in brain activation between healthy children and adults while they performed number and colour comparison tasks (Experiment 3). The main result was that, compared to children of 10-11 years, adults showed higher activation in the left and right IPS during number comparison (relative to fixation periods). The ROIs analyses confirmed that the regions in and around the IPS, which were previously involved in number processing, were more activated in adults than in children. Moreover, the colour task allowed us to test to what extent these changes in brain activation were specific to the number comparison task. When the number and colour comparisons were contrasted, only a weak region in the right superior parietal lobule extending to IPS showed greater activation in adults than in children. This was certainly due to the involvement of the IPS in colour judgments, as suggested by several studies (Kadosh et al., 2005; Pinel et al., 2004; Shuman & Kanwisher, 2004). Indeed, a modulation of brain activation in the IPS was found when colours were processed as magnitudes according to their luminance level (for a discussion, see Kadosh et al., 2008). This possibility is further confirmed by our second fMRI experiment. However, although the differences we observed were slight, these findings were the first support for specific age-related changes in IPS activity during an active numerical task. Concerning the role of frontal cortices in number-related development, no area was more activated in children relative to adults in any of the numerical contrasts, as previously reported in non-symbolic comparison (Ansari & Dhital, 2006) or simple calculation (Kawashima et al., 2004). Our results did not support the shift from frontal to parietal regions with age postulated by Ansari et al. (2005) and observed by Rivera et al. (2005) in verification of arithmetical problems. This apparent conflict in the data could be resolved by postulating an implication of working memory depending on frontal areas in calculation[24], but not in more basic numerical tasks such as symbolic number comparison. On the contrary, our ROIs analyses indicated that the left and right precentral gyrus was more activated for adults than for children during number comparison. Yet, these differences tended to disappear when contrasted with the colour task. Together, the increasing number-related activation in the IPS and, to a lesser extent, in the precentral gyrus with age could reflect the importance of these areas in the matching between number magnitude and numerical symbols during learning (for a similar conclusion, see Diester & Nieder, 2007).

In Chapter 7, we investigated the neural correlates of developmental dyscalculia. Brain activation of dyscalculic and control children was recorded while they performed number comparisons on pairs of Arabic numerals, or colour comparisons on pairs of non-numerical symbols (Experiment 4). In each pair, stimuli were separated by a close or a far on the relevant dimension. In control children, we found that the right IPS responded to numerical distance only, whereas the left IPS was influenced by numerical and colour distances. On the contrary, no significant modulation by numerical (or colour) distance was

[24] Note that the lack of differences between children and adults in frontal activity during calculation, reported by Kawashima et al. (2004), could be due to the fact that participants performed the tasks mentally.

observed in dyscalculic children. A similar weak number-related involvement of the right IPS was previously observed in dyscalculic children during non-symbolic number comparisons (Price et al., 2007). Together, these data combined with our behavioural results could reflect an impairment in the activation or construction of the number magnitude representation. Moreover, the fact that our dyscalculic participants showed weak activation in the left IPS, which was modulated by numerical and colour distance in controls, suggests an additional deficit in general magnitude processing. Further investigation is needed to assess performances of children with MD in comparing various non-numerical magnitudes. Another important question concerns the interpretation of group differences in brain activation given that dyscalculic and control children did not differ from each other in accuracy or latencies. Considering the hypothesis of an imprecise number magnitude representation leading to dyscalculia, we can speculate that, compared to the typical development, the weak involvement of the IPS in dyscalculic children should initially be associated with a slowdown or high error rates in number comparisons. As age and practice with numerical quantities increase, these children compensate for their difficulties but still have abnormal brain activations that reflect a deep deficit in areas dedicated to number magnitudes. Note that the age of our participants ranged from 9 to 11 years, whereas children as young as 5 years were able to compare the magnitude of Arabic numerals (Temple & Posner, 1998).

To sum up, our studies provide pieces of evidence that the difficulties of children with MD are specific to the numerical domain (Experiment 1), and concern not only calculation but also the comparison of number/numerosity magnitudes, especially for adjacent quantities (Experiment 2). Moreover, these findings mirror the weaker modulation of the left and right IPS by numerical distance in dyscalculic children relative to controls (Experiment 4).

2. Theoretical implications

Several hypotheses have been put forward to account for impairments in developmental dyscalculia. As reported in Chapter 3, the manipulation of number magnitudes is not the only factor that plays an important role in calculation. For instance, working memory and finger gnosia abilities are used by children for executing procedures and keeping track of intermediate results when solving arithmetical problems. Therefore, even though a majority of MD children might suffer from poor abilities in manipulating numerical quantities, other cognitive deficits could cause or increase mathematical difficulties. In a recent review, Wilson and Dehaene (2007) proposed that different subtypes of developmental dyscalculia might co-exist, as has been observed in adult patients with acalculia. In particular, children with “number sense” dyscalculia who lack an understanding of the meaning of numbers but are able to retrieve arithmetic facts could be distinguished from children with “verbal” dyscalculia characterised by an intact understanding of the meaning of numbers but an impairment in retrieving basic multiplication or small addition facts from memory. In line with this hypothesis, children with MD in the context of VCFS exhibited weaker performances than controls on number comparisons, large addition and subtraction problems, but not on multiplication, small addition and subtraction problems (De Smedt et al., 2008; De Smedt et al., 2007). Up to now, such a distinction has not really been examined in children without genetic syndrome. A main reason is that the majority of studies have selected their MD participants according to difficulties in remembering arithmetic facts. We and others have found, however, that children with poor arithmetical abilities also show weak performances in basic numerical skills depending on number sense (e.g., Landerl et al., 2004). Future research should focus on the possibility of different subpopulations of MD children by using different selection criteria.

Our findings suggest that developmental dyscalculia is associated with a deficit of the number magnitude representation. Alternatively, dyscalculic children could have a problem in accessing number-related magnitudes from numerical symbols, rather than in the representation *per se* (Rousselle & Noël, 2007). The access versus semantic representation deficits debate was initially raised within the language domain to account for dissociations in aphasic patients following brain injury or degenerative disease affecting the left hemisphere. Warrington and Shallice (1979; see also Warrington & Cipolotti, 1996) proposed various criteria[25] for distinguishing access and representation deficits. First, while inconsistent performance pattern would favour an access deficit, it was suggested that a relative consistency of performance would support a representation deficit. A second criterion referred to the effect of priming which was expected to improve access to semantic information, but not the representation itself. Finally, the authors suggested that frequent items were deeply represented in semantic memory, and could be better preserved against a deficit than less frequent items. However, it is likely that the frequency of the items also influences access to semantic representations. More recently, discrepancies between poor performances on tasks requiring explicit semantic processing and high performances on tasks requiring more implicit semantic processing have been postulated as supporting an access deficit (Laatu, Portin, Revonsuo, Tuisku, & Rinne, 1997). However, this dissociation between access and representation deficits has been criticised. Indeed, it has been shown that the criteria could not account for the performance pattern exhibited by some patients (e.g., Howard, 1985). Moreover, they were used in brain-damaged adults with acquired difficulties, and did not really appear relevant in the context of developmental deficit. To the best of our knowledge, only one study has tried to disentangle access versus representation deficit in developmental dyscalculia (Kaufmann et al., 2004). A young dyscalculic adult (MO) was presented with production and verification tasks on addition and multiplication problems in order to investigate the nature of his difficulties in retrieving arithmetic facts. The data provided no clear distinction between the two hypotheses, as MO's performance pattern was compatible with both access and representation deficits.

In an attempt to distinguish a deficit in number magnitude representation from a deficit in access to it, we contrast the predictions of each hypothesis using the aforementioned criteria. An access deficit postulates only a slight link between one numerical symbol and its semantic representation, leading to inconsistent performances in comparing two related-number magnitudes. However, as shown in Chapter 3 (see Table 3-2), there is no evidence of higher variances in children with MD than in children with MD when they compared the magnitude of Arabic numerals (Noël, 2002; Rousselle & Noël, 2007). Furthermore, our findings indicated that children with MD did not show a greater variance than controls for symbolic relative to non-symbolic number comparisons (see

[25] Other criteria were proposed by the authors, such as a sensitivity to the presentation rate, but these are irrelevant to our question.

Appendix 5). Considering the second criterion, the priming effect is supposed to improve the access to a semantic representation when this connection is impaired. Yet one would expect the same impact on a less precise number representation if one postulated that priming leads to a semantic pre-activation which may in turn enhance discriminations relative to adjacent number magnitudes. Similarly, the frequency of items does not allow us to dissociate access versus number representation deficits as the numerical quantities used in our experiments were very frequent (from 1 to 9). Of particular interest is the possible discrepancy between automatic and intentional tasks. While the access deficit hypothesis postulates relatively unimpaired performances in automatic number processing, data indicate that dyscalculic participants had problems even without any explicit processing of the number magnitudes. Compared to controls, they were slower and showed no facilitation effect in comparing various perceptual dimensions of Arabic numerals (Rubinsten & Henik, 2005). In another study using a similar Stroop-like paradigm (Rousselle & Noël, 2007), group differences were found neither in latencies nor in the size congruity effect. However, MD children needed longer delays than controls before the appearance of the physical difference, reflecting a slowdown in the activation/comparison of number-related magnitudes. In our opinion, the earlier criteria did not really enable a dissociation between access and representation deficits with regard to developmental dyscalculia. While some of them favour a representation deficit, others cannot disentangle the two hypotheses.

More convincing evidence for a deficit in number magnitude representation could be put forward. First, the access deficit hypothesis cannot easily account for the fact that, compared to controls, children with MD show a different slope of the numerical distance (or other effects), which depends on the number magnitude representation. Indeed, although not specified by the hypothesis, one could speculate that the access deficit influences all numerical symbols indifferently, leading to a general slowdown rather than a modulation of the numerical distance effect. Yet, it is likely that the access deficit increases as the proximity between number magnitudes decreases, resulting in a greater impairment for close than for distant number magnitudes. Nonetheless, while the access deficit hypothesis predicts an impairment in non-symbolic number processing only, we have shown that the difficulties encountered by children with MD appeared in comparing symbolic numbers, but also in comparing non-symbolic quantities. A second argument concerns the neuroimaging data, especially the fact that dyscalculic children showed no modulation in the IPS by numerical distance. The question is how such a lack of sensitivity to number magnitudes in dyscalculia following symbolic (see Experiment 4 of the present thesis) and non-symbolic processing (Price et al., 2007) could be interpreted as a possible access deficit. This hypothesis would predict a weak involvement of areas dedicated to access to semantic representations from numerical symbols in dyscalculia. Therefore, one would expect dyscalculic children to show less brain activation in occipito-temporal regions reflecting Arabic numerals access processing (Pesenti et al., 2000), or in the precentral gyrus involved in the matching between numerical symbols and non-symbolic numerosities (Diester & Nieder, 2007). Furthermore, no group differences in brain activation were expected in non-symbolic number processing. Last but not least, it is very unlikely that a deficit in access to number magnitudes have no impact on the representation itself during development. While precision between analog magnitudes increases with age, especially with the acquisition of exact numerical symbols, it may be that children with MD cannot benefit from this improvement (see below for greater details).

However, beyond our findings, non-symbolic quantities seem less affected than Arabic numerals in dyscalculia. Children with MD of various age groups were as fast as their control peers in comparing patterns of objects, and showed no differences in the slope of the numerical distance effect (Noël, 2002; Rousselle & Noël, 2007). Considering the difficulty in controlling for all continuous dimensions that naturally co-vary with numerosity during non-symbolic discrimination, it is possible that MD children are guided by these perceptual cues to compensate for their impairments relative to controls. It was found that even adults were unable to ignore the relative size of the circles when judging which of two arrays had more circles (Hurewitz, Gelman, & Schnitzer, 2006). Further support for this possibility is provided by our results of Experiment 2 showing that density and surface area influenced the accuracy of non-symbolic comparisons in MD, but not in control children. Alternatively, the greater impairment for symbolic numbers than for non-symbolic numbers in dyscalculia could be due to differences in the development of these numerical quantities. While preverbal numerical abilities appear within the first year of life, the learning of spoken number words and Arabic numerals begins at 2-3 years and 4-5 years respectively (see Chapter 1). Therefore, school-aged children have several years to improve their performances on non-symbolic processing, but only a few years to do this with numerical symbols.

Finally, we would like to underline the fact that the access and representation deficits are not necessarily incompatible. These hypotheses could be reconciled by postulating a two-factor theory about the impairment in developmental dyscalculia. First, dyscalculic children might initially have a weak “number sense”, reflected by a very imprecise representation of number magnitudes relative to non-dyscalculic children, which affects even preverbal numerical knowledge. Later on, children learn to map exact numerical symbols presented as number words and Arabic numbers onto the approximate number system. In the typical development, this mapping could result in important changes in the number representation in the form of increasing precision between analog magnitudes. In dyscalculic children, the deficit of the number magnitude representation could prevent them from benefitting from the increasing precision yielded by symbolic numbers. According to this view, developmental dyscalculia is determined by the early abilities in understanding and manipulating numbers, but also by the capacity to acquire a finer representation of numbers with age. The probability of suffering from an additional symbolic access deficit would depend on the level of impairment in the number magnitude representation. Some children might be able to compensate for their difficulties through the manipulation of numerical symbols, whereas others would not. This might explain why sometimes a discrepancy between dyscalculic and control children is observed, and sometimes not.

Support for greater precision with symbolic than with non-symbolic numbers comes from the recent adult model proposed by Verguts and Fias (2004). The model predicts that, unlike symbolic numbers, non-symbolic numerosities need to be summed through an intermediate step (i.e., summation coding) before they can be mapped onto the number magnitude representation. As the noise in the summation coding increases in proportion with the number of inputs that are being summed, the non-symbolic inputs activate a fuzzy representation of numbers which leads to a monotonous numerical distance effect. On the contrary, the symbolic inputs activate a more distinct and less noisy representation of numbers as the intermediate summation coding is not required[26]. Consistent with this model, qualitatively different priming performances were observed for symbolic and non-symbolic numbers. The priming effect induced by Arabic numerals decreased monotonically

[26] The model implicitly supposes that symbolic number representations are first acquired through the simultaneous presentation of both symbolic and non-symbolic numerical inputs. This might explain why the processing of symbolic numbers inherits some characteristics related to the nature of the number magnitude representation, such as numerical distance and size effects (see also Ansari, 2008).

with the prime-target distance, resulting in a *V*-shaped pattern (Reynvoet, Brysbaert, & Fias, 2002). By contrast, the priming effect induced by dot displays was constant across all smaller magnitudes, leading to a steep pattern with a decreasing distance effect for magnitudes larger than prime only (Roggeman, Verguts, & Fias, 2007).

In this thesis, we have collected both behavioural and brain-imaging data favouring a basic number-related deficit in developmental dyscalculia. Nevertheless, one cannot ignore the fact that, except for extreme cases such as Charles (Butterworth, 1999b), dyscalculic children are able to select the larger of two Arabic numerals or two patterns of objects. They are just slower and more error-prone than age-matched children without any MD, especially for close numerical quantities. We have interpreted these poor performances as reflecting a very imprecise number magnitude representation, but what is the impact of this impairment on the general pattern exhibited by dyscalculic children? First, it should be noted that our results were based on the comparison of small numerical quantities ranging from one to nine. Therefore, even if some differences between MD and control children were weak, they appeared with very frequent numbers/numerosities, and could be stronger with larger quantities. Second, we would like to stress the importance of the number magnitude representation in the manipulation of numerical quantities, but also in the development of more elaborate mathematical abilities. As shown in Chapter 1, the preverbal approximate system might serve as a foundation for the apprehension of the concept of cardinality (Butterworth et al., 2008), the matching between numerical symbols and their semantic values (e.g., Sekuler & Mierkiewicz, 1977), and the acquisition of exact arithmetical abilities (e.g., Gilmore et al., 2007). Moreover, we suggest that the integrity of the number magnitude representation is necessary to develop a well-formed network of arithmetic facts. A greater overlap between analog magnitudes, leading to difficulties in discriminating close numerical quantities, could prevent a strong link between an arithmetical problem and its correct response from being created. This might explain poor performances of dyscalculic children in storing or retrieving arithmetic facts from long-term memory.

Our findings suggest a link between difficulties in number magnitude comparisons and poor abilities in arithmetic. However, they do not demonstrate a causal role between a weak “number sense” and developmental dyscalculia. If a less precise representation of number magnitudes causes the difficulties encountered by dyscalculic children later in their development, it should be possible to find infants who exhibit poor ability in discriminating numerosities. For instance, even though the majority of 6-month-old infants are able to discriminate between numerosities of 3 versus 4 stimuli, it may be that others cannot distinguish 2 from 3 stimuli. Unfortunately, current research exclusively focuses on performances of school-aged children, and provides only little opportunity to demonstrate the existence of preverbal impairment. Of particular interest are the recent results showing a link between the individual ability to discriminate dot patterns at 14 years, and scores on calculation at 5 years (Halberda et al., 2008). Although these results are exciting, they could merely reflect the development of a more precise number representation in children with high ability in mathematics. More longitudinal studies are needed to examine whether weak numerosity discrimination could predict the probability of manifesting mathematical disabilities. Brain-imaging research should focus on the importance of the IPS in the development of number abilities.

3. Practical implications

Our findings suggest that the capacity to manipulate numerical quantities non-verbally and to connect numerical symbols to the number magnitude representation should have a crucial role on the remediation of dyscalculia. Nevertheless, very few intervention studies have been conducted with a view to helping young children at risk of MD, and many of those were collectively administered in the whole-class (Fuchs, Fuchs, Karns, Hamlett, & Katzaroff, 1999; Griffin, Case, & Siegler, 1994). Remediation programs have also been used in older children with MD, but mainly to improve the storing/retrieving of arithmetic facts (Hasselbring, Goin, & Bransford, 1988; Pellegrino & Goldman, 1987). More recently, Wilson and colleagues (A. J. Wilson et al., 2006) developed an adaptive computer game for the remediation of developmental dyscalculia. This approach has been successfully used to improve language and reading performance in children with language impairment (SLI) and dyslexia (Merzenich et al., 1996; Tallal et al., 1996). The software included various numerical tasks which aimed to enhance number sense. The training was also designated to increase the association between representations of number and space, as well as the connection between the preverbal number representation and Arabic numerals. Finally, participants were trained to enhance their fluency of access to basic addition and subtraction facts. We briefly report the initial results from ten week training course for a sample of nine children of 7-9 years with mathematical difficulties (Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). A pre-post change in speed was observed in a dot enumeration task for the subitizing range but not the counting range. Regarding number comparisons, although children were significantly faster after training during both symbolic and non-symbolic processing, a larger improvement was found with symbols. However, there were no changes in the slope of the numerical distance effect. Accuracy strongly increased for subtraction problems, but not for addition problems. Although these findings are encouraging, they need further investigation to clarify the contribution of number sense to remediation of dyscalculia. In particular, it is difficult to determine whether training changes are due to number or spatial manipulations as these variables are often confounded. Moreover, the small sample and the variability in the criteria for selecting children (from 1st to 37th percentile) prevent any strong conclusion about the impact on dyscalculia remediation being drawn.

4. Merits and limits of this thesis

The combination of behavioural and brain-imaging studies can be considered as a merit. The hypothesis of a deficit in number magnitude representation was investigated using various lines of research. Our questions concerned the specificity of the difficulties encountered by children with MD; the impact on symbolic and non-symbolic number comparison; and the neural correlates of the performance pattern in dyscalculia.

Relatively homogenous samples of children were assessed in the studies conducted in this thesis. The age of our MD participants ranged from 9 to 11 years, with a mean age around 10 years. They all had poor arithmetic fact abilities, normal IQ, and no reading difficulties. However, they were selected using different criteria, which could constitute a potential limit. As mentioned earlier, while children who participated in our fMRI experiment were diagnosed as having dyscalculia on the basis of a clinical criterion of two years below their chronological age, scores below the 15th percentile on arithmetical tests served to select the participants in behavioural studies. This criterion is higher than the earlier reported estimate that around 6% of children have some form of MD, but enabled us to avoid children with comorbid dyslexia or ADHD. Although these children had difficulties in arithmetic or mathematics reasoning, they could not all be strictly defined as dyscalculic. It would be interesting to assess different children groups identified as MD using less-to-more stringent criteria in order to compare their performances in number comparison.

Although we focused on the development of numerical abilities, our findings were mainly based on the comparison between children with MD and age-matched controls at a single point in time. A longitudinal design could be a fruitful approach to exploring the nature and types of difficulties that children experience in the elementary grades, and to examining the extent to which these difficulties persist or change over time. This approach has been widely used with reading difficulties, but rarely with MD. In several studies, Jordan and her colleagues compared measurements of reading and mathematics growth rates in children with MD only and children with difficulties in reading and mathematics (e.g., Jordan et al., 2003a; Jordan et al., 2003b). Yet no convincing differences were found in the rate of development in mathematics between the two groups of MD children. Similarly, although they found that low-income kindergartners performed worse than high-income kindergartners on various numerical measures related to "number sense", both groups progressed at the same rate during the course of the year (Jordan, Kaplan, Olàh, & Locuniak, 2006).

5. Perspectives for further research

Several new avenues of research have been proposed throughout this general discussion. In particular, future studies should investigate numerical abilities of young children before formal education in an attempt to detect those at risk of manifesting dyscalculia or other forms of MD. Longitudinal designs would be useful for distinguishing subpopulations of children with MD. More experiments are also needed to determine the role of non-numerical processes involved in number processing such as finger gnosia, visuospatial attention and working memory. Similarly, the link between arithmetic and reading abilities is unclear, and would in itself, constitute the subject of another thesis. Concerning the deficit of the number representation in dyscalculia, it could be interesting to explore whether children with MD are also impaired in magnitude comparisons on non-numerical materials sharing semantic properties with numbers such as physical size, colours, or letters. Some studies have suggested that these dimensions are adequately processed by children with MD, but they do not use them as continuum magnitudes (Landerl et al., 2004; Rousselle & Noël, 2007). Furthermore, it would be revealing to use a combination of behavioural and brain-imaging investigation to address these questions. Neuroimaging experiments are necessary to examine differences in brain activation amongst subpopulations of MD children, or to demonstrate noticeable changes in brain activity associated with remediation of dyscalculia, as reported in children with dyslexia (Temple et al., 2003).

More generally, current research lacks a theoretical background that makes the link between early numerical knowledge in infant and adult abilities. Even the famous triple-code model (Dehaene & Cohen, 1991; Dehaene et al., 2003) which is able to account for many behavioural and functional data, offers no developmental perspective. Our review in Chapter 1 pointed out four main stages in the acquisition of basic numerical abilities from infancy to childhood. First, a preverbal representation is available in the first year of life and is mainly used to discriminate between small numerosities. A second stage reflects the way that children acquire a more precise representation of numbers through the use of verbal and finger counting. A third stage is represented by the understanding of Arabic numbers which serves as the foundation for more elaborate mathematical achievement. Finally, a last stage refers to the learning of strategies and concepts related to simple calculation which, in turn leads to the acquisition of an arithmetical network in long-term memory.

However, several important questions remain open concerning typical and atypical development of numerical abilities. For instance, what exactly happens between infancy and adulthood? How does the number magnitude representation evolve throughout lifespan? It has been suggested that exact and approximate systems interact with each other during verbal counting and Arabic numerals processing, but the impact of these interrelations on the number magnitude representation is as yet largely unknown. What is the role of the auxiliary cognitive functions such as working memory or attention in these potential changes? Some of these issues have been addressed recently, but have not yet been tested (Ansari, 2008; Kadosh et al., 2008). Further investigation is needed to examine the role of the number magnitude representation on the acquisition of new numerical abilities. The possible impact of new knowledge on the number magnitude representation should also be considered. Moreover, current studies on developmental dyscalculia mostly refer to adult models of number processing and calculation when trying to differentiate some of the component modules of numerical skills. However, ignoring the complex trajectory of number development prevents any strong conclusion about the origin(s) of the deficit being drawn.

To conclude, a lot of work remains to be done to gain a better understanding of developmental dyscalculia. The aim of the present thesis was not to provide any ultimate answer to the origin(s) of this learning disability, but rather to stress the importance of basic numerical abilities for further acquisition in mathematics.