Both Specific and General Cognitive Factors Account for Dyscalculia

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Abstract

The first part concerns factors that relate to very basic number processing and concludes that DD could arise from a difficulty in accessing the magnitude value of symbolic numbers (Arabic numbers or number words). The second part concerns the role of general cognitive factors. In particular, the authors present two recent studies showing that hypersensitivity to interference could lead to difficulties in storing arithmetical facts in memory. Lastly, the question is raised of how to use new neuropsychological constructs to inform teachers' decisions in classrooms, and some ideas for adaptations in the classroom based on the described constructs are sketched.

Keywords: dyscalculia, number magnitude, symbolic numbers, arithmetic, arithmetical facts, interference, memory.

Introduction

Developmental dyscalculia (DD) is a persistent and specific disorder of numerical development and mathematics learning that is not the direct consequence of intellectual disability, inadequate education, or a sensory deficit (see *DSM IV*, American Psychiatric Association, 1994).

The difficulties encountered by people with DD are varied; they can concern the mastery of the symbolic number systems (permitting one to read and write Arabic numbers and to understand the base-10 system), the storage of arithmetic facts in long-term memory (for example, remembering that 5 + 4 = 9 or 8 x 3 = 24), or the achievement of calculation procedures or problem solving.

Various proposals to account for these difficulties have been made. Some assume the existence of a basic number deficit; others emphasise the role of general cognitive factors. In this paper, we will develop one hypothesis for each of these proposals: basic deficit in the construction of an accurate number representation and hypersensitivity to interference.

A basic number deficit

Some authors have hypothesised that a purely numerical deficit could result in dyscalculia. For example, Butterworth (1999, 2005) suggested that DD is the consequence of a malfunction affecting the basic representation of the number magnitude. Thus, DD children would be deprived of 'number sense' or the representation of the quantity (Landerl, Bevan, & Butterworth, 2004). Therefore, any number processing would be problematic.

But what is this 'number sense'? A series of studies has shown that babies are born with an innate ability to represent numerical quantity in an approximate way. This system is called the Approximate Number System or ANS (Feigenson, Dehaene, & Spelke, 2004; Lipton & Spelke, 2003, 2004; Xu, 2003; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). This system permits one to distinguish between the numerosity (or number of elements) of two collections that differ from each other by a sufficient ratio. At six months, the child can distinguish collections that enter into a 1/2 ratio (such as 8 and 16, for example) but not those that enter into a 2/3 ratio (like 8 and 12 or 16 and 24, see for example Xu & Spelke, 2000). At nine month of age, the child can distinguish collections that differ by a ratio of 2/3 but not those within a 3/4 ratio (Xu & Ariaga, 2007). The threshold of discrimination is called the number acuity. This acuity evolves throughout childhood (Halberda & Feigenson, 2008). Some authors consider this the basis of future numerical learning, including arithmetic and mathematics. Indeed, it has been shown that the measurement of the ANS acuity taken at age 14 is correlated with performance in mathematics at different school ages, including kindergarten (Halberda, Mazzocco, & Feigenson, 2008).

Along similar lines, several researchers have proposed that DD could result from a malfunction of this innate representation of numerical quantity (Butterworth, 1999, 2005; Landerl, Bevan, & Butterworth, 2004; Wilson & Dehaene, 2007). In support of this hypothesis, several studies have shown that the ANS acuity of DD children was poorer than that of control children. Thus, in a task requiring the selection, without counting, of the larger of two collections of dots, DD children are less efficient than the control children when collections are numerically close (Mazzocco, Feigenson, & Halberda, 2011; Piazza et al., 2010). Similarly, Mussolin, Mejias, and Noël (2010) observed that DD children were slower and less accurate than control children when they had to compare two small but close numerosities. Finally, differences also appeared in numerical estimation tasks where the children had to estimate the number of dots that were quickly displayed. In these tasks, DD children's estimates were more variable and less accurate than those of children without learning disabilities (Mejias, Mussolin, Rousselle, Grégoire, & Noël, 2012; see also Mazzocco, Feigenson, & Halberda, 2011).

Access to the representation of number magnitude from symbolic codes

However, other studies have provided results that do not support this hypothesis. On the one hand, in a population of unselected children, several studies failed to find any significant correlation between the ANS acuity measured in collection comparison tasks and performance in a mathematics test (e.g. Holloway & Ansari, 2009; Mundy & Gilmore, 2009, and see De Smedt, Noël, Gilmore, & Ansari, 2013 for a review). On the other hand, several studies comparing the performance of DD children and children without learning disabilities in collection comparison tasks, have failed to find any differences between the two groups (de Smedt & Gilmore, 2011; Iuculano, Tang, Hall, & Butterworth, 2008; Landerl & Kölle, 2009; Rousselle & Noël, 2007). However, in all these studies, DD children were less efficient than control children in comparison tasks of Arabic numbers. These data support the hypothesis of Rousselle and Noël (2007) that the core deficit in dyscalculia does not concern the ANS itself but rather the access to the representation of number magnitude from symbolic codes (i.e. numbers presented in Arabic digits or in words).

Table 1:

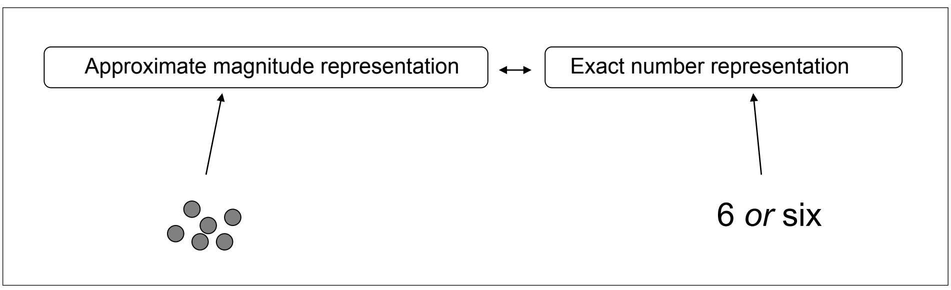
Arabic number and dot collection comparison in children with dyscalculia (DD) or in control children with no learning difficulties (C).

References	Age	Arabic digits	Dot collections
De Smedt & Gilmore (2011)	-	DD < C	DD = C
Rousselle & Noël (2007)	7 years old	DD < C	DD = C
Landerl, Bewan & Butterworth (2004)	8-9 years old	DD < C	-
Iuculano et al. (2008)	8-9 years old	DD < C	DD = C
Landerl & Kölle (2009)	8, 9, 10 years old	DD < C	DD = C
Landerl, Fussenegger, Moll & Willburger (2009)	8, 9, 10 years old	DD < C	DD < C
Piazza & al. (2010)	10 years old	-	DD < C
Mussolin, Mejias & Noël (2010)	10-11 years old	DD < C	DD < C
Price, Holloway, Rasanen, Vesterinen, & Ansari (2007)	12 years old	-	DD < C
Mazzocco, Feigenson, & Halberda (2011)	14 years old	-	DD < C

How can we explain these contradictory results? If we list all the studies that compared the performance of DD and control children in tasks requiring magnitude processing of non-symbolic (set of points) or symbolic numbers (Arabic numerals or verbal numbers), a clear age effect appears (see Table 1). Indeed, with respect to non-symbolic tasks, dissociation occurs between the studies that tested young children (6-9 years) and those that tested older children (10 and over): only the latter found significant differences between the two groups at the expense of DD children. On the contrary, for the comparison of symbolic numbers (Arabic digits), DD children's performance was systematically poorer than that of control children, whatever the age of the children tested. Thus, the first deficit observed in DD children would not affect the processing of number magnitude in itself but rather the access to number magnitude indicated by symbolic codes (Arabic numerals or words). The deficit observed in the collection process appears only secondarily. Given this observation, we must first admit that the hypothesis of a deficit of the ANS as the basis for DD does not hold water. Indeed, if this was the case, difficulties in collections comparison should be observed at a young age. Besides, if the difficulties in processing symbolic numbers were explained by their connection to a defective ANS, they could only be secondary to the observation of a deficient ANS, and not precede it. Another interpretation is therefore required.

Some developmental theories suggest that learning a number symbol system triggers the creation of a new number representation system in the human ontogeny (see Carey, 2001, 2004; Wiese, 2003a, 2003b, 2007; Noël, Grégoire, Meert, & Seron, 2008). With a semantic content based on the ordinal information included in the sequence of symbolic numbers (counting string), this new representation would represent the exact numerical value, unlike the ANS, which is an approximate representation of the number magnitude. Indeed, when the child has to understand the cardinal value of number words, he/she has to reach a precise representation. 'Seven' or '7' refers to the exact amount of seven, not six or eight.

Figure 1:



This distinction between an innate approximate numerical representation, on the one hand, and an exact representation of the number that would develop through symbolic numerical codes, on the other hand (see Figure 1), provides a new understanding of the performance profile observed in DD. Indeed, as shown in Table 1, the first difficulty observed in DD children concerns their ability to handle the magnitude representation of symbolic numbers. One might therefore consider that the basic deficit in DD children concerns the development of an accurate number representation elaborated through the learning of a symbolic number system. A difficulty in this respect is actually observed at any age and consistently across studies.

But why, later in development, do DD children show difficulty, compared to control children, in comparing collections? According to the developmental model of Carey (2009), numerical symbols lead the child to develop an accurate representation of the number, which then connects to the approximate numerical representation of the ANS. One might therefore assume that this connection leads to a refinement of the representations of the ANS, that is to say, to an increase in its acuity. One could also imagine that the handling of exact numerical representations in exact calculation also leads to a refinement of the ANS representations. In DD children who are struggling to develop an accurate representation of the number from the symbols and manipulate this representation in arithmetic, this refinement process may be delayed or less effective. Therefore, an initial difficulty in processing the magnitude of symbolic numbers could slow down the process of refining the acuity of the ANS. This would lead to subsequent and significant differences between DD and control children in tasks measuring the acuity of the ANS. This hypothesis seems plausible. Indeed, Piazza, Pica, Izard, Spelke, and Dehaene (2013) studied the Mundurucu people, whose language contains only a few words for numerical quantities and who do not develop oral or written counting systems. Currently, some of these people have access to school and learn the Portuguese number system. The authors observed that Mundurucus who had not gone to school have an ANS acuity equivalent to the one measured in Italian six-year-old children. However, those Mundurucu people who went to school and received a mathematical education showed a better number acuity than the others. Therefore, the acuity of the ANS increases both through natural age-related maturation (as seen in babies) as well as through education and in particular, via the learning of a symbolic number system and its use in numerical tasks such as counting and calculation.

In summary, the analysis of DD children's performance leads us to postulate the existence of a basic deficit in the construction of an accurate number representation. This difficulty would disrupt the process of refinement of the ANS and lead later on to immaturity in the development of these approximate representations, which would result in reduced numerical acuity.

Hypersensitivity to interference

Other authors were interested in the role of general cognitive factors in typical and atypical numerical development of the child. Many general cognitive factors have been considered. In the context of this article, we focus on the role that general cognitive factors can play in very specific numerical learning, namely, the acquisition of arithmetic facts. Indeed, this acquisition has been the subject of much research and is very often problematic for children with DD. Many DD children calculate answers instead of retrieving them from memory and when they try to recover them from memory, they often make mistakes (Geary, 2005). In connection with these observations, several hypotheses have been proposed.

First, it has been suggested that establishing, in long-term memory, an association between the terms of a calculation and its answer requires the co-activation in working memory of the representation of both the problem and the answer. This would be particularly difficult for people with dyscalculia for two reasons. First, when DD people solve a calculation, they often use immature counting strategies that are long and effortful so that the problem is no longer active in memory when they obtain the answer. Second, DD people could have reduced short-term memory capacity (Geary, 2005), which would not allow them to co-activate the problem and the answer together.

The second hypothesis proposed is that people with dyscalculia could have general difficulties in storing or retrieving information in long-term memory (Geary & Hoard, 2001; Geary, 2005).

Third, it has been argued that problem-response associations are often learned by rote in the form of verbal routines (Dehaene & Cohen, 1997) and accordingly, it has been hypothesised that people with dyscalculia could have a specific difficulty in storing or retrieving such verbal routines or processing phonological aspects of language (Wilson & Dehaene, 2007).

Fourth, people with dyscalculia might have inhibition difficulties and therefore may not manage the interference created by other arithmetic facts activated during the presentation of the problem.

An examination of each of these assumptions shows that low working memory capacity (central executive component, Noël, Seron, & Trovarelly, 2004; Swanson & Jerman, 2006) and low phonological awareness (De Smedt, Taylor, Archibald, & Ansari, 2009) may partly explain these learning difficulties. However, problems of information retrieval from long-term memory (Mussolin & Noël, 2008) or of inhibition (Censabella & Noël, 2008; van der Sluis, de Jong, & van der Leij, 2004) do not seem to be good candidates to explain difficulties in learning arithmetic facts.

A case study of a woman who has difficulty storing arithmetical facts in memory

Recently, De Visscher and Noël (2013) proposed a new hypothesis regarding severe difficulties in learning arithmetical facts. These authors did a comprehensive study of a person, DB, with a very high IQ and good mathematical reasoning but specific difficulties in building a network of arithmetic facts in memory. Since the primary grades, DB had found mental calculation problematic, particularly when learning the multiplication tables. A thorough cognitive assessment showed that DB performed well in tests measuring attention, executive function, and short- and long-term memory. However, in a global mathematics test, she performed abnormally slow (-5.56 standard deviation from the mean (SD)). This slowness was also seen in a task that involved solving single-digit additions (-3.13 SD) and even more strongly when she was asked to perform single-digit multiplications (-7.43 SD).

What prevented this intelligent and determined woman from creating a network of arithmetic facts in long-term memory? De Visscher and Noël (2013) first tested different assumptions found in the literature: a deficit in the number magnitude representation, a problem in accessing the magnitude of symbolic numbers, or a problem in encoding or retrieving verbal routines from long-term memory. The results of these investigations clearly showed that DB had no impairment of these processes. Thus, another explanation had to be found.

Research on the arithmetical facts network in the typical adult shows that the different elements of the network are strongly associated with each other. The presentation of a problem evokes the correct response associated with it but also activates other responses that are associated with one or other of the calculation terms (e.g. 6 x 4 and 18) or even answers associated with the terms of the calculation, but in another operation (for example, 5 + 3 and 15, Campbell & Timm, 2000). So this is a network with much interference (Campbell, 1995; Verguts & Fias, 2005). Barrouillet, Fayol and Lathulière (1997) proposed that people with dyscalculia have difficulty managing the interference created by other arithmetic facts activated during the presentation of the problem.

On this basis, one could easily imagine that sensitivity to interference would not only cause problems when retrieving the response from memory, but would also cause difficulties when learning these facts and constituting this network. Indeed, at the time of being stored in memory, features shared by different items cause interference and affect the storage (Oberauer & Kliegl, 2006). This interference is described as proactive (Jonides & Nee, 2006). Thus, when a child learns arithmetic facts, he/she has to store associations of items that share many features, in this case digits (e.g. in '6 x 4 = 24' and '7 x 4 = 28', the two problems share the digits 4 and 2), which introduces interference. Consequently, one can imagine that people with high sensitivity to interference would find it more difficult to encode arithmetic facts.

This sensitivity to interference was measured in DB with several paradigms. Two of them are described here. First, we evaluated DB's ability to memorise combinations of pairs of words: words that are very different from each other (associated pairs of Wechsler III) or close pairs of words (first names associated with family names). While DB had no difficulty with dissimilar words, her performance was clearly deficient for similar words. A second task required the storage of associations between a first name, a last name and a country, for example, 'Gilles Arlot lives in Benin'. The person had to store the country in which a given person was living. In some cases, the same first or last name was shared. For instance, the participant had to learn that 'Gilles Arlot lives in Benin' and also that another 'Gilles' lives in another country. In those cases, the level of interference was even higher. Again here, DB showed a hypersensitivity to interference with clearly impaired performance when she had to memorise associations that shared common traits.

In summary, this single-case analysis showed that a specific difficulty in learning arithmetical facts could be due to a difficulty in learning associations of items with several overlapping features, which induce interference.

A study on low-performing fourth-graders

This observation of an association of disorders in a single-case study is, however, not very strong proof of this hypothesis. Following the first study, De Visscher and Noël (2014a) conducted another study to test their hypothesis on a larger sample. One hundred children from 4th grade (9-10 years old), the grade at which children in school learn to memorise the multiplication tables, were tested collectively to examine their fluency in solving small addition and multiplication calculations. From the study cohort, two groups of 23 children were constituted: children with the lowest performance (low group) and control children with normal performance (typical group). These two groups were matched for age, gender, and school classroom. An individual computerised assessment of their multiplication capacities confirmed this distribution of children. Then, these two groups of children were subjected to a memory task in which the interference level was manipulated. In this task, three associations between a character and a location (in the form of pictures: for example, the picture of Asterix next to a mountain picture) were successively presented to the child, who had to memorise them. In the testing phase the pictures of characters and locations were presented to the child, who had to verify whether the associations corresponded to the ones he/she had just learned. The first block was followed by another block of the same type, which combined the same characters and places differently. Again, the successive presentation of the three character-location pairs was followed by a test phase. Then, other characters and other places were presented and the procedure was repeated five times.

The manipulation of the interference happened in the test phase (where half the items are true). In both the true and the false items, some items interfered a great deal while there was less interference with the others. For example, if in block 1, 'Asterix – Mountain' and 'Marsupilami – the store' were presented and in the test phase, 'Asterix – Mountain' was shown, then this was true and not interfering. However, if 'Marsupilami – the mountain' was shown, this pair did not match the original and was false and interfering since in the original showing this place and character were presented, but not together. Similarly, if in the next block, 'Asterix – the store' was presented and in the test phase, 'Asterix – Mountain' was shown, this item was false and interfering since it corresponded to a former association that interfered with the new learning.

Analyses of the results of this task show that the two groups of children are equally good at verifying the items with low interference. However, for the interfering items, a highly significant difference appears between the two groups, with higher performance for the typical group than for the low-arithmetical fact group.

These results suggest that children with a weak arithmetic fact network show greater sensitivity to memory interference than typically developing children. These results are in line with those of Passolunghi, Cornoldi, and De Liberto (1999), who showed that children with dyscalculia had difficulties in working memory tasks in which they had to inhibit the information that was no longer relevant.

Note, however, that this sensitivity to interference in memory does not correspond to an overall inhibition deficit, since these two groups of children did not differ in their degree of ability to resist a dominant response in the classical Stroop task (De Visscher & Noël, 2014b). Similarly, several studies have shown that DD children can inhibit a dominant response as in the Stroop paradigm as easily as most other children (Censabella & Noël, 2008, van der Sluis, de Jong, & van der Leij, 2004).

In summary, dyscalculia is a disorder that can take various forms and has multiple causes. We conclude that specific as well as general cognitive factors may account for dyscalculia. We have underlined one hypothesis related to specific basic number deficits: the hypothesis of a difficulty in building an accurate representation of a symbolic number's magnitude. Dyscalculia may also be due to a more general cognitive deficit. We have underlined the hypothesis that a very high sensitivity to interference could be related to difficulty in encoding arithmetic facts in long-term memory.

Ideas for the classroom

The question arises whether neuropsychological evidence and theoretical constructs can be used in classrooms. We end this article by presenting some principles and ideas that in our view ought to be further examined by educational professionals. We suggest that evaluation and rehabilitation of dyscalculia should take into account the heterogeneity of the possible forms and causes shown above. Teachers should also be informed of these specific learning disabilities and contact specialised professionals when they suspect this type of problem. Moreover, knowing the usual difficulties in the child's numerical development, teachers could add some games to their pallet of tools.

To enhance children's comprehension of the cardinal value of number words or Arabic digits, teachers could propose some specific exercises. Indeed, it is not sufficient to teach pre-schoolers the counting list or the counting procedure for enumerating sets of items; the emphasis should be on the cardinal value of the number words. For instance, the teacher could present a collection of items (e.g. seven apples) for a short time (e.g. two seconds) and ask the children to guess how many items there are. Then the children could count the collection and get feedback on their estimates. Conversely, they might be asked to grab seven tokens at once, and then count them to see how good their approximation was.

Also, using a number line and asking children to position numbers on that line reinforces the link between the exact representation of number symbols and the analogue representation of the spatial number line. Several intervention studies using spatial tools have resulted in significant improvements in DD children (e.g. Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). Another number line game developed by Ramani and Siegler (2008) has proved beneficial for kindergarten children. A number line made of 10 coloured squares is placed in front of the children with a number from 1 to 10 written on each of the squares. The game is a race in which children have to move a token from Square 1 to Square 10. The child uses a spinner to see how many steps (1 or 2) he/she is allowed to move. While moving his/her token, the child has to read the numbers out loud (e.g. a child on Square 3 who spins a 2 should say 'four, five' as he/she moves the token). For older children, other spatial games have been developed in which they have to estimate, on a number line, the approximate result of an arithmetical operation (Vilette, Mawart, & Rusinek, 2010; Kucian et al., 2011). All these exercises will help children make sense of symbolic numbers and arithmetical operations.

Much less is known about how to deal with the problem of high sensitivity to interference in learning arithmetic facts. However, acknowledging that this memorisation process may be especially difficult for some children with this particular memory problem is a good first step. Indeed, in these cases, it is useless to blame the child or ask him/her to copy multiplication tables an endless number of times. Rather, it might be more beneficial to allow him/her to have access to the Pythagorean table so that she/he can circumvent this impairment and have the possibility of tackling more complex problems.

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Dansk resumé

Specifikke såvel som generelle faktorer kan forårsage dyskalkuli

Denne artikel giver en oversigt over de forslag, der i tidens løb har været til, hvad der kan være årsag til dyskalkuli, DD. Første del omhandler faktorer, der relaterer til helt basal talopfattelse. Her konkluderer artiklens forfattere, at dyskalkuli kan stamme fra en vanskelighed med at opfatte størrelsesværdien af symboliserede tal, det være sig arabertal eller talnavne på modersmål og andre sprog. Den anden del omhandler generelle kognitive faktorer. Forfatterne præsenterer to nylige studier, som peger på, at hypersensitivitet over for interferens fører til vanskeligheder med at lagre aritmetiske fakta i hukommelsen. På basis af de behandlede teoretiske begreber skitseres afslutningsvis nogle idéer til, hvordan artiklens resultater kan anvendes til at forbedre matematikundervisningen. På basis af de

behandlede teoretiske begreber skitseres afslutningsvis nogle idéer til, hvordan artiklens resultater kan anvendes til at forbedre matematikundervisningen. Disse idéer anbefales til videre overvejelser og afprøvning.

Nøgleord: dyskalkuli, talstørrelse, symboliserede tal, aritmetik, aritmetiske fakta, interferens, hukommelse.

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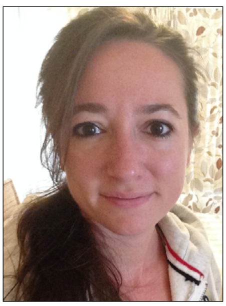

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