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Research report

A case study of arithmetic facts dyscalculia caused by a hypersensitivity-to-interference in memory

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ABSTRACT

While the heterogeneity of developmental dyscalculia is increasingly recognized, the different profiles have not yet been clearly established. Among the features underpinning types of developmental dyscalculia suggested in the literature, an impairment in arithmetic fact retrieval is particularly prominent. In this paper, we present a case study of an adult woman (DB) with very good cognitive capacities suffering from a specific and developmental arithmetic fact retrieval deficit. We test the main hypotheses about developmental dyscalculia derived from literature. We first explore the influential hypothesis of an approximate number system deficit, through estimation tasks, comparison tasks and a priming comparison task. Secondly, we evaluate whether DB's mathematical deficiencies are caused by a rote verbal memory deficit, using tasks involving completion of expressions, and reciting automatic series such as the alphabet and the months of the year. Alternatively, taking into account the extreme similarity of the arithmetic facts, we propose that a heightened sensitivity to interference could have prevented DB from memorizing the arithmetic facts. The pattern of DB's results on different tasks supports this hypothesis. Our findings identify a new etiology of a specific impairment of arithmetic facts storage, namely a hypersensitivity-to-interference.

1. Introduction

Developmental dyscalculia (DD) is a severe and persistent learning disability that concerns mathematical skills. According to the DSM IV (Diagnostic and Statistical Manual of Mental Disorders), the diagnostic criterion for mathematical disorder is a deficit in standardized tests assessing mathematical ability, which interferes with academic achievement or daily living, and which cannot be explained by a sensory deficit or by educational deprivation (American Psychiatric Association, 2000). Based on these criteria and depending on the study, the prevalence of children with mathematical disabilities is between 3 and 6% (Badian, 1983; Gross-Tsur et al., 1996; Kosc, 1974; Lewis et al., 1994). Two main characteristics of dyscalculia are generally agreed: a difficulty in learning and remembering arithmetic facts, and a difficulty in executing calculation procedures (Landerl et al., 2004).

There are two distinct perspectives on the etiology of DD. One is to regard DD as due to a specific impairment of the approximate number system (Piazza et al., 2010; Wilson and Dehaene, 2007). This approximate number system is conceptualized as a logarithmically-compressed mental number line

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which represents numerical quantities as Gaussian curves (Dehaene, 1992). Accordingly, large numbers/numerosities are represented less precisely than small ones. These characteristics lead to the distance effect (Moyer and Landauer, 1967) [the fact that it is easier to compare two numerically distant numbers (e.g., 1 and 9) than two close ones (e.g., 8 and 9)].

In line with this approach, Mussolin et al. (2010) have found a larger comparison distance effect (CDE) for both symbolic and non-symbolic numbers in DD children, compared to control children. Similarly, Piazza et al. (2010) have shown lower non-symbolic number acuity (i.e., lower precision of the number line) in DD children than in typically developing children. Using a priming paradigm in which two successive numbers have to be compared to the standard 5, Reynvoet et al. (2009) showed that response to the second number was faster if it was primed by a close number rather than by a distant number. Moreover a smaller priming distance effect (PDE) was associated with poorer math performance in children (Defever et al., 2011). Finally, using number estimation tasks, Mejias et al. (2012) observed that DD participants were less precise than controls in estimating the number of dots in a set by producing an Arabic number, in producing a set of dots to match a given Arabic number, and in producing the same number of identically-sized dots as seen in a previous collection of dots of various sizes.

However, other studies found that the performance of DD children was only impaired when they had to process the magnitude of symbolic numbers; sets of items were not affected (De Smedt and Gilmore, 2011; Iuculano et al., 2008; Rousselle and Noël, 2007). Accordingly, Rousselle and Noël proposed that the deficit lies in the link between symbolic numbers and their magnitude representation.

The other way of tackling the origin of DD is to focus on deficits in diverse general cognitive processing which potentially prevent the development of mathematical skills. Among these general cognitive processes, the capacity of the working memory has been the subject of several studies. For instance, McLean and Hitch (1999), Passolunghi and Siegel (2004) and Swanson and Jerman (2006, for a meta-analysis) have shown that the central executive component of the working memory in children with DD has a smaller capacity than that of typically developing children. Nevertheless, the findings for this second approach have also been controversial. For instance, Landerl et al. (2004) and Schuchardt et al. (2008) did not find any evidence for a deficit of the central executive function in their sample of DD children.

All these studies tested groups of DD children without taking into account the heterogeneity of their profiles. This could substantially influence the findings and could lead to inconsistent outcomes. Single case studies (Butterworth, 1999; Kaufmann, 2002; Ta'ir et al., 1997; Temple, 1992), group studies (Geary et al., 1999) and literature reviews (Rubinsten and Henik, 2009; von Aster and Shalev, 2007; Wilson and Dehaene, 2007) all indicate distinct profiles of mathematical disabilities. The frequent combination of dyscalculia with dyslexia or with attention deficit and hyperactivity disorder (ADHD), has led researchers to suspect multiple etiologies for this problem. Models of adult numerical cognition have also suggested that different neural networks could sustain different number processing that could be selectively impaired (see, for instance, Dehaene et al., 2003).

Despite this heterogeneity, difficulty in quickly retrieving arithmetical facts (over-learned single-digit problems) appears to be a general hallmark of DD. This has been noticed since the early 1970s (Slade and Russel, 1971), is consistently reported in the literature (Geary et al., 1999), and seems to be a persistent trouble (Jordan and Montani, 1997). Arithmetic facts refer to problems for which we retrieve the correct answer from memory. In adults, single-digit multiplications are known to be mainly retrieved from memory. Solving additions can involve both direct retrieval (mainly for sums up to ten) or counting-based procedural strategies (e.g., Roussel et al., 2002). Concerning subtraction, Thevenot et al. (2010) have shown that subjects highly skilled in arithmetic mainly retrieve the answer for subtractions with minuend up to 17, while lower-skilled subjects retrieve the answer only for problems with a minuend up to 10. Finally, for divisions, subjects usually use related multiplication facts while direct retrieval strategy is rare (Robinson et al., 2006).

While typical children show a transition from a procedural strategy to a memory-based resolution by developing arithmetic facts network, this does not seem to be the case for many DD children (Garnett and Fleischner, 1983; Geary et al., 1991; Jordan and Montani, 1997). Because DD children have to solve problems by computing the answer which is absent from their long-term memory, they are slower and produce more errors than typically developing children.

This paper consists of a case study of an individual with a very specific deficit of arithmetic facts, particularly multiplication facts. Focusing on this specific profile, we investigated the explanatory power of three main theories: (1) the possibility of a defective approximate number system, (2) the verbal memory deficit hypothesis and (3) the hypersensitivity-to-interference in memory hypothesis.

The hypothesis of a defective approximate number system has been described above and corresponds to the current dominant explanation for DD. The second hypothesis has been suggested by Wilson and Dehaene (2007). Among several profiles of DD, they proposed the existence of a verbal memory dyscalculia that is characterized by a selective impairment of arithmetic facts (especially multiplication facts) and a possible difficulty in learning the counting sequence. This proposition was based on the hypothesis that multiplication facts are learned as rote verbal memory. This was supported by the fact that brain-damaged patients with selective multiplication impairment, also suffered from larger deficits in rote verbal memory, as witnessed by their difficulties in reciting verbal sequences such as the alphabet or the months of the year (Dehaene and Cohen, 1997, patient BOO). Some patients have a reading deficit (Cohen and Dehaene, 2000) or a language impairment (Lemer et al., 2003, patient BRI) in addition to the selective multiplication impairment. In normal populations, performance in multiplication correlates with other language skills, in particular, phonological awareness. This is true for adult students (De Smedt and Boets, 2010) as well as for children in Grades 4 and 5 (De Smedt et al., 2009). Accordingly, a selective impairment in multiplication might result from a rote verbal memory deficit (which would be evident in difficulties in reciting verbal sequences, or other well-learned verbal expressions), or from a larger language-based problem (which would potentially result in weaknesses in language production, reading or phonological awareness). As our patient DB was suffering from a severe deficit in multiplication, this possible cause was tested.

The third hypothesis considered here is hypersensitivity-to-interference in memory. Memory is known to be associative and to be less efficient when having to store intertwined similar information (e.g., Hall, 1971). Proactive interference leads to difficulties in fixing new associations because of previously encoded related information (see Jonides and Nee, 2006 for a review). When the child has to learn arithmetical facts, (s)he is in a situation where there is considerable overlap between previously encoded items and new ones. Dehaene (1997) made an analogy between this situation and that of memorizing an address book with “Charles David works in Albert-Bertrand Street; Charles Guillaume works in Bertrand-Albert Street; Guillaume Etienne works in Charles-Etienne Street, etc.” The similarity between arithmetic facts and its consequent interference have been described and studied in a retrieval situation with typically developing adults who have successfully built an arithmetical fact network. For instance, connectionist models (Campbell, 1995; Verguts and Fias, 2005) have highlighted the existence of interference caused by a densely interconnected memory structure composed of associations among numerical problems, operands and answers. According to some recent models of working memory, interference can also play a major role during encoding and storage stages. In the representation-based interference model, Saito and Miyake (2004) assume that the amount of representational overlap (between the items to be memorized and those to be processed) determines the recall performance in a complex span test. Similarly, in Farrel and Lewandowsky’s (2002) Serial Order in a Box model, the central concept is that, in a short-term serial recall task, the novelty of an incoming item determines its encoding weight. If the item is similar to items which have already been encoded, its encoding weight will be less than if it is more novel. In other words, interference means that features shared by items in working memory are overwritten, resulting in less activation of the representation of every item (Oberauer and Kliegl, 2006), which reduces the probability of recalling the items. The similarity of associations provokes interference and disrupts recollection. Yet recollection is known to be crucial in learning associations (Yonelinas, 2002).

Based on these considerations, and given that learning multiplication facts is a serial memory task, and that problem–response associations share several features, we propose that hypersensitivity-to-interference might hamper this storage. Accordingly, we developed tasks to assess such sensitivity in DB.

In summary, this paper aims to study one particular profile of DD, characterized by a selective deficit in arithmetical facts. After a global assessment of our patient’s general cognitive capacities and her math abilities, we will first address the hypothesis of an approximate number system deficit. Secondly, we will test the rote verbal memory hypothesis (Dehaene, 1992). Finally, our hypothesis of hypersensitivity-to-interference will be explored.

2. Case report

Our patient DB is a woman, employed part-time in business management and born in 1967 [she was 42–43 years old during the investigation (November 2009 to March 2011)]. DB is French–Dutch bilingual and has smatterings of several other languages. She spoke French at home. She started school in French and switched to a Dutch school in Grade 4 up to the end of the secondary school. In 1995, she was diagnosed with dyscalculia and high potential. Since primary school, she faces huge problems in learning multiplications, and mental calculation is hard for her. She compensates by finger counting and using a calculator. Visuo-spatial processing and perceptual approximates are said not to be problematic.

This study started with a general cognitive assessment and a thorough mathematical investigation. Subsequently, DB’s competence with arithmetical facts was explored in depth and this led us to test all three main hypotheses: the approximate number system hypothesis, the rote verbal memory hypothesis and the hypersensitivity-to-interference hypothesis.

Most of the neuropsychological tests come from published standardized test batteries but some paradigms have been reproduced from published sources. In these cases, DB’s performance was compared to that of 11 control participants, matched for gender, educational level and age [mean age: 43.37, standard deviation (SD): 2.76, Control group A]. This control group was also used for some of the experimental work. Throughout the time of the research, we tested two other control groups for the experimental investigation. Control group B met the same criteria ($N = 9$, mean age: 44.63, SD: 3.96) and Control group C were also matched on the additional criterion of being Dutch–French bilingual ($N = 11$, mean age: 45.06, SD: 3.92). The control group used is specified for each task.

The computer experiments were programmed using E-prime software 1.1 (Schneider et al., 2002) and displayed on a 1280 × 1024 resolution screen with a computer running the Windows XP operating system. Participants were positioned about 60 cm from the screen. The tasks required either a motor response (pressing keys on the keyboard) or a verbal answer (speaking into the microphone, known as the voice key).

For every test, the percentage of correct responses (PCR) and the median of the reaction times (RTs) for the correct trials were calculated. The intervals shown in the graphs are the standard errors of the means of the control group. To test for the presence of a deficit, Crawford and Howell’s (1998) modified *t*-test was used to compare DB’s performance to the control group’s performance. Specially developed for case studies, this technique allows us to determine whether a single patient is significantly impaired compared to a small control group. Crawford and Garthwaite’s (2005) residual standardized difference test (RSDT) permits us to test the significance of the dissociation between two tasks. For intra-group statistical analyses, we used paired sample *t*-tests, repeated measures analysis of variance (ANOVA) (if necessary, we made the Bonferroni adjustment) and linear regressions. When Mauchly’s test of sphericity was significant for one factor, the greenhouse-Geisser correction was used for this factor.

3. General cognitive assessment

3.1. General neuropsychological assessment

DB underwent a general neuropsychological assessment in November and December 2009. The results (summarized in Table 1) indicate that DB had normal or above normal abilities in all cognitive domains: full-scale IQ, attention processing, executive functioning, memory capacities, reading, motor speed, and finger gnosia. The only difficulty we identified was her poor performance on the Brown–Peterson paradigm (Brown, 1958; Peterson and Peterson, 1959). In this task, participants are asked to recall three letters either immediately, or after a delay of 5, 10 or 15 sec during which pairs of numbers have to be reversed (full delays), or after a 15-sec delay with no secondary tasks (empty delay). In the short full delay (5 sec), DB performed below average because she actually recalled letters presented in the previous trial. With longer delays, she made the same type of errors, but as the performance of the control group decreased, her standardized score fell in the normal range.

3.2. General mathematical assessment

Table 2 summarizes DB's performances in the first test of her mathematical capacities (undertaken in November and December 2009), including general and more specific mathematical tests. The raw scores of all the tests are given in Table 2, and are compared to those of Control group A.

The global arithmetical test, initially created by Shalev et al. (2001) and slightly modified by Rubinsten and Henik (2005), is composed of number facts and complex calculations using the four operations, on integers, decimals and fractions. DB showed normal accuracy on this test [$t(10) = 1.053$, $p = .159$], but was significantly slower (total time taken to complete the whole test) than the controls [$t(10) = 5.328$, $p < .001$]. However she scored in the normal range ($+.33\sigma$) on the arithmetic subtest of the Wechsler Adult Intelligence Scale - third edition (WAIS-III).

In the dyscalculia screener software (Butterworth, 2003), DB also performed well (in terms of both speed and accuracy) on the dot enumeration and numerical Stroop test parts. She was accurate in the verification of multiplication [$t(10) = -.672$, $p = .258$] and addition [$t(10) = .290$, $p = .389$] but was abnormally slow in both tasks [respectively, $t(10) = 5.110$, $p < .001$ and $t(10) = 1.809$, $p = .05$].

This deficit in arithmetic problems was confirmed by the Tempo-Test-Rekenen (de Vos, 1992), in which subjects are required to complete, for each operation separately, as many calculations as possible in 1 min. This test starts with simple single-digit problems and ends with more complex multi-digit problems. In 60 sec, she produced significantly fewer responses than the controls in subtraction [$t(10) = -3.066$, $p < .01$], multiplication [$t(10) = -3.038$, $p < .01$] and division [$t(10) = -2.185$, $p < .05$], and her score on additions was also below the average for the control group [$t(10) = -1.482$, $p = .084$], although not significantly so.

On the Université Catholique de Louvain (UCL) calculation battery (Seron et al., 2001; control group of ten adults between the ages of 40 and 59 who had had some college education), DB displayed normal conceptual knowledge of arithmetic. This subtest comprises verification of principles (e.g., $a + b = b + a$) on algebraic equations [6 items; $t(9) = .454$, $p = .330$] and on calculations [6 items; $t(9) = 0$, $p = .5$]. However, she showed poor encyclopedic numerical knowledge [$t(9) = -3.516$, $p < .01$]. This subtest is composed of four items on autobiographical numerical information (e.g., How much do you weight?) and eight items on encyclopedic numerical knowledge (as historical dates, e.g., In which year did the French Revolution take place?), 12 questions are verbally asked and 12 others are written questions. DB was weak on historical dates (e.g., she did not know the year in which World War I started), but knew autobiographical numerical information.

In summary, DB is a case of pure impairment of arithmetic facts, with good conceptual knowledge. She also has difficulty memorizing numbers linked to events. Her general cognitive functioning (intelligence, attention and memory) is very good, with the exception of a difficulty with a central executive task due to interference errors. This provides us with a rare opportunity to explore the nature of a pure arithmetic facts deficit.

4. Experimental study

The first step in our experimental study was to characterize DB's deficit in arithmetical facts. After identifying her difficulty, we tested the stability of her production by using the multiplication production task twice. Secondly, we imposed an automatic response by limiting the response time. Finally, to determine whether DB had a complete network of arithmetic facts but trouble in accessing them, or whether the facts were not actually storied in her memory, she was submitted to a table membership judgment task, and to a verification-multiplication task with lures (operand-related or not).

4.1. Characterization of the arithmetical facts impairment

DB's performance was first established with a production task using single-digit operations. When asked her preferred language for arithmetic tasks, our bilingual subject designated her dominant language, namely French. We nevertheless ran some arithmetic trials on both languages, and when questioned once on her preferred language, she picked French again.

4.1.1. Production tasks with the four arithmetical operations

4.1.1.1. Material and procedure. DB was initially given a production task using the four operations. Items were displayed in Arabic format until a response was produced orally (voice key). In the addition task, all 54 possible combinations of numbers between 0 and 9 except $0 + 0$ were used; the larger operand was always presented first. The multiplication task consisted of the 36 combinations of 2–9, with the smaller

Table 1 – Patient DB's general neuropsychological assessment.

Functions/Tests		DB's score		DB's percentile (P) or z-score
General				
WAIS-III (Wechsler, 2000)	Verbal IQ	115		1.00σ
	Performance IQ	131		2.07σ
	Full-scale IQ	124		1.60σ
Attention				
Selective visual attention				
d2 (Brickenkamp, 1998)				
	Speed (GZ)	609		P100
	Quality (F)	18 (2.9%)		P75
Divided attention	Mean RT	692 msec		P[18–21]
TEA (Zimmermann and Fimm, 1994)	Missing	1		>P18
Sustained attention				
ZAZZO 10', 1974				
	Speed	145 sec		[0–1σ]
	Quality	4.52%		[0–1σ]
Executive functioning				
Cognitive inhibition				
Stroop test (Godefroy and GREFEX, 2008)				
	Naming	0 err, 40 sec		P[5–100], P50
	Reading	1 err, 50 sec		P[10–100], P75
	Interference	2 err, 68 sec		P10, P[90–95]
Behavioral inhibition	Mean RT	362 msec		P76
Go No Go – TEA (Zimmermann and Fimm, 1994)	Missing	0		>P79
Planning				
Tower of London (Lussier et al., 1998)				
	Number of trials	16		P75
	Successful first trials	10		>P90
	Mean planning time	2.3 sec		>P95
	Mean execution time	4.7 sec		0σ
Cognitive flexibility	Mean RT	438 msec		P100
TEA (Zimmermann and Fimm, 1994)	Errors	4		P[34–38]
Memory				
Working memory (WM)				
Central executive				
	Backward digit span (*WAIS-IV*, Wechsler, 2011)	13/14		1.67σ
	Brown–Peterson paradigm ($N = 23$) (Brown, 1958; Peterson and Peterson, 1959)	Correct sequences	Total no of letters correctly recalled	
	0 sec	5	15	.19σ|.19σ
	15 sec empty	5	15	.33σ|.31
	5 sec full	2*	9**	−2.56σ|−3.24σ
	10 sec full	3	11	−.98σ|−1.37σ
	15 sec full	3	11	−.30σ|−.39σ
Verbal short-term memory				
	Forward digit span (*WAIS-IV*, Wechsler, 2011)	25/30		2σ
Visual short-term memory				
	Spatial span ($N = 23$) (*Corsi Bloc tapping test*, Corsi, 1972)	6		.26σ

Table 1 – (continued)

Functions/Tests		DB's score	DB's percentile (P) or z-score
Verbal episodic memory			
California Verbal Learning Test (CVLT, Poitrenaud et al., 2007)			
	List A – Total {1–5}	68	.6σ
	List B	10	1.2σ
	Short delay free recall (5-min) – List A	15	.5σ
	Short delay cued recall – List A	15	.3σ
	Long delay free recall (20-min) – List A	14	.05σ
	Recognition	16/16	.4σ
	False recognition	1	−1σ
WMS-III (*MEM III*, Wechsler, 2001) – *Story recall*			
	Story A and B recall	26/50	0σ
	Total recall	46	.33σ
	Learning curve	5	0σ
	Delayed recall	25	−.33σ
	Recognition	26/30	
Visual episodic memory			
WMS-III (*MEM III*, Wechsler, 2001) – *Facial subtest*			
	Short delay recall	35/48	−.67σ
	Long delay recall	40/48	.67σ
Doors test (Baddeley et al., 1994)		23/24	P90
Visuo-constructive processing			
Rey Complex Figure (*copy*, Rey, 1959)		36/36	P100
Reading (words)			
Phonolec (Oudry et al., 2008)			
	Number of correct words	116/120	−.24σ
	Speed	85 sec	−.17σ
Motor speed			
Dyscalculia screener			
	Right hand	305 msec	−1.38σ
	Left hand	262 msec	.45σ
Finger gnosia			
Galifret-Granjon's Battery (1958)			
	Isolated touching (right and left hands) ($N = 10$)	20/20	.47σ
	Successive touches (right and left hands) ($N = 10$)	40/40	.52σ
	Simultaneous touches (right and left hands) ($N = 10$)	40/40	.91σ
	In between test (Group A)		
	Right hand	28/30	.80σ
	Left hand	29/30	.05σ
	Motor imitation (right and left hands) (Group A)	20/20	0σ

* Indicates impaired scores with $^*p < .05$, $^{**}p < .01$.
NB: Except for the standardized tests, DB is compared either to the Control group A or to a non-specific sample whose size is indicated (N=).

operand presented first, plus eight rule problems ($n \times 0$, $n \times 1$). The subtractions were the 54 possible combinations of numbers between 0 and 9 (excluding 0 − 0). And finally, the divisions included all 64 possible combinations and 12 rule problems (0/n, n/1, n/n).

4.1.1.2. Results. Disregarding rule problems, DB's accuracy was similar to that of the Control group A for all the four operations [addition: DB: 97.78%, controls: 97.57 ± 1.65%, $t(10) = .123$, $p = .452$; multiplication: DB: 94.44%, controls: 97.47 ± 2.14%, $t(10) = -1.359$, $p = .102$; subtraction: DB: 98.61%, controls: 98.36 ± 1.62%, $t(10) = .149$, $p = .442$; division: DB: 86.72%, controls: 95.14 ± 5.79%, $t(10) = -1.393$, $p = .097$]. However, she was significantly slower than controls in multiplication [DB: 2317 msec, controls: 998 ± 177 msec, $t(10) = 7.114$, $p < .001$] and in addition [DB: 1164 msec, controls: 794 ± 118 msec, $t(10) = 3.000$, $p < .01$], but not in subtraction [DB: 936 msec, controls: 851 ± 183 msec, $t(10) = .441$, $p = .334$] and division [DB: 1642 msec, controls: 1209 ± 318 msec, $t(10) = 1.304$, $p = .111$] (Fig. 1).

Table 2 – Patient DB's mathematical assessment.

Tests	N	DB's raw scores		Control subjects mean (SD)		Modified t-test	
		Accuracy	RT (msec)	Accuracy	RT (msec)	Accuracy	RT
General battery (Rubinsten and Henik, 2005)							
	80	78	2157 sec	72.09 (5.38)	825 (239) sec	1.053	5.328***
Problems							
Arithmetic (WAIS-III, Wechsler, 2000)	–	16	–	–	–	NS = 11	
Basic tasks – Dyscalculia Screener (Butterworth, 2003)							
Dot enumeration	68	67	1467	65.64 (1.29)	1279 (276)	1.015	.651
Numerical Stroop	42	42	770	41.45 (.69)	632 (89)	.759	1.477
Arithmetic facts							
Dyscalculia Screener (Butterworth, 2003)							
Verif. of additions	28	27	1681	26.73 (.90)	1255 (226)	.290	1.809*
Verif. of multiplications	40	38	2654	38.82 (1.17)	1179 (276)	−.672	5.110***
Tempo-Test-Rekenen (de Vos, 1992)							
Additions	–	32	–	36.27 (2.76)	–	−1.482	–
Subtractions	–	22	–	32.73 (3.35)	–	−3.066**	–
Multiplications	–	17	–	34.73 (5.59)	–	−3.038**	–
Divisions	–	16	–	31.00 (6.57)	–	−2.185*	–
Conceptual knowledge of mathematics (UCL calculation battery, Seron et al., 2001)							
Verification of principles	6	6	–	5.8 (.42)	–	.454	–
Verification of operations	6	6	–	6 (0)	–	0	–
Encyclopaedic numerical knowledge (UCL calculation battery, Seron et al., 2001)							
	24	17	–	22.7 (1.55)	–	−3.516**	–

*$p < .05$, **$p < .01$, ***$p < .001$.

DB shows an arithmetic facts impairment, particularly obvious in multiplication and in a lesser extent in addition. Her good performance in subtraction likely comes from the very simple problems used in the production task (single-digit problems). Among the 44 items, 23 were problems involving 0 or 1 as subtrahend or as difference. For the other problems, she looked her fingers to "behold" the answer. Contrariwise she performed badly in the Tempo-Test-Rekenen, in which two-digit problems are presented after the first 15 single-digit problems.

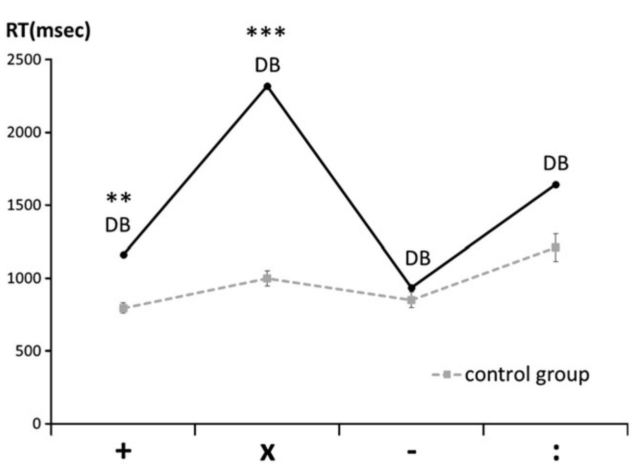

Fig. 1 – The RTs of DB and Control group A on the arithmetical production task for the four operations. N.B. The bars represent the control group's standard errors.

We decided to focus on multiplication problems because they are known to mainly involve the retrieval strategy, which is less used in other operations (Roussel et al., 2002). Moreover, in multiplication the compensatory strategies often result in longer RT, while it is not always the case for other single-digit operations. In order to evaluate the stability of her deficit a second, longer version of the multiplication production task was then administered at two different times.

4.1.2. *Multiplication task: stability of performance*

4.1.2.1. Material and procedure. To test the stability of DB's performance she undertook an additional multiplication production task twice 5 months apart (October 2010 and March 2011), with the digits presented in both possible positions (i.e., larger first and smaller first). This task consisted of 16 rule problems (four $\times$ 0, four $\times$ 1, and their reverse problems), the 28 problems with operands between 2 and 9 and their 28 reverse problems, and eight tie problems. These 80 problems were displayed in a pseudo-random order, such that two successive problems never had the same operand or answer, and identical problems in the opposite order were separated by at least six other problems. The screen was black with a white window in the middle, where the problem appeared when the experimenter pressed a key. The problem remained visible until the participant gave the answer orally. After the test, we asked her to explain her strategies on different types of items, such as the $\times$ 9 problems, the $\times$ 5 problems, the most complex problems (7×8, 7×6 or 6×8), or the tie problems.

Table 3 – RT for DB and for Control group C in the multiplication production task according to the type of problem (March 2011).

Type of problems	DB	Control group ($N = 11$)		Modified *t*-test
	RT (msec)	Mean (RT, msec)	SD	
Rules	944	828	103.91	1.069
Ties	1438.5	930.95	127.77	3.803**
Large	2368	1251.41	249.53	4.284***
Medium	2566	1064.95	251.68	5.710***
Small	1245.5	885.77	147.12	2.341*
Spearman's rho between problem size and RT	.568	.567	.095	.008

*$p < .05$, **$p < .01$, ***$p < .001$.

4.1.2.2. Results. DB's average accuracy and RT for all the problems except those concerning rules were significantly below the average of the control group both in October 2010 (Control group B) [accuracy: DB: 95.31%, controls: 98.60 ± 1.29%, $t(8) = -2.411$, $p < .05$; RT: DB: 1766 msec, controls: 985 ± 204 msec, $t(8) = 3.634$, $p < .01$] and in March 2011 (Control group C) [accuracy: DB: 85.16%, controls: 95.53 ± 3.99%, $t(10) = -2.491$, $p < .05$; RT: DB: 1774 msec, controls: 1022 ± 155 msec, $t(10) = 4.630$, $p < .001$]. There was a significant Pearson correlation between DB's RTs for the 67 items she completed successfully in both sessions [$r(65) = .612$, $p < .001$]. The position of the larger and smaller operands had no significant effect on her RTs in either session [Oct 2010, paired sample *t*-test: $t(23) = -.128$, $p = .899$; March 2011: $t(20) = -.286$, $p = .778$].

DB made a total of 13 errors in the two sessions: four of these were operand-related errors (e.g., $5 \times 4 = 24$), three were table errors (e.g., $3 \times 9 = 28$), three were non-table errors (e.g., $7 \times 6 = 44$) and three were non-responses. To get her answers, DB reported using computational strategies: for the problems with the operand 9, she worked out $(n \times 10) - (1 \times n)$. For the operand 5, she calculated $(n \times 10)/2$ or she visualized blocks of 5 and added them (e.g., for 3×5 she added three blocks of 5). Every problem was decomposed into smaller calculations [e.g., 6×4 became $(2 \times 6) \times 2$; 6×8 became $60-(2 \times 8)$ and 2×8 is $8 + 8$ so $8 + 2 + 6$]. She reported that she hardly ever retrieves answers (except for very small problems).

A problem-size effect was calculated on the last multiplication session (March 2011) by computing the Spearman's rho correlation coefficient between the response time and the sum of the operands. This was significant for DB [$\rho(54) = .568$, $p < .001$] and was similar to that of the control group[1] [mean $\rho = .567 \pm .095$, $t(10) = .008$, $p = .497$]. Although DB's problem-size effect was similar to that of the controls, she was significantly slower than them for all types of problems[2] except the rules (Table 3). The fact that she was slower than controls on tie and small problems, which are known to be predominantly retrieved from memory by adults (Graham and Campbell, 1992), is in agreement with her report that she needs procedural strategies while controls use retrieval strategies.

To summarize, DB is much slower than the control participants in completing the multiplications, and she calculates the products rather than retrieving them from her memory. This could indicate that she has a very poor arithmetical fact store. Alternatively, she might have a high confidence criterion (Siegler, 1988) and thus calculates all the answers even when she has retrieved the product from her memory. To test this possibility, a time-limited production task, which forced DB to retrieve the answer from her memory, was undertaken.

4.1.3. *Time-limited production of multiplications*

4.1.3.1. Material and procedure. The time-limited production task was based on that developed by Censabella (2007). Sixteen problems (eight small: 2×3, 2×4, 5×2, 4×3, 5×3, 4×5, 3×3 and 4×4; and eight large: 6×7, 8×6, 9×6, 7×8, 7×9, 9×8, 7×7 and 8×8) were displayed in eight successive blocks. Each block contained all the problems in a pseudo-random order, alternating small and large problems. Half of the problems started with the larger operand, and the other half with the small one. The problems appeared in a box in the middle of the screen for 1500 msec, during which time the participants had to produce a response aloud into the microphone (voice key). They were instructed to give the answer as quickly as possible without computing it.

4.1.3.2. Results. Globally, DB was significantly less accurate and slower than the Control group C overall [accuracy: DB: 48.43%, controls: 87.04 ± 10.26%, $t(10) = -3.601$, $p < .01$; response times: DB: 1036 msec, controls: 798 ± 107 msec, $t(10) = 2.136$, $p < .05$]. More precisely, for the small problems, she was less accurate than the control group on four problems [5×2: $t(10) = -2.887$, $p < .01$; 4×3: $t(10) = -15.588$, $p < .001$; 4×5: $t(10) = -6.062$, $p < .001$; 4×4: $t(10) = -3.105$, $p < .01$] and slower than the controls on all but three of the problems (see Table 4). She was actually both as accurate and fast than the controls on two out of height problems (2×3 and 3×3). For the large problems, DB gave no correct responses (0% of correct response) except for 8×8 (which she answered correctly seven of the eight times it appeared). She simply did not respond to most of the problems, but she also made eight table errors (e.g., $7 \times 7 = 48$, or 64, or 45 on the different occasions it appeared), and four operand-related errors (e.g., $4 \times 3 = 15$).

[1] The correlation of Spearman was significant for ten of the eleven control subjects.

[2] Problems are distributed as follows: large = the two operands are above or equal to 5; medium = one operand is below 5, the other is above 5; small = the two operands are below or equal to 5, with the 5×5.

Table 4 – PCR and RTs for DB and Control group C for each problem in the time-limited production of multiplications task.

Problem ($N = 8$)	DB		Control group ($N = 11$)		Modified *t*-test	
	PCR	RT (msec)	PCR (SD)	Mean (SD) of RT (msec)	PCR	RT
2 × 3=	100	875	98.86 (3.77)	774 (102)	.289	.944
2 × 4=	100	1014.5	97.73 (7.54)	724 (103)	.289	2.694*
3 × 3=	100	914.5	96.59 (9.42)	768 (136)	.346	1.036
5 × 2=	87.5	904	98.86 (3.77)	725 (130)	−2.887**	1.320
4 × 3=	37.5	–	98.86 (3.77)	776 (94)	−15.588***	–
5 × 3=	100	1241.5	100.00 (.00)	769 (138)	0	3.289**
4 × 4=	75	1182	95.45 (6.31)	785 (125)	−3.105**	3.046**
4 × 5=	87.5	1120	99.43 (1.88)	754 (107)	−6.062***	3.267**
6 × 7=	0	–	85.23 (23.60)	863 (159)	−3.458**	–
8 × 6=	0	–	85.23 (27.43)	862 (167)	−2.975**	–
7 × 7=	0	–	98.86 (3.77)	794 (121)	−25.115***	–
9 × 6=	0	–	48.86 (32.33)	895 (222)	−1.446	–
7 × 8=	0	–	64.77 (32.63)	955 (205)	−1.901*	–
7 × 9=	0	–	74.43 (28.84)	996 (206)	−2.471*	–
8 × 8=	87.5	1209	90.34 (17.54)	912 (231)	−.155	1.229
9 × 8=	0	–	59.09 (36.59)	912 (168)	−1.546	–

*$p < .05$, **$p < .01$, ***$p < .001$.

These results suggest that DB only has the arithmetic facts relating to very small problems (such as 2 × 2 or 2 × 3) in her memory, although she claims to have made great efforts to learn her tables.

Two other tasks were used to explore the possibility of a storage deficit: a table membership judgment and a multiplication verification task.

4.1.4. *Table membership judgment task*

4.1.4.1. Material and procedure. In the table membership judgment task the participants had to decide whether the number displayed was a possible result for a multiplication of two single-digits, by pressing a left-hand key (yes) or a right-hand key (no) on the keyboard[3]. This task was similar to that used by Cohen and Dehaene (1994), except that we restricted the number of items to 23 within-table and 23 outside-table problems. We removed {10, 20, 30, 40} from the possible results, because they can be accepted using the wrong criterion (product of 10). We matched the 23 outside- and 23 within-table numbers on parity (14 even, 9 odd) and size (mean of within-tables: 38 ± 20 and mean of outside-tables: 42 ± 21). These numbers were displayed in a pseudo-random order, with no more than three same responses (yes or no) in a row. Two blocks of these 46 items were presented to the participants.

4.1.4.2. Results. DB performed significantly worse than the Control group C on accuracy [DB: 66.30%, controls: 95.36 ± 4.48%, $t(10) = -6.203$, $p < .001$], although her RT was similar to theirs [DB: 939 msec, controls: 933 ± 213 msec, $t(10) = .024$, $p = .491$]. More precisely, she performed badly with the odd within-table numbers and with the even outside-table numbers (Table 5). She accepted all even numbers as table facts, and dismissed too many odd numbers as non-table. DB also took significantly longer than the controls to decide about odd numbers. The odd–even profile of DB was not at all typical of the control group. This task showed that she used the strategy of looking at the parity to help her, but it was certainly not infallible.

4.1.5. *Multiplication verification task*

4.1.5.1. Material and procedure. We created a multiplication verification task to test two effects: the true/false effect and the operand-related effect. The true/false effect occurs when it is easier to accept a correct answer then to dismiss a false one. With the operand-related effect it is easier to reject a non-table than an operand-related lure. Given that Verguts and Fias (2005) have shown that the consistency of the neighbors of the answer has an effect (i.e., when a neighbor shares the same decade it is in competition with the correct answer) we controlled for consistency. We therefore used six consistent lures, i.e., sharing the same decade with the correct response, and six inconsistent lures, for both types of error response (operand-related and non-table lures).

The task consisted of twelve problems associated with either twelve operand-related lures, twelve non-table lures or twelve correct responses (twice for the latter, so that the number of correct and incorrect stimuli was the same). The distance between the false and the true response in the operand-related and non-table lure conditions was similar (the sum of the absolute distances was 56 and 58 respectively). The parity of the lures was also controlled across the two lure conditions: either they were the same parity, or the two items were counterbalanced according to the parity of the correct response (e.g., 3 × 8 and 3 × 9, see Appendix A).

4.1.5.2. Results. Overall, DB's accuracy was similar to that of Control group B in detecting the operand-related lures [DB: 91.67%, controls: 92.59 ± 6.51%, $t(8) = -.135$, $p = .448$] and authenticating the correct answers [DB: 95.83%, controls:

[3] In order to decrease the working-memory load, a green "yes" (on the left side of the screen) and a red "no" (on the right) remained visible throughout the experiment.

Table 5 – PCR and RTs for DB and Control group C on the table membership judgment task, for both conditions (within and outside-tables) according to the parity of the numbers.

	DB		Control group (N = 11)		Modified t-test	
	PCR	RT (msec)	PCR (SD)	Mean (SD) of RT (msec)	PCR	RT
Within-tables						
Even	100	636	97.40 (3.60)	824 (122)	.690	−1.477
Odd	83.33	1172	95.45 (6.95)	865 (180)	−1.671(*)	1.631(*)
Outside-tables						
Even	0	–	90.26 (14.82)	1443 (658)	−5.831***	–
Odd	100	1568	100.00 (.00)	903 (240)	0	2.651*

(*)p .06 or .07, *$p < .05$, ***$p < .001$.

95.37 ± 3.26%, $t(8) = .135$, $p = .448$]. However, DB performed significantly worse than the control subjects on detecting the non-table lures [DB: 91.67%, controls: 99.07 ± 2.78%, $t(8) = -2.530$, $p < .05$]. She was also significantly slower in every condition [operand-related lures: DB: 3389 msec, controls: 1524 ± 278 msec, $t(8) = 6.356$, $p < .001$; non-table lures: DB: 4601 msec, controls: 1415 ± 304 msec, $t(8) = 9.954$, $p < .001$; correct: DB: 3054 msec, controls: 1303 ± 214 msec, $t(8) = 7.744$, $p < .001$], with large variances in each condition.

The true/false effect was calculated with both types of lures, by subtracting the accuracy on the lure (operand-related *or* non-table) from the accuracy on the correct answer. While the control subjects performed better at rejecting the non-table lures than accepting the correct answer, DB showed the reverse effect [DB: 4.17%, controls: −3.70 ± 4.39%, range: −8.33–0, $t(8) = 1.700$, $p = .06$]. There was a similar true/false effect on the operand-related lures [DB: 4.17%, controls: 2.78 ± 8.33%, $t(8) = .158$, $p = .439$]. The true/false effect was also calculated on RT, by subtracting the RT on the lure (operand-related *or* non-table) from the RT on the correct answer, and dividing this difference by the sum of these two RTs. DB's response times were more affected than those of the control subjects by non-table lures [DB: −.20 msec, controls: −.04 ± .05 msec, $t(8) = -2.848$, $p < .01$]. Finally, DB and the control groups displayed similar true/false effects with the operand-related lures [DB: −.05 msec, controls: −.08 ± .07 msec, $t(8) = .334$, $p = .373$].

The operand-related effect on accuracy (as measured by the difference between the accuracy on non-table and operand-related lures) was not different for DB and for the controls [DB: 0%, controls: 6.48 ± 6.94%, $t(8) = -.885$, $p = .201$]. However with RTs (measured by subtracting the RT on non-table lures from the RT on operand-related lures, and dividing this difference by the sum of these two RT) the operand-related effect was smaller with DB than with the controls [DB: −.15%, controls: .04 ± .05%, $t(8) = -3.319$, $p < .01$].

To summarize, DB has a strong and stable deficit in simple multiplication. She cannot correctly retrieve an answer without computing it, or evaluate whether a number is part of the multiplication table, and her operand-related and true/false effects in a verification task are different from those of the control group. These results support the hypothesis that her arithmetic facts network is almost non-existent, which means that she has apparently never stored these facts in her memory.

DB's very specific deficit allows us to explore the origins of this trouble. Three hypotheses proposed in the literature were tested: (1) the approximate number system deficit hypothesis, (2) the rote verbal memory deficit hypothesis, and (3) the hypersensitivity-to-interference hypothesis.

4.2. *Origin of DB's arithmetical facts impairment*

4.2.1. *Approximate number system deficit*

Some researchers (Piazza et al., 2010; Wilson and Dehaene, 2007) have suggested that DD might be due to an impairment of the approximate number system, or to defective access to it from symbols (Rousselle and Noël, 2007). We therefore explored DB's approximate representation of magnitude and its access from symbols by means of three types of task: numerical estimation tasks (Mejias et al., 2012), magnitude comparison tasks, and a priming comparison task (Reynvoet et al., 2009).

4.2.1.1. Estimation tasks.

4.2.1.1.1. Material and procedure. Participants were asked to estimate the number of black dots displayed for 1 sec on a gray screen, by turning a potentiometer. The answer (Arabic number or number of dots) increased in magnitude as the button on the potentiometer was turned. Four conditions were used. Two different types of dots were displayed as stimuli, one using identical dots, and the other dots of different sizes. In condition A, the participant had to estimate the number of identical dots displayed by producing an Arabic number (with the potentiometer). Condition B was similar to A, except that dots were of different sizes. In conditions C and D, the subject had to respond by producing a collection of identical dots, of the same numerosity as the collection of heterogeneous dots displayed just before (condition C), or corresponding to the Arabic number displayed just before (condition D).

Seven numerosities were presented (9, 12, 16, 21, 26, 34 and 64) six times in each condition, providing a total of 42 stimuli per condition. The estimation tasks and the control group data were taken from Mejias et al. (2012). The sample included 22 participants (six males) aged between 17 and 54 (mean = 24.41), with no learning disabilities.

4.2.1.1.2. Results. The precision of participants' numerical estimation was calculated as an absolute error score (AES) computed as follows: $AES = |x_i - T|$, where x_i is the

Table 6 – Accuracy (AES) and variability (COV) of DB's and the control subjects estimates in the four conditions (A, B, C and D).

Measures	DB	Control subjects ($N = 22$)		Modified t-test	p (One-tailed)
		Mean	SD		
AES A	5.64	5.13	1.82	.274	.393
AES B	4.26	6.08	1.70	−1.047	.153
AES C	3.83	5.39	1.51	−1.010	.162
AES D	3.14	5.41	2.92	−.760	.228
COV A	.11	.15	.04	−.978	.170
COV B	.11	.19	.04	−1.956	.032
COV C	.15	.16	.03	−.326	.374
COV D	.12	.13	.04	−.245	.405

participants' estimate on trial *i* and *T* is the target value. The variability of participants' estimates was indicated by the coefficient of variation (COV = SD/Mean) of his/her estimate. Having a small AES and COV means having good precision and a stable estimate. As can be seen in Table 6, DB's estimates were as precise and as stable as those of the control subjects, in every condition (A–D). She actually performed slightly better than the control group.

When linear regressions of the COVs in the four conditions were calculated for the seven numerosities, DB's slope ($\beta = .001$) was not significant, and was similar to the mean of the controls' slope [controls $\beta = .001 \pm .001$, $t(21) = -.425$, $p = .500$]. This indicates that her COV is stable across the different numerosities. DB thus appears to have normal numerical estimation capacities.

4.2.1.2. Comparison tasks.

4.2.1.2.1. Material and procedure. The comparison task consisted of picking the square containing more bars from two squares arranged on either side of the center of the screen. The participant had to press the right (left) key if the right (left) square had more bars (Fig. 2). In the first condition, the density of the bars was controlled, while in the second condition the total black surface was equal for all numerosities (surface controlled). An Arabic condition permitted access to the approximate number system from symbols to be tested (Condition 3). Finally, in order to explore continuous magnitudes, a comparison of the length of the bars was included (Condition 4).

The number pairs used in all conditions were selected by size and distance (size × distance: small–small: 1-2, 2-3, 3-4; small–large: 1-4, 1-5, 2-5; large–small: 6-7, 7-8, 8-9; large–large: 5-8, 5-9, 6-9). A block consisted of 12 different pairs randomly displayed in both directions. The experiment comprised a training block (eight other number pairs: 2-4, 4-2, 6-4, 6-8, 4-8, 8-4, 4-6, 8-6) and two experimental blocks (2 × 24 items).

4.2.1.2.2. Results. Overall, DB performed very well. She was as accurate and as fast as Control group A in each of the four conditions (Table 7).

Given that few errors were committed, only the RTs were used to explore the size and distance effects. The size effect was measured by subtracting the RT of the small size pairs from that of the large size pairs. The distance effect was

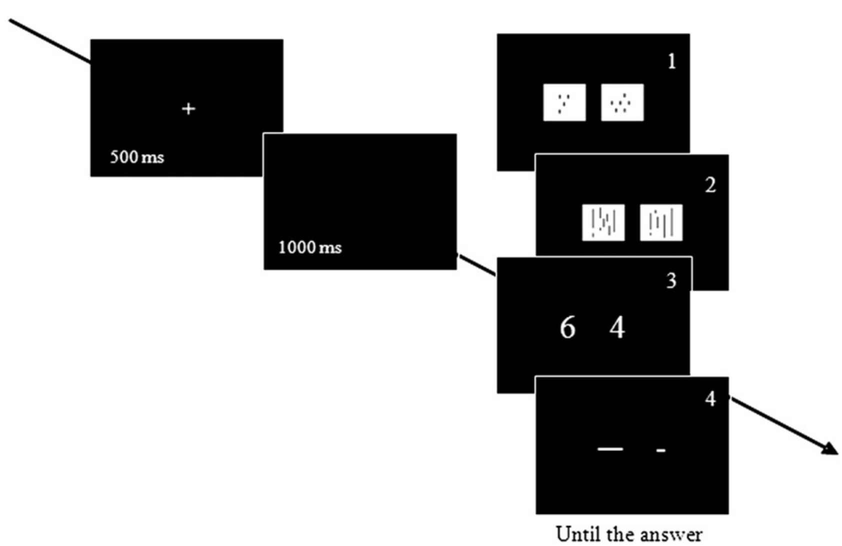

Fig. 2 – Time course of the comparison task.

Table 7 – PCR and RTs for the four conditions of the comparison task, for DB and Control group A.

	PCR				RT (median, msec)			
	DB	Controls ($N = 11$)	$t(10)$	p (One-tailed)	DB	Controls ($N = 11$)	$t(10)$	p (One-tailed)
		Mean (SD)				Mean (SD)		
Bars (density)	100	98.48 (1.35)	1.077	.153	536	605.73 (97.98)	−.681	.256
Bars (surface)	100	94.13 (3.20)	1.755	.055	748.5	886.91 (288.63)	−.459	.328
Arabic digit	100	98.48 (1.35)	1.077	.153	561.5	514.36 (69.22)	.652	.265
Length	100	99.43 (1.35)	.404	.347	446	508.82 (76.26)	−.789	.224

calculated by subtracting the RT of the large distance pairs from that of the small distance pairs. The analysis revealed no differences between DB and the controls in any of the conditions (Table 8). This indicates that DB's approximate number system works normally and can easily be accessed to/from Arabic numbers.

4.2.1.3. Priming comparison.

4.2.1.3.1. Material and procedure. In order to evaluate the internal representational overlap of numbers (semantic representation of quantities) via the symbolic system, we replicated Reynvoet et al.'s (2009) experiment. In this task, participants had to quickly decide if the Arabic number displayed was larger or smaller than five. The first target constituted the prime for the following target. The first target disappeared as soon as the subject had responded, and after 200 msec the following target appeared and remained visible until an answer was given. A gap of 2000 msec separated the next two targets. Prime stimuli were digits between 1 and 9 and the target digits were 1, 4, 6 and 9. Each block included all 32 possibilities (eight primes × four targets), and the experiment contained one practice block and four experimental blocks (for more details on the task and on the statistical analyses, see Reynvoet et al., 2009).

4.2.1.3.2. Results. Given that the participants made very few errors, only the RTs of the correct responses were analyzed. Two analyses were conducted. The first one concerns the CDE [i.e., the distance between the digit displayed and the standard (five)]. Calculated on primes, the larger the CDE, the quicker is the response. Then a repeated measures ANOVA was run on the data from Control group A, with two within factors: the direction of the prime (i.e., whether the prime was larger or smaller than five) and the absolute distance between the prime and five (1–4). While no significant effect was observed for the direction [$F(1,10) = .437$, $p = .523$], a main effect of distance appeared [$F(1.554,15.537) = 25.334$, $p < .001$]. Linear regressions on RT as a function of the absolute distance were conducted individually for every control subject and for DB. DB's slope ($\beta = -25.79$) was similar to that of the controls [mean $\beta = -23.34 \pm 8.77$, $t(10) = -.267$, $p = .397$].

The second analysis concerns the PDE (i.e., the effect of the distance between the prime and the target). For the targets alone, the larger the PDE, the slower is the response. Following Reynvoet et al. (2009), three categories of trials were excluded; those where the two motor responses (prime and target) were different, those where the prime and the target were equal, and those where a mistake was made on the prime. One control subject was rejected from the analyses because she showed interference rather than facilitation, even for the repetition effect. The mean of the median of controls' RTs on the targets were submitted to a three-way (Prime, Target, Distance) repeated measures analysis. This showed a significant main effect of distance [$F(2,9) = 4.780$, $p < .05$]. There was no significant difference between the slopes of the controls' linear regressions (mean

Table 8 – The size effect and the distance effect of DB and of the Control group A, for the four conditions.

	DB	Control subjects ($N = 11$)		Modified t-test
	RT (msec)	Mean RT (msec)	SD	
Bars (density)				
Size effect	47	195	138	−1.032
Distance effect	67	167	113	−.845
Bars (surface)				
Size effect	502	623	745	−.156
Distance effect	358	365	567	−.012
Arabic digit				
Size effect	75	57	34	.506
Distance effect	46	58	43	−.267
Length				
Size effect	43	61	36	−.479
Distance effect	96	146	87	−.551

$\beta = 11.97 \pm 9.40$) and DB's slope [$\beta = 12.41$, $t(9) = .044$, $p = .483$][4].

In summary, DB's approximate number system works normally, as witnessed by her good performance in the estimation and comparison tasks. She also has no difficulty accessing this system from Arabic symbols, as revealed by the B and D conditions of the estimation task, the Arabic digit condition of the comparison task, and the priming comparison task. Finally, she has no problem processing non-numerical magnitudes, as shown in the length comparison task.

4.2.2. *Rote verbal memory deficit hypothesis*

According to the triple-code model of Dehaene et al. (2003), arithmetic facts, and more specifically multiplications, are resolved by retrieving a rote verbal memory. A rote verbal memory deficit should be manifested as a deficit in all verbal sequences (Wilson and Dehaene, 2007), and could be associated with a more general verbal difficulty (in language, reading, and even phonological awareness).

However, DB is bilingual and has smatterings of several other languages. Her reading capacities, phonological loop, and verbal IQ are very good. These facts do not support the hypothesis of a rote verbal memory deficit. Nevertheless we devised some tasks to test these capacities specifically. More precisely, we tested the speed of reciting the alphabet and the months of the year, the speed of producing the letter after a given one, the speed of completing familiar verbal expressions as well as phonological awareness capacities. Since all these tasks were verbal tasks, we used the bilingual Control group C.

4.2.2.1. Reciting the alphabet and months.

4.2.2.1.1. Material, procedure and results. In these tasks, the participants had to recite the alphabet and the months of the year as quickly as possible. DB recited the alphabet and the months of the year perfectly, in 8 and 5 sec respectively. Her performance was not significantly different from that of the control group [mean for alphabet: 5.5 ± 2.2 sec, $t(10) = 1.104$, $p = .148$; mean for months: 4.8 ± 2.3 sec, $t(10) = .075$, $p = .471$].

4.2.2.2. The next letter task.

4.2.2.2.1. Material, procedure and results. In the next letter task, a letter was displayed on the computer screen and the participants had to say the next letter in the alphabet, as quickly and accurately as possible (using the voice key). All 25 letters were tested in a pseudo-random order (such that no two succeeding letters or their answers were alphabetic neighbors). After a fixation cross of 500 msec, the letter was displayed in the center of the screen until the participant gave an answer. The letter then disappeared and was replaced by a blank screen until the experimenter pressed the enter key to start the next item.

In this task, DB performed well and at a normal speed [accuracy: DB: 98%, controls: $98.36 \pm 2.65\%$, $t(10) = -.131$, $p = .449$; speed: DB: 1252 msec, controls: 1087 ± 214 msec, $t(10) = .738$, $p = .239$].

4.2.2.3. Completion of verbal expressions task.

4.2.2.3.1. Material, procedure and results. In the completion of verbal expressions task, the participants listened to the beginning of a popular expression and had to complete it as soon as the color of the screen changed (corresponding to the end of the sound file). This task was composed of five practice trials and twenty experimental items.

DB scored 82.5% in this task, which was similar to the controls' score [$66.59 \pm 40.82\%$, $t(10) = .373$, $p = .358$]. Her RT was also similar to that of the control group [DB: 374 msec, controls: 419 ± 253 msec, $t(10) = -.169$, $p = .435$].

4.2.2.4. Phonological awareness tasks.

4.2.2.4.1. Material, procedure and results. Finally we used computerized versions (using E-prime) of Bosse and Valdois's (2009) deletion task [in which the subjects have to repeat the word they heard without its first phoneme (20 items)], and acronyms task [in which they have to combine the first phonemes of two words they hear (10 items)].

There were no significant differences between DB and the control group in accuracy [deletion: DB: 97.50%, controls: $98.64 \pm 2.34\%$, $t(10) = -.466$, $p = .326$; acronyms: DB: 100%, controls: $88.18 \pm 14.71\%$, $t(10) = .769$, $p = .230$] or in RT [deletion: DB: 576 msec, controls: 679 ± 456 msec, $t(10) = -.217$, $p = .416$; acronyms: DB: 750 msec, controls: 820 ± 641 msec, $t(10) = -.105$, $p = .459$].

To sum up, all the tasks testing DB's rote verbal memory showed that her performance is normal.

4.2.3. *Hypersensitivity-to-interference hypothesis*

Dehaene (1997) suggested that the learning of multiplication is like the learning of associations in an address book, where the associations share similar and redundant items (e.g., names). A single-digit multiplication table has three elements, the first two selected from ten possibilities (0–9), and the last one corresponding to a combination of two elements from these ten possibilities. These intertwined associations correspond to the 90 possible multiplications. Given that arithmetical facts are particularly prone to interference because of the number of features they share, we propose that, in accordance with recent working-memory models, a heightened sensitivity to interference could prevent the storage of arithmetic facts.

To investigate this assumption, we tested DB's capacities to learn new associations, in paired-associate tasks. Firstly, we used two paired-associate learning tasks which differed in their level of similarity. Secondly, we created a learning association task in which identical features were shared, and used this to evaluate the effect of interference from feature overwriting on DB's learning. Finally, we directly measured her sensitivity to interference by using a verbal and a visual recent-probes task.

4.2.3.1. Verbal paired associates Wechsler Memory Scale-III (WMS-III) and "family name – first name" associates.

4.2.3.1.1. Material and procedure. In order to investigate sensitivity to interference in a learning context, we compared two associative memory tasks. First, we used the verbal paired-associate subtest of the WMS-III (French version of WMS-III, 2001), in which the participants had to memorize

[4] Only one of the linear regressions on the controls was significant. DB's analysis was also not significant. The priming effect only appeared in the group analysis.

eight pairs of words. The words are distinct objects or animals, which can easily be discriminated or imagined (i.e., they are low interference associates). Then we took more interfering paired associates matched for length (Bourdeaux, 2006). These consisted of eight family names associated with first names, which are less imaginable, and more difficult to differentiate (i.e., highly interfering associates). In each condition, the procedure started with a listening phase in which all the pairs were read aloud by the experimenter. Then the participant was asked to supply the word associated with the one said by the experimenter, recalling all the eight pairs. This procedure was run four times.

4.2.3.1.2. Results. DB scored well, compared to the norms of the WMS-III, in both immediate (.33σ) and delayed (+1σ) memory. This result was consistent with previous investigations, which had shown her to have a good memory. She performed similarly to Control group C for low interference associations (WMS-III), in terms of total PCR for the four learning sessions [DB: 81.25%, controls: 86.93 ± 16.11%, $t(10) = -.338$, $p = .371$] (Fig. 3). However, her performance was abnormally low for the highly interfering "family name – first name" associations [DB: 40.63%, controls: 69.32 ± 14.44%, $t(10) = -1.902$, $p < .05$].

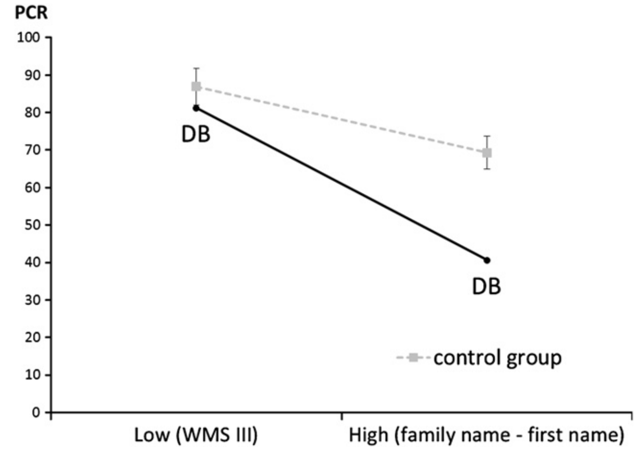

Fig. 3 – DB and Control group C's performance on the low interfering (WMS-III) and high interfering (family name – first name) paired-associate learning tasks.

4.2.3.2. "First name – family name – country" task.

4.2.3.2.1. Material and procedure. To explore the hypothesis concerning overlapping interference, we selected twelve associations of first name, family name and country to be learned. Six associations shared common elements, so in this respect the task was akin to learning a multiplication table. Common male Belgian first and family names were associated with countries in Africa or Asia, and the participants had to learn where these twelve people lived. The level of interference was manipulated by using the same or different first names or family names in the associations. As can be seen in Appendix B, six associations shared first or family names (highly interfering), and the other six did not (low interference). Three of the six people in each condition lived in Africa and the other three in Asia.

Five successive learning and recall phases were followed by a verification phase. During the learning phase, each of the twelve associations was presented aloud by the computer and the participant was given 3 sec to repeat it aloud. After this learning phase, the first name and family name of one person was spoken aloud and the participants had to recall the country in which that person lived, using the voice key. The correct answer was provided as feedback. This recall procedure was run for all the associations in a pseudo-random order, before restarting the learning phase. After five learning and recall phases, the experiment ended with a verification phase. Here the participants had to decide if the first name, family name, country associations read out were correct or not, by pressing a key on the left or the right of the keyboard[5]. All 12 people were presented once with their correct country, and once with a wrong country (another country from the low-interference group with a low-interference name, and another country from the high-interference group with a high-interference name). The associations were presented in a pseudo-random order, such that two successive trials shared no features.

4.2.3.2.2. Results. The measure of recall accuracy is the total PCR for all five recall phases, according to the condition (high or low interference association)[6]. DB's performance was worse than that of Control group B when memorizing both the low [DB: 30%, controls: 59.58 ± 18.03%, $t(7) = -1.547$, $p = .083$], and the high [DB: 10%, controls: 41.67 ± 13.69%, $t(7) = -2.182$, $p < .05$] interference associations, although only the difference on the high-interference items reached the 5% level of significance. The effect of interference, as measured by the relative difference in PCR of low interference associations and highly interfering associations, was significantly bigger for DB than for the control subjects [DB: .67, controls: .30 ± .07, $t(7) = 5.183$, $p < .001$].

In the verification task, DB performed well on the low interference associations (100%) but only at the chance level for high interfering associations (DB: 58%, controls: 74 ± 23%).

These findings show again that, in an interfering context, DB does not memorize associations properly, particularly when they are composed of the same elements.

4.2.3.3. Recent-probes tasks: verbal version.

4.2.3.3.1. Material and procedure. In order to explore the hypersensitivity-to-interference hypothesis further, we measured DB's sensitivity to interference directly, using new versions of the recent-probes task (introduced by Monsell, 1978). The task requires participants to decide if a word that is displayed on screen was among four words that had been

[5] In order to decrease the working-memory load, a green "true" (on the left of the screen) and a red "false" (on the right) remained visible throughout the experiment.

[6] The RT was not studied because DB gave too few correct responses. One of the Control group B participants was discarded because she explicitly announced she was not interested in making the effort necessary to memorize the data.

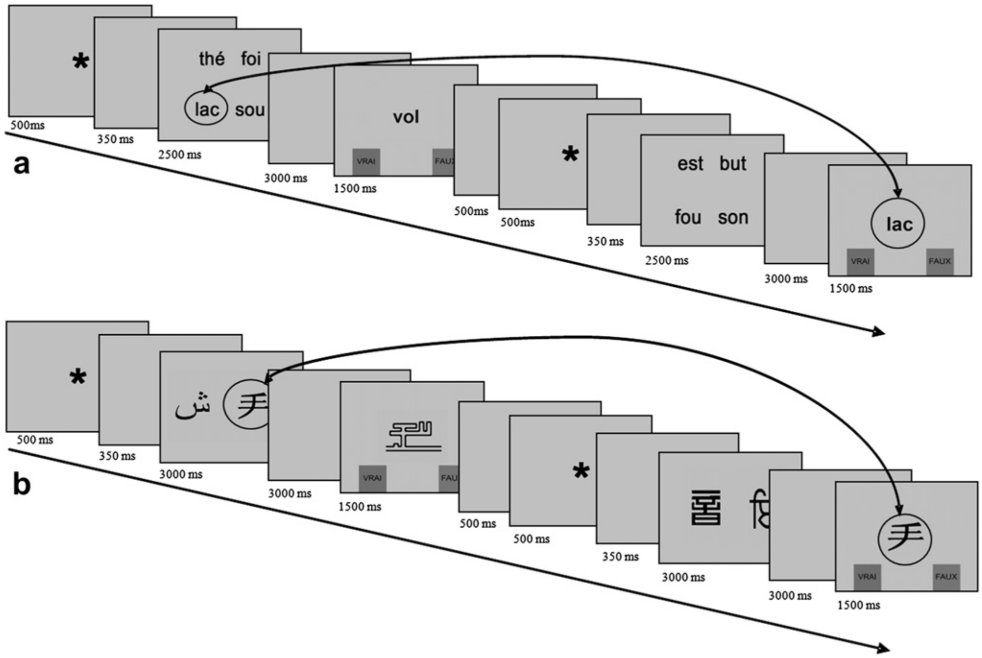

Fig. 4 – Time course of (a) the verbal and (b) the visual recent-probes tasks.

displayed 3 sec earlier. Three conditions of the target were used: the positive target (PT) (when the target had been present in the four previous words), the negative target (NT) (when the target was not present and had never been presented before), and the negative lure (NL) (when the target was not present, but had been included in the preceding trial). This condition is interesting because a familiarity effect interferes with the recollection.

The words were chosen according to the criteria of frequency (high written frequency) and syllabic length (one-syllable nouns) and the number of letters (2, 3 or 4) was controlled (data base: www.lexique.org). One trial was composed of four stimuli words and one target, similar in length but with different first letters (onset) and rhyme. Forty-eight trials were presented in a pseudo-random order, with no more than three identical answers in a row. Moreover, the arrangement of PTs and NTs on the screen was balanced across the four possible positions. The procedure is illustrated in Fig. 4a. After a fixation cross, the four words were displayed for 2500 msec. A gap of 3 sec was then followed by a single word, which remained for 1500 msec, during which the participants had to press a key on either the right or the left side of the keyboard to indicate whether they thought the word was included in the corresponding set of four words[7].

4.2.3.3.2. Results. DB performed as well as the Control group B on this task, both in accuracy and speed [accuracy: PT: DB: 91.67%, controls: 95.83 ± 2.95%, $t(8) = -1.342$, $p = .108$; NT: DB: 91.67%, controls: 92.59 ± 8.78%, $t(8) = -.100$, $p = .461$; NL: DB: 83.33%, controls: 72.22 ± 17.68%, $t(8) = .596$, $p = .284$; Median RT: PT: DB: 815 msec, controls: 942 ± 130 msec, $t(8) = -.921$, $p = .192$; NT: DB: 793 msec, controls: 961 ± 162 msec, $t(8) = -.986$, $p = .176$; NL: DB: 987 msec, controls: 1095 ± 125 msec, $t(8) = -.822$, $p = .217$]. Her interference effect, measured by the accuracy for NT minus the accuracy for NL, was also similar for DB and the control group [DB: 8.33%, controls: 20.37 ± 13.89%, $t(8) = -.822$, $p = .217$].

It is possible that DB's very efficient phonological loop prevented interference by refreshing the words. We therefore created a visual meaningless version of this task, using foreign scripts or non-semantic signs, which had to be processed visually rather than verbally.

4.2.3.4. Recent-probes tasks: visual version.

4.2.3.4.1. Material and procedure. The visual version of the recent-probes task was equivalent to the verbal one, except that two (rather than four) stimuli were presented for 3000 msec (not 2500 msec) because of the difficulty level of the task (see Fig. 4b). A pre-test was undertaken with three subjects in order to choose the most meaningless signs.

4.2.3.4.2. Results. While DB was very good at recognizing PTs [DB: 95.83%, controls: 77.77 ± 14.73%, $t(8) = 1.163$, $p = .139$] and NTs [DB: 100%, controls: 94.44 ± 5.89%, $t(8) = .894$, $p = .199$], she had significantly more difficulty than the control group rejecting NLs [DB: 41.67%, controls: 78.70 ± 12.58%, $t(8) = -2.794$, $p < .05$]. There were no significant differences in RTs [PT: DB: 884 msec, controls: 954 ± 147 msec, $t(8) = -.455$,

[7] In order to decrease the working-memory load, a green "true" (on the left of the screen) and a red "false" (on the right) remained visible throughout the experiment.

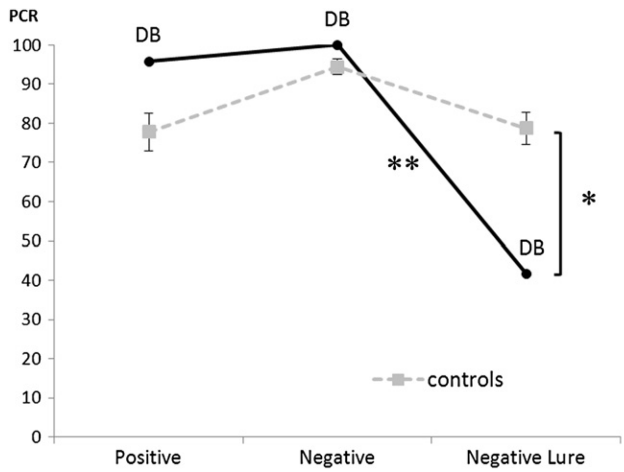

Fig. 5 – The PCR given by DB and Control group B in the visual recent-probes task for the three conditions (PT, NT and NL).

$p = .331$; NT: DB: 923 msec, controls: 836 ± 146 msec, $t(8) = .568$, $p = .293$; NL: DB: 982 msec, controls: 973 ± 175 msec, $t(8) = .051$, $p = .480$]. As illustrated in Fig. 5, a significant dissociation between NT and NL was revealed by the RSDT [$t(8) = 3.048$, $p < .01$]. These findings show that DB has a heightened sensitivity to interference.

5. Discussion

This paper aimed to tackle the origins of DD by means of a case study. The hypothesis that DD has multiple origins has been driven by the presence of diverse co-morbidity, by the heterogeneity of profiles (Rubinsten and Henik, 2009; Wilson and Dehaene, 2007) and by the multi-component models of adult numerical cognition (Dehaene et al., 2003). An attempt to identify different causes of DD was made by comparing children with only math disability to children with co-morbid math and reading disabilities (Robinson et al., 2002). Landerl et al. (2009) found a number-module deficit in cases of dyscalculia, with an additional phonological deficit in cases of co-morbid dyscalculia and dyslexia. This work did not therefore support the hypothesis of a different origin of DD according to the presence or absence of associated dyslexia.

In order to explore one origin through one profile, we studied a single case, DB, in depth. Through the detailed investigation, our case study DB reveals a very specific profile of dyscalculia. In a general mathematical assessment, DB's calculation capacities are marked by a crippling slowness, which was also noticeable in simple calculations. In single-digit arithmetic production tasks, she is significantly slower than controls in multiplication, and to a lesser extent in addition. Her extreme slowness, even on tie and small problems, can be explained by her use of computational strategies, while the control subjects used retrieval (Graham and Campbell, 1992).

According to Siegler (1988), if the strength of the associative activation between the problem and its answer does not exceed the confidence criterion, the person will not state the answer, and will use other strategies to reach the answer. In order to explore the hypothesis that DB had a severe confidence criterion, and to see if she possessed some arithmetic facts in memory, we forced her to produce the first answer activated by the problem, by using a time-limited multiplication production task. Under this condition, DB's PCR dropped significantly and drastically compared to the control subjects' ones. When she could not use a calculation strategy, she could only retrieve the answer to very small problems such as 2×3 and 3×3. DB was also significantly less accurate than the control subjects in a table membership judgment task. A multiplication verification task reinforced the hypothesis that she had never built an arithmetic facts network, because she did not show the classical deleterious effect of operand-related compared to non-table lures.

To sum up, despite her high level of intelligence, and her normal memory and attention skills, DB has never been able to build a satisfactory arithmetic facts network. We therefore decided to focus on this deficit and explore its possible causes. Addressing this issue is particularly relevant, given that arithmetic facts impairment is known to be a hallmark of DD (Geary, 1993; Geary and Hoard, 2001; Jordan et al., 2003; Jordan and Montani, 1997; Russell and Ginsburg, 1984; Shalev and Gross-Tsur, 2001; Slade and Russel, 1971), and that it is even sometimes used as a selection criterion for DD children (Landerl et al., 2004; Mussolin and Noël, 2008).

One influential hypothesis for the origin of DD is that a faulty approximate number system hinders mathematical learning (Piazza et al., 2010; Wilson and Dehaene, 2007). We investigated this hypothesis by means of numerical estimation tasks (Mejias et al., 2012), number-magnitude comparison tasks and a priming comparison task (Reynvoet et al., 2009). In none of these tasks did DB's performance differ significantly from that of the control group. She could approximate the number of dots in a set or produce a set corresponding to a given cardinal number. In the number-magnitude comparison task, her distance effect was similar to that of the control subjects. She could also process the magnitude of symbolic numbers in the Arabic digit comparison, and in the estimation tasks with Arabic digits. Finally, she showed a similar PDE to control subjects, which indicates that the precision of her number-magnitude representation is perfectly normal. All these results indicate a good approximate number system and good access to it from symbols. While a strong arithmetic facts impairment is a widely recognized feature of DD, DB's case constitutes evidence that it does not necessarily stem from a deficit in the approximate number system.

As DB's deficit was very specific to simple calculations, in particular, multiplication and, to a lesser extent, addition facts, we considered Dehaene's (1992) hypothesis of a rote verbal memory deficit. Brain-damaged patients with selective multiplication-facts impairment have been shown to suffer from an associated deficit in rote verbal memory tasks such as reciting the alphabet or the months of the year (Dehaene and Cohen, 1997). In normal population, performance in multiplication is also correlated with phonological awareness (De Smedt and Boets, 2010; De Smedt et al., 2009).

In DB's case, this hypothesis did not seem very plausible as she has a good verbal IQ, is bilingual and has normal reading capacities. Nevertheless, her verbal abilities were tested carefully. The results clearly dismissed this hypothesis in her case: she was perfectly able to recite, at a normal speed, the alphabet and the months of the year. She was as fast and as accurate as controls in saying the letter following a presented one. She could complete well-known verbal expressions adequately, and she did not differ from the control group in the phoneme deletion or the acronym tasks which were devised to test her phonological awareness. These results thus indicate that, in DB's case, the very specific impairment in building multiplication and addition facts was not due to a rote verbal memory deficit.

Of course, a rote verbal memory deficit could still be a possible cause of arithmetic facts dyscalculia. However, several studies cast doubt on this hypothesis. In particular, Landerl et al. (2009) compared groups of control, dyslexic, dyscalculic and dyslexic-dyscalculic children in a phoneme deletion task. Performance on this task was only influenced by the presence of reading difficulties, irrespective of whether they were associated with dyscalculia. Similarly, Mussolin and Noël (2008) compared fourth-grade children in the lowest 15% on a multiplication fluency task with those whose multiplication skills were above average, on their ability to select the correct word to end a proverb. The results clearly indicated that there was no difference between the two groups of children in this rote verbal memory task.

On the other hand, interference in the retrieval of arithmetic facts by the activation of neighboring facts has been widely observed (Campbell, 1995; Verguts and Fias, 2005, priming effects e.g., Jackson and Coney, 2005). In this paper, we considered the hypothesis that interference also has a major influence when individuals are learning the arithmetical facts (i.e., creating strong bonds between a problem and its solution).

During the storage stage, memorization is hindered when the items to be remembered are similar to one another. This has been observed in many different paradigms both in long-term [such as paired-associated learning (e.g., Hall, 1971)] and short-term (e.g., immediate recall paradigms such as Conrad and Hull, 1964; to Conlin et al., 2005) memory.

According to Oberauer and Kliegl (2006), any two items have a certain degree of overlap in their features, with more similar items sharing a larger proportion of feature units. When items have to be stored in working memory, the features of item representations interact with one another, which leads to mutual interference. This interference partially degrades the memory traces, which in turns leads to slower processing and to retrieval errors.

When children are learning arithmetical facts, they are in a situation where distinct associations have to be built with items that are very similar to one another (e.g., $3 \times 6 = 18$; $3 \times 8 = 24$; $6 \times 4 = 24$; $2 \times 9 = 18$). As we have seen, DB failed to store multiplication facts. When confronted with association learning tasks, she performed perfectly when the verbal paired associates were composed of dissimilar items, but had difficulty when the paired associates were composed of similar items (family names and first names). More powerfully, in the first name – family name – country task (that in some respects mimics the learning of multiplication tables), she performed poorly overall, and was even worse when the associations included shared first names or family names. She was unable to store the correct associations between these names and their countries of residence and performed no better than the level of chance when asked to say whether the data given was correct or not.

In this type of experiment, the sensitivity to item similarity is typically due to greater proactive interference (Underwood, 1983). The hypothesis of high susceptibility to proactive interference in DB was tested using the recent-probes task (originally from Monsell, 1978). This paradigm is very simple and does not load heavily on executive control mechanisms. In the verbal condition, DB had no particular difficulty, as she used verbal rehearsal to deal with the task. However, in the visual version of the task, she had considerable difficulty rejecting NLs, although she dealt perfectly well with positive and negative targets. The high sensitivity to proactive interference seen in this task can be related to DB's impaired score on the 5-sec filled-delay condition of the Brown–Peterson task, where she typically produced letters that had been presented in the previous trial.

Importantly, her difficulties in the recent-probes task were not due to memory problems per se, but to a very high sensitivity to proactive interference between the previous trial's target set and the current trial's negative response (see Jonides and Nee, 2006). Indeed, DB performed well on verbal short-term and long-term memory tasks. However, in the recent-probes task, there is a conflict between the familiarity of the NL (due to the fact that the item had been seen recently) and the lack of a contextual code that identifies the probes as member of the set of the current trial (Jonides and Nee, 2006).

In other words, being highly sensitive to interference means experiencing difficulties in retrieving the exact context of similar items which have been processed recently. In the case of arithmetic facts, the context is the problem, which has to be associated with the answer. Retaining similar items which are no longer relevant in working memory, without resolving the context issue leads to slowness or intrusion errors. Similarly, exploring the components of working memory in children with difficulties in mathematics (MD, performing below the 30th percentile on the standardized mathematics test), Passolunghi and Siegel (2004) found that, in a listening span task, MD children experienced significantly more intrusions than control children. Their findings could be interpreted as a hypersensitivity-to-interference, since in a similar task Saito and Miyake (2004) showed that mutual interference results from the representational overlap between the items being memorized and those being processed. Like DB, their MD children had similar storage capacities to those of control children.

It is important to distinguish hypersensitivity-to-interference from a general inhibition problem. Indeed, DB is able to inhibit automatic, dominant or prepotent responses, as shown by her normal performance on the color Stroop task and the go/no go task. Her cognitive profile thus adds to the dissociations among tasks involving inhibition already reported in brain-damaged patients (Hamilton and Martin, 2005) and in normal individuals (Friedman and Miyake, 2004).

We thus argue that in DB, a very high susceptibility to proactive interference led to an inability to store arithmetic facts, particularly multiplication facts but, to a lesser extent, addition facts as well. This conclusion can be related to Censabella and Noel's (2004) findings. They measured the sensitivity to interference in a color Stroop and a fan memory paradigm (Anderson, 1974) in an unselected population of adults. They observed that the participants who performed less well in a multiplication task (and, to a lesser extent, in an addition task), were more sensitive than the others to the fan effect. This suggests that they had a greater sensitivity to interference in memory. However, they were perfectly able to deal with the Stroop task, which indicates that they had no difficulty inhibiting a prepotent response.

DB's case illustrates how a non-specific cognitive deficit can lead to a specific symptom. A generally hypersensitivity-to-interference in memory only appears to be problematic in the circumscribed context of learning arithmetic facts. This learning requires very similar associated items to be processed, with few potential compensatory strategies (if time is limited). However, when we put DB in a context of memorization of very similar items the deficit appears, even if the material is non-numerical, while her daily complaint only concerns the mathematic field.

Unfortunately, we did not record the activation of DB's brain. However, based on the literature, we could draw some possible hypotheses regarding the neural correlates of her specific profile. Current neurofunctional studies of arithmetical development lead to the emergence of a three-stage model (see for instance, De Smedt et al., 2011). First, when no facts are available in memory such as at the beginning of the child's learning or when adults are confronted with large problems, activation is seen mainly in a fronto-parietal network (Molko et al., 2003; Stanescu-Cosson et al., 2000). This network seems to sustain the working memory and the attentional demand, with a specific role of the intraparietal sulcus to sustain the quantity-based processing in the calculations. Secondly, when the child is in the learning phase of arithmetic facts, an activation of the medial temporal lobe structures – in particular the hippocampus – is observed and suggests that these structures play a role in the initial phase of this learning. This is also in line with observations concerning the role of the hippocampus in associative memory more generally (Giovanello et al., 2009; Yonelinas, 2002). Finally, when facts are consolidated in memory, the activation is transferred to the angular gyrus. Strong structural and functional connectivity is indeed observed between the angular gyrus and hippocampal regions (Uddin et al., 2010). Accordingly, through development, decrease of the activation of the hippocampus is observed together with an increase in the activation of angular and supramarginal gyri (Rivera et al., 2005).

However, DD children do not easily go through these three phases and, like DB, they do not seem to ever build and consolidate arithmetic facts. For instance, children with low arithmetical fluency do not exhibit, like typical children, lower activation of the intraparietal sulcus for small compared to large problems. This is probably due to the fact that in both cases they need to use calculation strategies involving the fronto-parietal network while in typically developing children this network is mainly used for large but not for small problems (De Smedt et al., 2011).

In accordance with this literature, we might suggest that DB is still using her fronto-parietal network to solve problems and failed to establish strong associations in long-term memory. Possibly, her hippocampus did not succeed in encoding these associations between problems and answers.

Alternatively, other neurofunctional studies have pointed to the role of the left inferior frontal cortex in resolving proactive interference (for a review see Jonides and Nee, 2006). Furthermore, two case studies of brain-damaged patients suffering from lesions in the left inferior frontal cortex (inter alia) have been reported with selective deficits in resolving interference on the recent-probes task (Thompson-Schill et al., 2002) or a substantial susceptibility to proactive interference (Hamilton and Martin, 2005). This brain structure might possibly have a role in the learning phase of intertwined associations of arithmetical facts and peculiarities in the functioning of this brain region might explain the case of DB.

In summary, our study provides a new theoretical explanation of one of the causes of arithmetic facts dyscalculia. The adult subject DB has very good general cognitive abilities, but a specific deficit in arithmetic fact storage, mainly multiplication facts. We found that she suffers from a hypersensitivity-to-interference in memory and that this prevented her from storing very similar associations in memory, as is necessary for arithmetic facts.

Further inquiries are required to confirm this new theory. For instance, future studies could test the hypothesis in the early stages of numerical development and examine whether a heightened sensitivity to interference in memory hampers the storage of arithmetic facts. If the hypersensitivity-to-interference hypothesis is supported by supplementary data, then its implications, both in terms of the diagnosis and the treatment of children with DD will have to be considered.

Acknowledgments

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Appendix A

Stimuli used in the multiplication verification task.

Problem	Correct response	Operand-related lure	Non-table lure	Absolute distance		Consistency
				Operand	Non-table	
3 × 6	18	21	23	3	5	I
3 × 7	21	24	26	3	5	C
3 × 8	24	18	17	6	7	I
3 × 9	27	24	29	3	2	C
4 × 6	24	32	34	8	10	I
4 × 7	28	24	26	4	2	C
4 × 8	32	28	26	4	6	I
4 × 9	36	32	34	4	2	C
6 × 7	42	48	46	6	4	C
6 × 8	48	49	47	1	1	C
6 × 9	54	48	46	6	8	I
7 × 8	56	64	62	8	6	I
			Total	56	58	
			Mean (SD)	4.67 (2.15)	4.83 (2.76)	

Appendix B

The twelve associations of the "first name – family name – country" task.

Highly interfering			Low interference		
Gilles	Tilmant	Korea	Claude	Boudot	Thailand
Luc	Collard	Japan	Tom	Mellant	Vietnam
Jean	Collard	Laos	Paul	Dandois	Nepal
Jean	Tilmant	Mali	Marc	Pillon	Kenya
Luc	Arlot	Niger	Charles	Vasseur	Ghana
Gilles	Arlot	Benin	Frank	Baumans	Togo

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