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The Detrimental Effect of Interference in Multiplication Facts Storing: Typical Development and Individual Differences

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The difficulty in memorizing arithmetic facts is a general and persistent hallmark of math learning disabilities. It has recently been suggested that hypersensitivity to interference could prevent a person from storing arithmetic facts. The similarity between arithmetic facts would provoke interference, and learners who are hypersensitive to interference would therefore encounter difficulties in storing arithmetic facts in long-term memory. In this study, we created a measure of the interference weight for each multiplication by measuring the overlap of digits between multiplications. First, we tested whether the interference parameter could predict performance across multiplications by analyzing the data from undergraduates published by Campbell (1997). The interference parameter substantially predicted performance across multiplications. Similarly, the performance across multiplications was substantially determined by the interference parameter in 3rd-grade children, 5th-grade children, and undergraduates we tested. Second, we tested whether people with poor arithmetic facts abilities were particularly sensitive to the interference parameter. We tested this hypothesis in typical development by analyzing the data from the 3rd-grade children, 5th-grade children, and undergraduates. We analyzed data with regard to atypical development from a published case study of dyscalculia as well as from 4th-grade children, with either poor or good multiplication skills, tested twice 1 year apart. Results showed that the individual sensitivity to the interference parameter determined part of the individual differences in multiplication performance in all data sets. These findings show that the learning of multiplications is particularly interference prone because of feature overlap and that people who are sensitive to this parameter therefore encounter difficulties in memorizing arithmetic facts.

Keywords: arithmetic facts, proactive interference, multiplication, dyscalculia, interference parameter

Arithmetic facts are ubiquitous in daily life and are required in all computations. The ability to quickly retrieve the answer to basic arithmetic problems from the long-term memory (such as $2 \times 5 = 10$) is trained from primary school and constitutes the basis of more complex calculation. The retrieval of arithmetic facts is considered the most mature strategy in single-digit problems because it is much faster and less resource demanding than quantity-based or computing strategies. In addition to its relevance to the development of numerical cognition, learning arithmetic facts represents an ecologically valid memory task. In order to understand how arithmetic facts are stored in memory, researchers first investigated which arithmetic operations involved retrieval and which characteristics of the problem can influence performance.

Among the four arithmetic operations, single-digit multiplications are considered to be mainly solved by retrieval strategy. Single-digit additions are known to involve both direct retrieval (mainly for sums up to 10) and procedural strategies (e.g., Roussel, Fayol, & Barrouillet, 2002). Subtractions are rarely solved by retrieval but imply quantity-based processes, and they are sustained by brain regions other than those activated in multiplications (Barrouillet, Mignon, & Thevenot, 2008; De Smedt, Holloway, & Ansari, 2011; Yu et al., 2011). Finally, divisions are also rarely solved by direct retrieval but often involve access to multiplications (LeFevre & Morris, 1999). Consequently, the major scientific contributions regarding arithmetic facts have used multiplications and, to a lesser extent, additions.

Over recent decades, different models have been used to try to determine the factors that influence performance across the different multiplication facts. The most important and frequently reported effect is the problem size effect, according to which smaller single-digit multiplications are solved more quickly and accurately than larger single-digit multiplications (e.g., 2×3 compared with 7×8; e.g., Campbell, 1995; Campbell & Graham, 1985; LeFevre, Sadesky, & Bisanz, 1996). In addition to being influenced by the highly predictive power of the problem size, performance in single-digit multiplications is influenced by two other effects: the five effect and

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the ties effect. Controlling for magnitude, an advantage in performance is observed in the problems including the number five as an operand or including two identical operands (e.g.,Campbell & Graham, 1985; De Brauwer, Verguts, & Fias, 2006).

Theoretical models of arithmetic facts represent problems and answers linked in an interrelated associative network. The problem size effect is attributed to problem-specific differences in the strength of activation between problems and answers. Ashcraft (1982, 1987) suggested that this variability in associative strength stems from the frequency of usage of each problem, as he showed that smaller calculations are encountered more frequently than larger ones (Ashcraft & Christy, 1995). According to the Siegler's distribution of association model (Siegler, 1988), problems are associated with the correct answer but also with wrong answers generated by the subject in the past. When most associative strength is concentrated in the correct answer, the problem is represented by a peaked distribution that increases the probability of retrieving the correct answer. Contrariwise, when associative strength is dispersed among several answers, the problem is represented by a flat distribution that decreases the probability of retrieving the answer. The problem size effect resides in the fact that, during learning history, larger problems trigger more errors than smaller problems; hence, distributions for larger problems are flatter than those for smaller problems.

Another explanation for the problem size effect is provided by Campbell (1995). According to his modified network interfering theory, the problems activate magnitude representation of the answers. Because the psychophysical scale for magnitude representation is compressed as magnitude increases (Dehaene, 1992), the answer magnitude representations of larger number problems are more difficult to discriminate than those of smaller number problems. Due to their bigger similarity in the magnitude code, larger problems create more interference, and that increases the retrieval time.

Although many children create a proper arithmetic facts network during primary school, some of them encounter huge difficulties. More specifically, an arithmetic facts deficit is the hallmark of developmental dyscalculia (math learning disability without intelligence, sensory, or educational deprivation). Children with dyscalculia systematically encounter difficulties in arithmetic facts learning, and this trouble is persistent (Geary, Hoard, & Hamson, 1999; Jordan, Hanich, & Kaplan, 2003; Jordan & Montani, 1997; Slade & Russel, 1971). Most children with dyscalculia do not show the typical transition from a procedural computing strategy to a retrieval strategy (De Smedt et al., 2011; Garnett & Fleischner, 1983; Geary, Brown, & Samaranayake, 1991). Among the different explanatory theories, several studies have suggested that difficulties in arithmetic fact retrieval are due to a central executive impairment (Barrouillet & Lépine, 2005; Kaufmann, 2002; Noël, Seron, & Trovarelli, 2004; Temple & Sherwood, 2002). In particular, it has been suggested that difficulty in arithmetic fact retrieval is the consequence of a deficit in suppressing irrelevant information (Barrouillet, Fayol, & Lathuliere, 1997; Censabella & Noël, 2004; Geary, Hoard, & Bailey, 2012; Passolunghi, Cornoldi, & De Liberto, 1999; Passolunghi & Siegel, 2004).

In the same vein, De Visscher and Noël (2013) recently reported a case study (DB) of dyscalculia with a circumscribed impairment of arithmetic facts storage. In the context of perfect general cognitive functioning, results revealed that DB had a hypersensitivity to interference in memory. De Visscher and Noël formulated a new hypothesis according to which hypersensitivity to interference in memory prevents the storage of arithmetic facts because they are made of very similar associations (between two operands and the answer) corresponding to various combinations of the digits 0 to 9. Similarity between items to remember has been shown to create interference in memory. For instance, in a complex span test, the encoding weight of an item is determined by its novelty. That is, if this item is similar to previously encoded items, its encoding weight will be smaller than if it was dissimilar to them (serial order in a box model of Farrel and Lewandowsky, 2002). A way of quantitatively apprehending similarity is to consider the feature overlap between items, which has been suggested to partly account for forgetting in memory tasks (the interference-based forgetting model for feature overlapping of Nairne, 1990). In a situation where items are very similar and share lots of features, the feature overlap disturbs the storage of the items in working memory due to interference (Oberauer & Lange, 2008). Hence, long-lasting interference in long-term memory can result from this similarity interference in working memory (such as in paired-associate learning; e.g., Hall, 1971). That is, previously learned items will interfere with the new but similar items to remember, making this subsequent learning much arduous than if they were dissimilar to previous learning (proactive interference). Concretely, the recall of an AC list is reduced when preceded by a similar AB list compared to when preceded by a dissimilar DB list (Wickelgren, 1979). Learning arithmetic facts that share lots of common features can therefore be considered as a highly interfering memory task (Wickelgren, 1979, p. 242). Consequently, people with heightened sensitivity to interference in memory would encounter huge difficulties in learning arithmetic facts.

This new hypothesis on the arithmetic fact storage deficit was supported by a case study and has been tested in a larger group of fourth-grade children who were developing their arithmetic facts network (De Visscher & Noël, 2014). Twenty-three children with poor arithmetic fluency and 23 control children matched in gender, classroom, and age were submitted to an associative memory task with interfering and noninterfering associations of nonnumerical material. Results corroborated the hypersensitivity-to-interference hypothesis by showing poorer performance in the interfering condition by the children with poor arithmetic fluency compared to control children; the groups did not differ in the noninterfering condition. These studies produced data sustaining the theory that an arithmetic facts deficit could stem from hypersensitivity to interference in memory. However, despite a strong theoretical background, these studies entail some limitations. Both studies reported correlative data and therefore showed indirect relations between the arithmetic facts capacities and sensitivity to interference. Furthermore, these studies make use of the basic premise that arithmetic facts are interfering because of feature overlap, but they did not test this directly.

The similarity-based interference in arithmetic facts has been previously underlined in the network interference model (Campbell, 1995). According to this model, when a problem is presented it will activate the magnitude representation of answers (which explains the problem size effect; see above). In addition to the magnitude code similarities, Campbell's model includes a physical code similarity that creates interference (through operand-related problems) and explains the feature errors and the priming effects (see Campbell, 1987). According to this model, the two operands and the operation sign of a displayed problem will activate other problems according to the feature overlap (of digits and sign). A weight of interference is given according to the type of feature overlap (a weight for each common operand and sign). The problem node activation will depend on the total similarity corresponding to the sum of the feature matching (of operands and sign) and magnitude-similarity values (of answers). Campbell's work shows the effect of interference in retrieval and allows us to predict the types of errors or the problems that interfere with each other. In this article, the idea is to globally determine the level of proactive interference for each multiplication, simply by computing the number of feature overlaps between a problem and the previously learned problems, and test whether this determines its difficulty. The aim in this article is to evaluate the role of interference mechanisms within the typical and atypical learning of arithmetic facts (i.e., in the storage and the retrieval from long-term memory). The hypersensitivity-to-interference hypothesis postulates that arithmetic facts learning is an interference-prone situation, as a result of the feature overlap. According to the interference-based forgetting model for feature overlapping (Nairne, 1990; Oberauer & Lange, 2008), the more features items share, the weaker their memory traces will be.

Considering this, we calculated a level of interference for each arithmetical problem. We focused on single-digit multiplication problems because they are known to be mainly solved by retrieval. We considered the interference to be coming from the structure of the problems (different combinations of the basic 10 digits), and we calculated the degree of overlap of each multiplication with the others (taking into account the problem and its answer). Because the hypothesis is about proactive interference, the usual problem learning order was taken into account. The idea being that encoding interference in the learning stage results in long-term associative interference. Analysis of the feature overlap according to the learning order provides us with an interference parameter for the different multiplication problems.

First, we assess the prediction power of the interference parameter over performance across multiplication problems and compare it to that of the problem size effect, a parameter that has been shown to largely explain performance across problems. We evaluate the influence of the interference parameter in published data (Campbell, 1997) and, subsequently, through the development of the arithmetic facts network by analyzing the performance in different multiplication problems of third-grade children, fifth-grade children, and adults.

Second, we investigate the individual differences in multiplication and test whether individual sensitivity to the interference parameter of the problem predicts performance in multiplication. In other words, we test whether being sensitive to the feature overlap of the problems determines an individual's performance in multiplication. Another hypothesis could be that the performance is determined by sensitivity to the problem size. One can imagine that when someone has difficulties in multiplication, his or her difficulties will be exacerbated by the problem size. We challenge these two hypotheses in three different sections. First, we test whether individual sensitivity to the interference parameter in multiplication predicts the performance of third-grade children, fifth-grade children, and adults, beyond the sensitivity to the problem size. Second, we look at the previously published data of the case study DB and test whether she showed higher sensitivity to the interference parameter of multiplication problems than controls did and whether she showed sensitivity beyond the problem size effect. Finally, we challenge this hypothesis from a longitudinal perspective by testing children twice, once in the fourth grade and again 1 year later. This last experiment comprises two other investigations that refine the hypersensitivity-to-interference hypothesis. On the one hand, we investigate whether sensitivity to the interference parameter in multiplication is linked to sensitivity to interference in general, to inhibition capacities and/or to verbal memory capacities. On the other hand, we test whether the hypersensitivity to interference triggers difficulties in the retrieval stage due to a storage deficit or an access deficit.

The Interference Parameter

In order to test sensitivity to interference directly with arithmetic facts, we created a variable measuring the interference level of each problem. As mentioned, we focused on single-digit multiplication problems because they are known to be mainly solved by retrieval, and if not, to lead to a clear increase in reaction time. The 36 different combinations of operands from 2 to 9 (without the commutative problems) were taken into account. Because Campbell (1995; see also Rickard & Bourne, 1996) showed that commuted pairs are similar in difficulty and because we did not take into account the position of the digits in the problems, we did not differentiate them. Indeed, according to the feature overlap model (Oberauer & Lange, 2008), the position value of features does not play a role. The problems with 0, 1, or 10 as an operand were also excluded, as they are probably solved by rule-based strategies (e.g., Sokol, McCloskey, Cohen, & Aliminosa, 1991).

The aim is to determine the level of proactive interference for each problem based on the feature overlap concept described in interference-based forgetting memory models (Nairne, 1990; Oberauer & Lange, 2008). Specifically, the capacity to store and retrieve the product of a multiplication depends on the memory capacity to strongly bind two operands to the right answer. From a memory perspective, all single-digit multiplications are therefore associations composed of common features; namely, the 10 digits. Problems that share lots of features will be more interfering and will be less easily retrieved than problems with rare associations of digits (which are therefore more distinctive problems). We assume that the encoding-related interference in learning accumulates as more problems are added to the long-term representation and results in long-term associative interference. We thus calculated the number of associations a problem shares with the other problems and named this variable the interference parameter. The first parameter we created measured the feature overlap between all problems. Taking a developmental perspective into account and assessing the proactive interference of multiplications, we calculated the feature overlap of a problem with the previously learned problems only. The multiplication tables are usually taught starting with the two times table and working up to the nine times table. We therefore considered this order of learning. Comparing the power of these two parameters on the data of Study 1, the proactive interference parameter turned out to explain more variance than the full interference parameter. Besides, the proactive interference parameter theoretically agreed better with our hypothesis than the full interference parameter did. Only the proactive interference parameter has therefore been used in this article. All measures and factors that were part of the study are reported hereafter.

We calculated the frequency of association of two digits in all problems (considering both operands and product). We did not consider the frequency of one digit, because this amounts to considering the frequency of the answer digits only. Indeed, each operand appears the same number of times in all the problems (8 instances $\times$ 2 operands). So, for this reason and because we consider arithmetic fact learning to be an associative memory task, we calculated the frequency of co-occurrences of digits. The presence of only one digit is unlikely to cue a problem, but the co-occurrence of digits shows a particular association that can be more or less frequent and can trigger the activation of problems. For instance, the occurrence of two 2s is rare in multiplications because only two problems include two 2s: $2 \times 2 = 4$ and $2 \times 6 = 12$. So, these problems appear relatively distinctive compared to others. Contrariwise, the association of 2 and 8 is quite frequent because seven multiplications include them. The first problem we learn with this association (of 2 and 8) is $2 \times 4 = 8$. At this point there is no interference with previous problems. Proactive interference progressively increases from encountering $2 \times 8 = 16$, then $2 \times 9 = 18$, then $8 \times 3 = 24$, then $7 \times 4 = 28$, then $4 \times 8 = 32$, and eventually $8 \times 9 = 72$. The scoring method for the level of interference follows the principle of one point for each two-digit association shared with a previously learned problem. Consequently, when a problem shares three digits with a previously learned problem (such as $3 \times 9 = 27$, which shares three digits with $3 \times 7 = 21$), this overlap will score three points (because the association of three digits amounts to three possible combinations of 2 digits). An example of scoring is illustrated in Table 1. The six combinations of two digits belonging to the problem $3 \times 9 = 27$ (combination of the digits 2, 3, 7, and 9) are 23, 27, 29, 37, 39, and 79. Considering that children learn the two times table ($\times$2 up to 9) and then the three times table ($\times$3 up to 9), this problem is the 15th problem encountered. Among the 14 previously learned problems, 7 shared similar associations of digits (see Table 1). The number of similar digit associations with the previously learned problem represents the level of proactive interference that the current problem receives (9 in Table 1).

The problems learned in the first place are $2 \times 2 = 4$ and $2 \times 3 = 6$. They do not have any interference (level of interference is 0). The first feature overlap is encountered with the third problem learned ($2 \times 4 = 8$), which shares the digits 2 and 4 with $2 \times 2 = 4$. The problems encountered later are not necessarily the most interfering. The problem $7 \times 7 = 49$, for instance, is learned 31st but is ranked 16th in the interference weight. Conversely, the problem $4 \times 8 = 32$ is learned 20th but is the most interfering problem. The result of this computation is presented in Figure 1. All 36 multiplications are ordered according to their interference level, which is represented by a blue (gray) bar.

The aim in this article is to test whether the proactive interference based on the feature overlap of problems is an important factor for the typical and atypical development of an arithmetic facts network, beyond the effects already shown in the literature. Before reporting the analyses based on our data, we tested whether the interference parameter can explain differences of performance across multiplications by analyzing the data published by Campbell (1997). In this paper, Campbell tested 44 undergraduates and reported mean reaction time and number of errors for each multiplication problem (all multiplications including operands from 2 to 9, 64 problems). These data are used to test our interference parameter and compare it with the different effects (ties, five, and size effects) reported in the literature.

Table 1
Example of Scoring the Level of Proactive Interference With the Problem $3 \times 9 = 27$

$3 \times 9 = 27$	Previous problem	Combination 23	27	29	37	39	79
	$3 \times 2 = 6$	1					
	$2 \times 7 = 14$		1				
	$9 \times 2 = 18$			1			
	$3 \times 3 = 9$					1	
	$4 \times 3 = 12$	1					
	$3 \times 7 = 21$	1	1		1		
	$8 \times 3 = 24$	1					
Level of interference = 9							

Ties and Five Effects

First, the interference parameter could potentially explain the ties and five effects, because this parameter is based on the co-occurrence of digits. The ties have two identical digits in their digits combination (two identical operands), which is relatively rare among multiplication problems. The problems including the digit five as an operand are the only combinations of digits including the digit five (no answer comprises a five outside the five times table). Hence, these problems are less interfering according to the feature overlap interference based on digits.

We first test whether performance in ties problems and in five problems are similar (excluding the problem 5×5). The two types of problems showed similar performance, in terms of accuracy, $t(19) < 1$, and reaction time, $t(19) = -1.321$, $p = .202$. Consequently, these special problems are considered together. Compared to the other problems, these special problems are performed better, in terms of accuracy, $t(53.789) = 4.770$, $p < .001$, as well as reaction time, $t(58.845) = 5.400$, $p < .001$. More important, considering the interference parameter, the five and ties problems are shown to be less interfering than the other problems, $t(58.508) = 4.043$, $p < .001$; M (SD) of interference level: five and ties, 5.5 (4.3); other problems, 10.9 (6.5).

Finally, we ran a generalized linear mixed model on the reaction time across multiplications, including the categorical variable ties and five, the interference parameter, and their interaction. A main effect of the interference parameter was found, $F(1, 60) = 8.954$, $p = .004$. The ties and five effect was not significant, $F(1, 60) = 2.581$, $p = .113$, and there was no interaction ($F < 1$). The same model run on the mean accuracy across multiplications showed the same results, with a main effect of the interference parameter, $F(1, 60) = 6.151$, $p = .016$, and no effect of the ties and five variable nor interaction (both Fs < 1).

To conclude, the interference parameter seems to be a good theoretical explanation for the fact that ties and five problems are globally better performed than other problems.

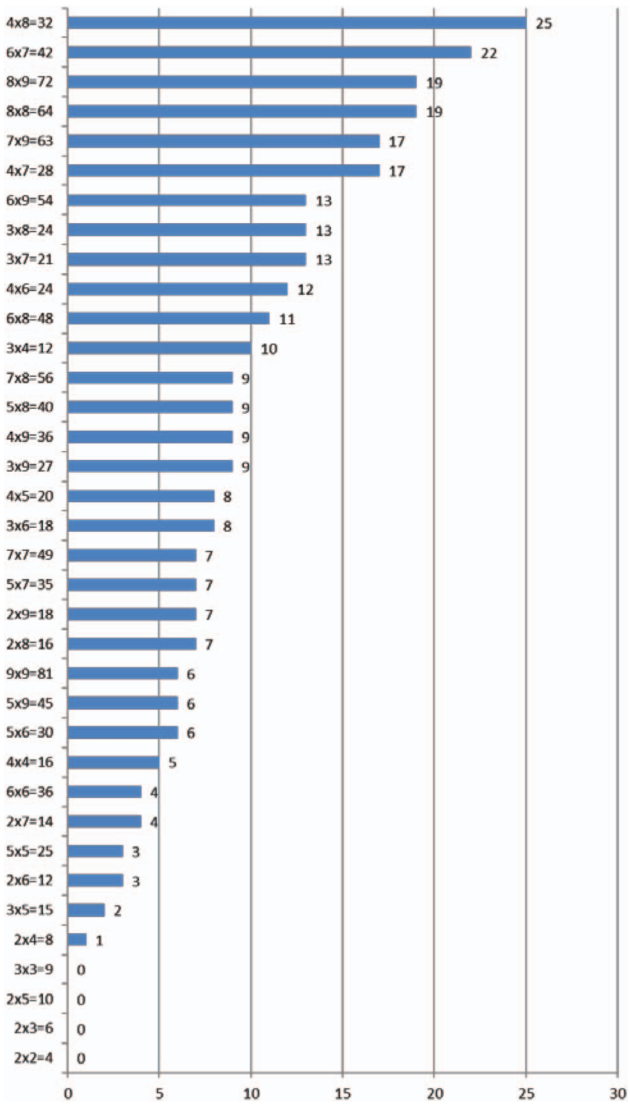

Figure 1. All 36 multiplications ordered according to the interference parameter, from the least interfering (bottom) to the more interfering (top). The gray bar (blue online) represents the feature overlap with the previously learned multiplications according to the learning order in the two times table to the nine times table. See the online article for the color version of this figure.

Size Effect

Several indices have been used in the literature to measure the problem size effect. The one that is more frequently used is the product of the two operands (Campbell, 1997). The other measures used correlate highly with the product of the operand, $r(35)$, calculated on the 36 multiplication problems described above: minimum operand, .948; maximum operand, .716; sum, .961; sum squared, .988. The only measure that seems to differ from the product is the maximum operand. In the data of Campbell (1997), the maximum operand correlated better with the reaction time than the product; respectively, $r(63) = .71$ and $r(63) = .50$. We therefore ran a linear regression with the problem size factor (maximum operand) and the interference parameter (see Table 2). Results showed that the two factors are significant and independently play a substantial role in arithmetic fact solving, in terms of reaction time and accuracy: *M* (*SD*) reaction time, 897 (101); accuracy, 11.53% of errors (12).

In our data (Study 1), the product was a better predictor of the performance than the maximum operand (see Appendix A). Hence, in all the following analyses we used the product as the problem size index. The Pearson's correlation between the interference parameter and the problem size (product) is significant, $r(35) = .544$, $p = .001$, but there is no complete overlap between them. The two parameters are compared in all subsequent analyses, in order to test whether the interference parameter is a determinant factor, even when the problem size is taken into account.

Study 1: Third-Grade Children, Fifth-Grade Children, and Undergraduates

The first study addresses two questions. First, we question whether the level of interference of a problem will account for the difficulty across multiplication problems. Previous studies (e.g., De Brauwer et al., 2006) have shown that the accuracy and speed of solving single-digit multiplications are functions of the problem size (i.e., size of the product). Here, we wanted to measure whether the interference parameter we developed is also able to predict the accuracy and response speed of multiplication problems even when the problem size is taken into account.

The second aim in this study is to see what accounts for the individual differences in a multiplication task. We explore whether the global performance of a person (accuracy and speed) is influenced by sensitivity to the problem size and/or to the interference parameter.

In order to explore the two factors' influence on the development of arithmetic facts network, we analyzed the multiplication performance of third-grade children, fifth-grade children, and undergraduate students.

Method

Participants. Thirty-eight third-grade children (17 girls, mean age = 8 years 10 months, *SD* = 5 months), 42 fifth-grade children (26 girls, mean age = 10 years 8 months, *SD* = 4 months), and 46 undergraduate students from the Université catholique de Louvain in Belgium (40 girls, mean age = 20 years 1 month, *SD* = 14 months) participated in this study. Children were recruited from two elementary schools in Brussels, composed of upper-middle-class families. Parents filled out a consent form. Undergraduate students received course credits for their participation.

The children's intelligence was assessed by means of two subtests of the Wechsler Intelligence Scale for Children—Fourth Edition (WISC–IV; Wechsler, 2005): Similarities and Picture Concepts. We averaged the two standard scores to achieve a global score (third graders, $M = 11.11$, $SD = 2.17$; fifth graders, $M = 11$, $SD = 2.08$). All children had a global standard score greater than or equal to 6, excluding general cognitive impairment.

Material and procedure. Children and students were tested in a quiet room in their school or university. All computerized experiments were displayed on the 15-in. screen of a laptop computer, using the E-Prime experimental software (version 1.1, Psychology Software Tools).

Table 2
Multiple Regression Analyses With the Interference Parameter and the Problem Size as Independent Variables and Performance as a Dependent Variable

Measure	Zero-order correlation	Partial correlation	t	p	β	R^2
Reaction time						
Interference parameter	.585	.324	2.678	.010	.273	.562
Problem size (maximum operand)	.715	.578	5.532	<.001	.563	
Accuracy (number of errors)						
Interference parameter	.552	.328	2.707	.009	.314	.432
Problem size (maximum operand)	.603	.428	3.694	<.001	.429	

Note. Based on data from Campbell (1997). Median reaction time is shown in the top half of the table; accuracy (number of errors) is shown in the bottom half of the table.

All the participants were submitted to a pool of tasks. Here, we report only the multiplication data that are of interest to this study. The computerized multiplication task included the 36 combinations of integers from 2 to 9 (without the commutative pairs). Half of the problems started with the larger operand and half with the smaller operand, so that the magnitude of the answers was similar in both the subsets (see Appendix B). Problems were presented following a pseudo-random order, so that no more than three successive problems were of the same type (smaller operand first, larger operand first, or tie problem) and that two successive problems never shared the same operands or the same answer. The trials started with a fixation cross lasting for 1 second, after which the multiplication problem (4 × 1 cm in size) appeared in white on a blue background until the participant answered. Participants were instructed to answer as fast and as accurately as possible by typing the answer on a numerical keypad. Their answer appeared next to the problem when they typed, and they had to confirm it by pressing the *Enter* key (marked with a green sticker). If the participant did not answer after 10 seconds, the problem was replaced by a question mark to push them to produce an answer. Before and after the arithmetic problems, participants were instructed to perform a copying task involving typing the numbers displayed as fast and as accurately as possible and confirming their answer by pressing the *Enter* key. This task included the answers to the 36 multiplications and allowed us to measure the motor speed for typing on the numerical pad. The accuracy and reaction time (of the validation key) were taken into account.

Results

Because the first aim in this study was to determine what accounts for the level of difficulty of a multiplication problem relative to the other problems, we calculated the average performance (mean accuracy and the median of reaction time; RT) for each multiplication separately for each group (provided in Appendix C). Multiple regressions with performance as the dependent variable and the interference parameter and the problem size (the product) as independent variables were run for each group (third-grade children, fifth-grade children, and adults).

With regard to the accuracy (see Table 3, first part), the problem size explained a substantial part of the variance in performance in the three age groups, with negative partial correlations of .6, .4, and .5 for third-grade children, fifth-grade children, and undergraduates, respectively. The interference parameter explained variance in the third-grade group only. All significant coefficients were negatively correlated, indicating a decrease in accuracy when the size of the problem or the level of interference increases.

The importance of the interference parameter is brought to light in the reaction time analyses (see Table 3, second part). In the third-grade children the interference parameter is significant (marginal significance for the problem size) and shows an effect size similar to the problem size. In fifth-grade children, the interference parameter shows high partial correlation and effect size. The problem size is close to significant. Finally, in undergraduates, the two factors are significant and show high partial correlation and effect size.

The second aim in this study was to examine which predictor was a significant determinant of the individual differences in multiplication performance: sensitivity to the interference parameter and/or sensitivity to the problem size. For this purpose, we measured the problem size effect and the interference parameter effect for each individual. We therefore calculated a multiple regression for each person, with the reaction time (of the correct responses) as the dependent variable and the problem size (the product) and the interference parameter as independent variables. The slope of each independent variable (for each individual) was used as the measure of the personal effect of the problem size and of the interference parameter. That permits us to contrast the sensitivity of each person to the two parameters and see which one can explain part of the global performance in the multiplication task.

Multiple regressions with the median RT as the dependent variable and the interference slope and the problem size slope as independent variables were run for each group (see Table 4).[1]

The two factors were significant in the three groups. All coefficients showed a positive correlation with the reaction time, meaning that increases in the individual effect implied increases in individual RTs. The interference parameter showed partial correlation of .421, .576, and .571, respectively, for third-grade children, fifth-grade children, and undergraduates.

[1] We also ran the same analyses with the median reaction time in multiplication corrected for the individual motor speed (median in multiplication minus the mean of the median of the two speed measure tasks). Results led to exactly the same conclusions.

Table 3
Multiple Regressions on Performance in Multiplications With the Interference Parameter and the Problem Size as Predictors

Measure	Zero-order correlation	Partial correlation	t	p	β	R^2
Accuracy						
Grade 3						
Interference parameter	−.697	−.520	−3.497	.001	−.403	.691
Problem size	−.760	−.632	−4.686	<.001	−.540	
Grade 5						
Interference parameter	−.466	−.235	−1.388	.175	−.233	.345
Problem size	−.554	−.405	−2.547	.016	−.428	
Undergraduates						
Interference parameter	−.504	−.238	−1.411	.168	−.217	.449
Problem size	−.645	−.512	−3.422	.002	−.527	
Reaction time						
Grade 3						
Interference parameter	.514	.329	2.001	.054	.338	.338
Problem size	.507	.316	1.917	.064	.324	
Grade 5						
Interference parameter	.625	.466	3.026	.005	.465	.451
Problem size	.546	.315	1.908	.065	.293	
Undergraduates						
Interference parameter	.683	.506	3.371	.002	.434	.615
Problem size	.695	.527	3.563	.001	.459	

Note. Models on accuracy (above) and on speed (below) are provided for the third-grade children, fifth-grade children, and undergraduate students.

When we ran the same analysis with accuracy as the dependent variable (percentage of correct responses), none of the coefficients were significant in all groups.

Conclusions

We first questioned whether the interference parameter accounts for the difficulty across multiplications, beyond the problem size. Results show that the interference parameter explains a substantial part of the reaction time for the three age groups. The level of interference of multiplication problems appears to affect the performance of the three groups negatively: The time needed to solve a multiplication increases as the level of interference increases.

Second, we tested whether the problem size and/or the interference effect influences the individual differences in multiplications performance. With regard to the speed, the interference effect determines a substantial part of the performance across subjects, in addition to the problem size effect, in the third-grade children, fifth-grade children, and undergraduates. With regard to accuracy, none of the factors could explain the performance in the three groups.

This study showed that the interference parameter influences the performance across multiplications and determines part of the individual differences in multiplication. These influences mainly concern reaction time.

Study 2: DB's Data

Because the interference parameter explains part of individual differences in multiplication tasks, we explore whether it can account for an arithmetic facts deficit in dyscalculia. We test its influence by reanalyzing published data from a case of develop-

Table 4
Multiple Regressions With the Average Speed in Multiplication and the Interference Parameter Slope and the Problem Size Slope as Predictors for the Third-Grade Children, Fifth-Grade Children, and the Undergraduates

Reaction time	Zero-order correlation	Partial correlation	t	p	β	R^2	M (SD) RT
Grade 3							
Interference parameter slope	.139	.421	2.750	.009	.454	.297	8,095 (2,253)
Problem size slope	.381	.532	3.720	.001	.614		
Grade 5							
Interference parameter slope	.362	.576	4.402	<.001	.912	.332	3,442 (846)
Problem size slope	.002	.481	3.424	.001	.709		
Undergraduates							
Interference parameter slope	.410	.571	4.559	<.001	.612	.361	2,080 (459)
Problem size slope	.227	.481	3.598	.001	.483		

Note. Reaction time (RT) is in milliseconds.

mental dyscalculia with selective impairment in the arithmetical fact network: the case of DB (De Visscher & Noël, 2013). As mentioned above, DB had perfect general cognitive functioning but showed hypersensitivity to interference in short-term and long-term memory (using nonnumerical material). In accordance with these previous findings, we first predicted that the interference parameter would substantially explain her response time in multiplications, beyond the problem size. Second, we predict that her interference slope (effect) would be steeper (larger) than that of the controls, beyond the problem size slope.

Method

Participants. DB was a 42-year-old woman at the time of the testing. She was diagnosed with high potential and dyscalculia. Eleven control participants matched in gender, age, and education constituted the control group (for further details, see De Visscher & Noël, 2013, pp. 55–56).

Material and procedure. DB and the control participants were submitted to a multiplication production task. Problems were displayed in the center of the screen until the participant answered. Participants were asked to respond as accurately and as fast as possible using the voice key. The 36 combinations of digits from 2 to 9 (without the commutative pairs) and 8 additional rule problems ($n \times 0$, $n \times 1$) were used. The rule problems are not considered here (for further details on the task, see De Visscher & Noël, 2013, pp. 55–56). The performance across multiplications (median reaction time and mean accuracy) of the control group and of DB is provided in Appendix D.

Results

If the rule problems are disregarded, DB was significantly slower than the control participants at this task (DB's median = 2,317 ms; controls' average medians = 998 (177) ms; modified Crawford $t(10) = 7.114$, $p < .001$) but showed normal accuracy (DB = 94.44%; controls = 97.47 (2.14)%, modified $t(10) = -1.359$, $p = .102$).

We first ran a multiple regression with the RT of DB as the dependent variable ($N = 33$; two errors and one technical problem with the voice key) and the two predictors—namely, the problem size and the interference parameter—as independent variables. The model was significant, $F(2, 32) = 6.782$, $p = .004$, and the two coefficients were marginally significant (see Table 5, Model 1). When we ran the first model, one outlier was highlighted (the problem $7 \times 7 = 49$, with more than 3 standardized residuals, 15,217 ms). Hence, a second model was run without this outlier (see Table 5, Model 2), improving the fit by 10%. In this last model, the interference parameter is significant and shows an important effect size. The problem size is not significant.

The slope of the linear regression of the interference parameter on the reaction time (of correct responses) was calculated for DB and each control. DB's slope was significantly steeper than that of the controls in a standard modified t test (Crawford & Howell, 1998; DB's slope = 277; controls' slope = 33 (15); $t(10) = 15.624$, $p < .001$). However, when we used the appropriate test developed by Crawford and Garthwaite (2004) for comparing slopes, Bartlett's test (Test a) was significant. This result means that there were differences among the controls' error variance, making the comparison of the patient's slope with that of the controls impossible.

We therefore calculated for each problem the Z score of DB's RT (DB's RT minus mean of the controls' RT/standard deviation of the controls' RT). This allowed us to measure the gap between DB and the controls for each problem. The hypothesis is that DB's deviation from the mean will increase with the increasing level of interference. We ran a multiple regression with the Z score of DB as the dependent variable and the two factors (interference parameter and problem size) as independent variables. The model was not significant. However, when running the model, the same 7×7 problem appeared to be an outlier (see Figure 2). Hence we ran a second model without this outlier. The fit of the model was consequently improved by 26% (see Table 6). The interference parameter was significant and showed a substantial effect size, but the problem size was not significant. This indicates that DB was more sensitive to the interference parameter than the controls were.

Conclusions

In a previous paper, we showed that DB suffered from hypersensitivity to interference, which disturbed her capacity to memorize very similar items. We interpreted that this hypersensitivity to interference was the cause of her arithmetic fact storage deficit. In this paper, a measure of the feature overlap between multiplication problems allowed us to directly assess the hypothesis of a hypersensitivity to the interference weight of the different multiplication problems. Results showed that the interference parameter determined a substantial part of DB's response time in the multiplication task, but the problem size was not significant. Furthermore, she was more sensitive to the interference parameter than the controls were. These current results corroborate the previous findings and directly show that the abnormally slow response time of DB in multiplication was due to her hypersensitivity to the interference weight of the problems.

Table 5
Multiple Regression on the Reaction Time of DB With the Interference Parameter and the Problem Size as Independent Variables

Reaction time	Zero-order correlation	Partial correlation	t	p	β	R^2
Model 1 ($N = 33$)						
Interference parameter	.486	.322	1.860	.073	.326	.311
Problem size	.482	.313	1.807	.081	.317	
Model 2 ($N = 32$)						
Interference parameter	.620	.500	3.108	.004	.519	.411
Problem size	.463	.209	1.153	.258	.193	

Note. Model 1 includes all data. Model 2 excludes one outlier.

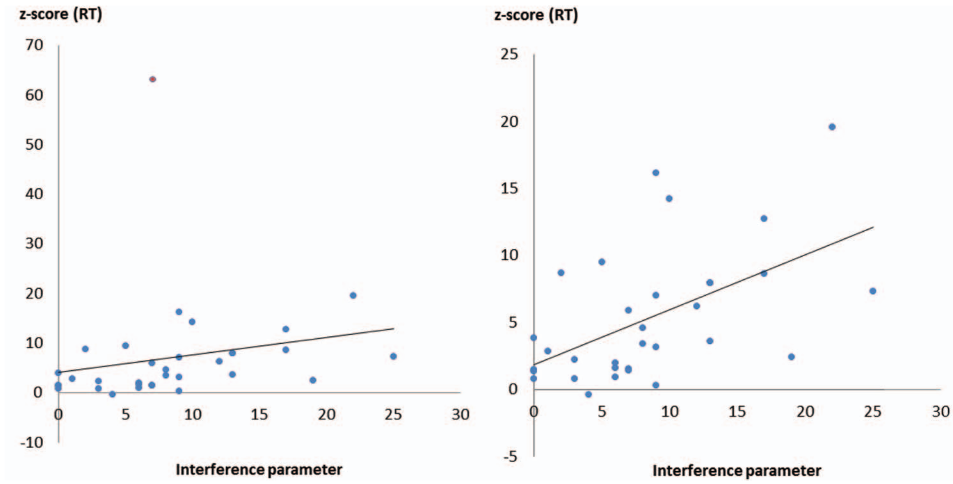

Figure 2. Response time of DB in *z*-score (compared to the controls) for each problem according to the interference parameter, with the outlier in the graph on the left and without it on the right. See the online article for the color version of this figure. RT = reaction time. See the online article for the color version of this figure.

Study 3: Longitudinal Data

In a previous study, we showed that fourth-grade children with poor arithmetic facts fluency experienced higher sensitivity to interference in a nonnumerical associative memory task than control children did (see De Visscher & Noël, 2014). In the present study, we reanalyze the data from this study (Period 1) and report original data from the same children tested 1 year later (Period 2). In Wallonia (Belgium), Grade 4 is an important school year in which the storing of multiplication facts is emphasized. We first test whether the interference parameter and/or the problem size effect predicts the individual differences in multiplication in fourth grade and again 1 year later. Accordingly, the same multiplication production task was used during the two periods of testing. Subsequently, three main questions are addressed in order to refine the hypersensitivity-to-interference hypothesis.

First, we explore whether sensitivity to the interference parameter reflects a general sensitivity to interference. We therefore measure the correlation between the sensitivity to the interference parameter (in the multiplication task) and the sensitivity to interference in a nonnumerical task (the associative memory task of the first period of testing). Second, we want to determine whether this sensitivity to interference is a specific concept or whether it is confounded with close concepts such as inhibition capacities, verbal memory, or associative memory capacities. To that end, we tested the inhibition capacities with a Stroop color task, the verbal memory capacities with a words list memory task, and the associative memory capacities with a (noninterfering) paired-associates memory task. Correlations between these measures and the sensitivity to interference were calculated.

Third, we verify the assumption according to which hypersensitivity to interference disturbs the retrieval strategy by using a time-limited multiplication task. According to the hypothesis, being sensitive to interference hampers the storing of arithmetic facts and consequently does not allow a retrieval strategy to be used when solving those arithmetic facts. The multiplication production task without time limitation allowed children to use different strategies, such as computing strategies or retrieval strategies. We therefore used a multiplication production task in which children had only 2 seconds to answer, forcing them to use a retrieval strategy.

Fourth, we directly address the original hypothesis; namely, that hypersensitivity to interference prevents a person from storing arithmetic facts. When showing an arithmetic facts deficit in an individual, the question is whether this deficit is due to a storing deficit or to an access deficit. In the case study DB, we investigated this question in detail and found out that she presented a

Table 6
Multiple Regression on the Score-Z of Reaction Time of DB (Deviation From the Mean) With the Interference Parameter and the Problem Size as Independent Variables

Score-*Z* RT	Zero-order correlation	Partial correlation	t	p	β	R^2
Model 1 (N = 33)						
Interference parameter	.197	.101	0.558	.581	.115	.059
Problem size	.222	.144	0.799	.430	.164	
Model 2 (N = 32)						
Interference parameter	.535	.558	3.617	.001	.649	.321
Problem size	.120	−.220	−1.217	.234	−.218	

Note. Model 1 includes all data. Model 2 excludes one outlier. RT = reaction time.

storage deficit. From this case study we postulated that hypersensitivity to interference disturbs the storage of very similar items. In this study, we used a multiplication table membership judgment task in order to disentangle between a storage versus an access deficit. Indeed, in the case of a deficit of access to the stored arithmetical facts, production is impaired but recognition of a number as being one of the multiplication's answers should be spared. When a child can recognize whether or not a number belongs to a multiplication table's answers, this means that he or she has created an arithmetic facts network to a certain extent. Conversely, difficulties in this task reveal a storage deficit.

We therefore tested whether children who are more sensitive to the interference parameter encounter more difficulties in a judgment task than the controls do. If that is the case, the results would support the assertion that sensitivity to interference disturbs the storage process; otherwise, they would support the assertion that sensitivity to interference disturbs access to arithmetic facts.

Method

Participants. Among 101 fourth-grade children, coming from three elementary French-speaking schools composed of upper-middle-class families, 23 children (11 girls) with poor arithmetical fluency and 23 control children were selected as follows. We selected the three or four children who had the lowest score in their classroom in single-digit multiplications and additions fluency tasks but normal scores in a processing speed task (subtest Symbols from the WISC–IV; Wechsler, 2005) and for whom we had matched controls in the same class. One child was eventually excluded because he was unwell on the day of the individual testing. Control children were matched in gender, age, and class and scored in the arithmetical fluency task at one standard deviation at least above their low arithmetic fluency child peer. The first period of testing took place on the same day or after a maximum of 2 weeks after the selection phase. The second period of testing was conducted 1 year later. Children were individually tested in a quiet room. The study has been approved by the ethical committee of the Psychological Sciences Research Institute of Université catholique de Louvain (Belgium). Parents filled in a consent form for their child's participation.

Material and procedure. The first period of testing included a measure of reasoning (Picture Concepts subtest from WISC–IV; Wechsler, 2005), a computerized multiplication task, and an associative memory task with two levels of interference (further details and the results of this first time period can be found in De Visscher & Noël, 2014).

The second period of testing comprised the same computerized multiplication task, a words list and a paired-associates memory task (respectively, Children's Memory Scale [CMS], Cohen, 2001, and Wechsler Intelligence Scale for Adults [WMS], Wechsler, 2011), a color Stroop task (Albaret & Migliore, 1999), a time-limited multiplication production task, and a multiplication table membership judgment task.

Memory and inhibition tasks. In the words list memory task (CMS; Cohen, 2001), the experimenter orally presented 14 words and children were instructed to recall as many words as possible, irrespective of the presentation order. After the child responded, the experimenter reminded the child of the words he forgot. This procedure was repeated three times so that the children were given four opportunities to memorize as many words of the list as possible. The total of words recalled during the four recall sessions was converted into a standard score.

In the paired-associate memory task (WMS; Wechsler, 2011), the experimenter orally presented 8 unrelated word pairs and then successively proposed the first word of each pair, to which the child had to recall the associated word (in a pseudo-randomized order). When the child made a mistake, the experimenter gave him the correct answer. This procedure was repeated three times so that the children were given four opportunities to memorize the paired associates. The total of the paired words recalled during the four recall sessions was converted into a standard score.

The color Stroop task included four subtests of 45 seconds each (Albaret & Migliore, 1999). The two first subtests consisted in reading as many words as possible in 45 seconds. The reading test comprised color words written in black (first test) or in a color of ink that was incongruent with the color words (second test). The third subtest was a color naming task during which children had to name the color of filled squares. The last subtest used the color words written in incongruent color ink sheet, and children were instructed to give the ink color (and therefore inhibit the written word). The inhibition score is computed by subtracting the words' color ink naming scores from the squares' color naming scores.

Multiplication tasks. The computerized multiplication task used in the two periods of testing included the same 36 problems mentioned above (see Appendix B). The problems were presented in a pseudo-random order according to the same criteria described previously. The problems were displayed on a gray background until the child answered using the voice key. Five easy additions were used to familiarize the children with the task (for further details, see De Visscher & Noël, 2014).

In the time-limited multiplication task, children were instructed to answer each single-digit multiplication problem before the bomb explodes (within 2 seconds). In order to force them to answer and decrease any potential anxiety, they were asked to say the first answer they thought even if they "guessed." All the combinations of integers from 2 to 9 (64 problems) were presented twice (in two separate blocks). In each block, the problems were presented according to a pseudo-random order, so that two successive problems never had the same answer or a same operand and so that commutative pairs were separated by 7 problems at least. After a 1-second fixation cross, the problem appeared along with a picture of a bomb for 2 seconds and was followed by for a picture of the bomb exploding 500 ms (with a sound).

In the multiplication table membership judgment task, children were instructed to decide as accurately and rapidly as possible whether the number displayed was an answer to a multiplication question (from the two to the nine times tables). Before they started the task, children received complete instructions and examples to ensure their understanding. The task included 46 two-digit numbers that were presented twice (in two separate blocks). Half of the numbers were answers to multiplications. The other half were not answers to multiplications and were matched in size and parity (see Appendix E).

Results and Conclusions

The mean accuracy and median RT for each multiplication problem for Periods 1 and 2 are provided in Appendix F.

Predictive power of the interference parameter. In this section, we test whether individual sensitivity to the interference parameter and the problem size predicts the individual performance differences in a multiplication task.

The slope between the reaction time (for correct responses) in the multiplication production task (without time limitation) and the two predictors (i.e., the problem size and the interference parameter) were calculated for each individual with multiple regression analyses.

First period of testing. Concerning accuracy, multiple regression with the interference slope and the problem size slope as independent variables showed massive influence from the interference slope with large partial correlation and effect size (see Table 7). The problem size slope reached significance ($p = .051$) but showed half effect size. This indicates that being sensitive to the interference and, to a lesser extend to the problem size decreases global accuracy in the task. With regard to the median of reaction times, the multiple regression with the interference slope and the problem size slope as independent variables showed a substantial effect from the interference parameter only. This indicates that being sensitive to the interference parameter increases the time needed for solving multiplications.

Second period of testing. We followed the same procedure for the second period of testing (1 year later). With regard to accuracy, the interference slope showed high partial correlation and effect size, indicating that as the sensitivity to the interference parameter increases the global accuracy decreases. The problem size slope was not significant.

Concerning the RTs, both slopes were significant, with high partial correlations and effect sizes (see Table 8). The major result is that sensitivity to the interference parameter was associated with lower accuracy and longer RTs in multiplications.

Cross period prediction. Finally, we tested whether the two slopes stemming from the first period of testing predicted performance 1 year later. The multiple regression on accuracy and that on reaction time (Period 2) both led to the same conclusion that the interference slope was a good predictor of performance 1 year later, but the problem size slope was not a significant predictor (see Table 9).

Sensitivity to proactive interference, inhibition, and verbal memory capacities. During the first period of testing, we evaluated the children's sensitivity to interference of children by using a kind of recent-probes task paradigm in an associative memory task, in which children had to memorize associations of cartoon characters and places. Propositions of character–place associations were then presented to the child, who had to judge whether these were true or false. Some of these propositions were interfering and the others were noninterfering (see De Visscher & Noël, 2014, for more details). We observed that children with poor arithmetical fluency performed worse than the controls in the interfering condition but not in the noninterfering condition. It was thus concluded that they showed increased sensitivity to interference compared to children with normal arithmetical fluency.

The first aim in this section is to test whether the sensitivity to interference in multiplication is correlated with this nonnumerical measure of sensitivity to interference. The second aim is to test whether this sensitivity to the interference parameter in multiplication in some way reflects the inhibition capacities or verbal memory capacities or if instead it is a distinct concept. We therefore calculated the sensitivity to interference in the associative memory task of each child as follows ($N = 46$):

$$\mathrm{STI} = 100 - \frac{\%\ \mathrm{CR\ on\ interfering\ trials}}{\%\ \mathrm{CR\ on\ noninterfering\ trials}} \times 100,$$

where STI is the sensitivity to interference measure and % CR is the percentage of correct responses. This measure represents the STI in terms of percentage. The higher the STI measure, the more sensitive the person is. During the second period of testing, we collected a measure of inhibition with a color Stroop task and a measure of verbal memory with a words list recall task and with a paired-associates memory task (see the Method section above).

Due to the existence of nonnormally distributed residuals in these statistical models, we used the nonparametric Spearman correlations (two-tailed), adjusted for multiple comparisons with the Bonferroni correction. The correlations are computed between measures of the same period of testing. Table 10 resumes the correlations between the interference slope of the first period of testing with the STI (Period 1) and the interference slope of the second period and the inhibition and verbal memory measures (words list and paired associates, all Period 2).

Results show a positive correlation between sensitivity to the interference parameter during Period 1 and sensitivity to interference in a nonnumerical associative memory task (Period 1). Conversely, sensitivity to the interference parameter does not correlate with any inhibition or verbal memory measures. Let us note that the same results appear if we calculate the correlations between the three last tasks and the interference slope in Period 1. This means that sensitivity to interference in a multiplication task reflects a

Table 7
Multiple Regression in the Performance (Mean Accuracy and Median RT) of Fourth-Grade Children With the Interference Parameter Slope and the Problem Size Slope as Independent Variables for the First Period of Testing

Period 1	Zero-order correlation	Partial correlation	t	p	β	R^2	M (SD) % CR RT
Mean accuracy							
Interference parameter slope	−.484	−.544	−4.255	<.001	−.580	.300	89.7 (9.2)
Problem size slope	−.071	−.293	−2.009	.051	−.274		
Median RT							
Interference parameter slope	.575	.599	4.908	<.001	.639	.360	2,934 (1,496)
Problem size slope	−.042	.208	1.398	.169	.182		

Note. Reaction time (RT) is shown in milliseconds. CR = correct responses.

Table 8
Multiple Regression on the Performance (Mean Accuracy and Median RT) With the Interference Parameter Slope and the Problem Size Slope as Independent Variables for the Second Period of Testing (Grade 5)

Period 2	Zero-order correlation	Partial correlation	*t*	*p*	β	R^2	*M* (*SD*) % CR RT
Mean accuracy							
Interference parameter slope	−.457	−.412	−2.965	.005	−.418	.224	90.1 (9.9)
Problem size slope	.255	.137	0.909	.369	.128		
Median RT							
Interference parameter slope	.612	.694	6.328	<.001	.721	.493	2,246 (841)
Problem size slope	.142	.435	3.169	.003	.361		

Note. Reaction time (RT) is shown in milliseconds. CR =correct responses.

general sensitivity to interference but does not correspond to dominant response inhibition or (associative) memory capacities.

Retrieval strategy deficit: Storage deficit or access deficit? During the second period of testing, the children were submitted to a time-limited multiplication production task, aimed at getting a measure of their retrieval strategy (see the Method section). The time-limited multiplication task forces the children to produce an answer for each problem in the assigned time (2 seconds). This procedure permits retrieval capacity to be measured by preventing other strategies from being used. We therefore tested whether sensitivity to the interference parameter of multiplication (interference slope) correlated with performance in this task measuring retrieval performance.

We also used a multiplication table membership judgment task to test the hypothesis that hypersensitivity to interference prevents a person from storing arithmetic facts. We therefore tested whether children who are more sensitive to the interference parameter encounter more difficulties in a judgment task than the controls do. If that is the case, the results would support the assertion that sensitivity to interference disturbs the storage process; otherwise, they would support the assertion that sensitivity to interference disturbs access to arithmetic facts.

We used Spearman's nonparametric correlation for the reason mentioned above. We used the slope of the second period of testing, because the time-limited multiplication production task and the judgment task were submitted during this period of testing. The interference slope correlated negatively with accuracy in the time-limited multiplication production task, $\rho(45) = -.750$, $p < .001$. In the table membership judgment task, the interference slope did not correlate with accuracy but correlated with the mean reaction time; respectively, $\rho(45) = -.230$, $p = .125$, and $\rho(45) = .433$, $p = .003$. These results indicate that children who are the more sensitive to the interference parameter of multiplication are also those who perform less well in the time-limited multiplication task and who are slower in the table membership judgment task.

Discussion

The aim in this article was to test whether the learning of arithmetic facts is an interference-prone situation and so whether, consequently, this learning is disturbed in case of hypersensitivity to interference in memory. According to the interference-based forgetting memory model (e.g., Oberauer & Lange, 2008), the feature overlap between items to be remembered determines the quality of their memory trace. The more features items share, the less strongly they will be held in the memory. On the basis of this theory, we created a parameter measuring the feature overlap between the 36 multiplication problems, taking into account the usual learning order (from the two times table up to the nine times table). This interference parameter therefore represents the proactive interference weight for each multiplication problem. We assumed that interference during learning would result in long-term associative interference. Two main questions were addressed in this article and are successively discussed hereinafter.

First, we tested whether the interference parameter can predict, beyond the problem size, difficulty across different multiplication problems. By analyzing the data from Campbell (1997), the interference parameter has been shown to determine part of the speed and accuracy across multiplications, in undergraduates. Furthermore, the interference parameter could explain the ties and the five effects. In the first study, we tested this hypothesis through the development of the multiplications network with third-grade chil-

Table 9
Multiple Regression on the Performance (Mean Accuracy and Median RT) of Fifth-Grade Children (Period 2) With the Interference Parameter Slope and the Problem Size Slope (Tested in Grade 4, Period 1) as Independent Variables

Period 1 (VI) → Period 2 (VD)	Zero-order correlation	Partial correlation	*t*	*p*	β	R^2	*M* (*SD*) % CR RT
Mean accuracy							
Interference parameter slope	−.373	−.409	−2.942	.005	−.437	.168	90.1 (9.9)
Problem size slope	−.031	−.185	−1.236	.223	−.184		
Median RT							
Interference parameter slope	.554	.592	4.816	<.001	.632	.350	2,246 (841)
Problem size slope	.000	.249	1.686	.099	.221		

Note. Reaction time (RT) is shown in milliseconds. CR =correct responses; VI = interference parameter slope and problem size slope; VD = mean accuracy and median RT.

Table 10
Spearman Correlations Between Sensitivity to the Interference Parameter and a Nonnumerical Sensitivity to Interference, Inhibition, and Verbal Memory Capacities

Spearman's rho	STI, Period 1	Inhibition (Stroop), Period 2	Words list (CMS), Period 2	Paired-associates (WMS), Period 2
Interference slope, Period 1	.506***			
Interference slope, Period 2		.114	−.297	.066

Note. STI = sensitivity to interference; CMS = Children's Memory Scale; WMS = Wechsler Intelligence Scale for Adults.
*** $p = .001$ with Bonferroni correction.

dren, fifth-grade children, and undergraduate students. The results showed that performance in multiplication was massively influenced by the two factors investigated—namely, the interference parameter and the problem size—but in different ways. On the one hand, the problem size largely influenced accuracy in multiplication (third-grade children, fifth-grade children, and undergraduate students). This indicates that the higher the value of the multiplication's answer, the more error prone this multiplication is. On the other hand, the interference parameter largely influenced the reaction time needed for solving the multiplication problem for all three age groups. When individuals respond correctly, the average reaction time increases as the interference weight of the problem increases. One interpretation is that high-interfering problems are retrieved by fewer individuals than low-interfering problems are. Results seem to reflect that the interference parameter influences the storage of arithmetic facts in the memory. Highly interfering problems are not stored, and more time is needed to solve them as a computing strategy is being used. This result supports the hypothesis that feature overlap provokes interference that disturbs storage in the memory. Our findings corroborate those of Zbrodoff (1995), who showed that the learning of alphabet–arithmetic associations mimics the problem size effect better when problems differ in frequency and in similarity. The difference with this theory is that the frequency was replaced by the order of learning in our model. The present results complement the findings of Zbrodoff, which suffer from an interpretative limitation. Indeed, in the alphabet–arithmetic task, the similarity was manipulated by using the same letter several times or only once in calculation associations (e.g., using $A + 2 = C$, $A + 3 = D$, $A + 4 = E$, but using the first operand G only once). The similarity stemmed therefore from the operand overlap. However, the digits 0 to 9 are used the same number of times as operands in multiplication tables. Although this similarity showed a detrimental effect upon performance, the interpretation of this similarity in actual arithmetic problems was compromised. By using the similarity between co-occurrence of digits in the all digits' associations (including the operands and its answer), our findings reconcile Zbrodoff's results with this interpretation.

Current results are also in line with Campbell's studies, which showed that solving arithmetic facts is an interference-prone situation. Our work differs along at least two dimensions, however. First, our hypothesis looks at the encoding stage (which constitutes a premise in the interference parameter), whereas Campbell showed that interference occurs at the retrieval stage of the completed arithmetic facts network. Our studies complement Campbell's theory by showing that interference plays a role at the encoding stage as well. Campbell and Graham (1985) actually assumed that proactive interference could account for the problem size effect, but they did not test this hypothesis as far as we know. By using an alphaplication task in which participants had to learn associations of letters mimicking the arithmetic facts learning, Graham and Campbell (1992) showed that performance in problems encountered later was poorer than in problems introduced in the first set of the learning task. This supports the idea that the order of learning plays a role, but Graham and Campbell did not manipulate the interference level between the problems. Our data support their assumption of a proactive interference in arithmetic facts learning. Second, in our theory, the whole association (both the problem and its answer) is considered when calculating the physical feature overlap, whereas Campbell (1995) took only the operands and operand sign into account. On the basis of Campbell's work, Griffiths and Kalish (2002) previously aimed to test whether the similarity of problems creates interference that explains the pattern of errors observed in adults. For this purpose, they used a tree-sorting task that enabled them to collect perceived similarity ratings. Participants were asked to rate the perceived similarity of the multiplication problems, and this rating was converted into a low-dimensional spatial representation inversely relating the similarity to distance. Results supported the assertion that similarity between multiplications was involved in the explanation of the pattern of errors in adults. Our study, in which the similarity is objectively measured by the feature overlap between digits, is in accordance with this previous study and shows that similarity between multiplications determines the performance across multiplications and across subjects. Our findings are also in line with the fan effect (e.g., Pirolli & Anderson, 1985), showing that concepts that appear several times in an associative memory task are retrieved more slowly than concepts used once. The similarity between the associations to be learned creates interference that delays reaction time in retrieving.

Future research should address the contradiction between the Verguts and Fias (2005) model and our hypothesis. Indeed, the former suggested that the neighbor problems will compete or cooperate according to their consistency with the actual response. For instance, the problem $6 \times 7 = 42$ will cooperate when solving the problem $6 \times 8 = 48$ because of the consistency in the decade of the answers. Contrariwise, the problem $7 \times 8 = 56$ will compete when solving the problem $6 \times 8 = 48$ because of inconsistency between the decade and the unit of the two answers. A problem having more consistent neighbor problems will be better performed than a problem having less consistent neighbor problems. However, in accordance with our feature overlap measure, consistent neighbor problems should provoke more interference than inconsistent neighbor problems. Our results are therefore in opposition with the Verguts and Fias (2005) theory. We should mention however that they consider only the neighbor problems (which have a similar operand to the ongoing problem) and not the entire set of problems, as we did.

The interference parameter we created is based on the feature overlap model (Nairne, 1990; Oberauer & Lange, 2008) and could potentially be subject to discussion. First, we decided to take into account the order of learning in accordance with the Graham and Campbell (1992) finding, showing that problems encountered later were poorly memorized compared to earlier problems, in their alphaplication task. As far as we know, the order of learning in Wallonia usually starts with the two times table and continues progressively up to the nine times table. This order of learning depends on the educational strategies and is likely to vary across cultures. Second, we decided to consider the digits as the feature composition of arithmetic facts. In accordance with Oberauer and Lange (2008) we did not take into account the order of the features in the item, meaning that decades and units were not considered differently. In previous research, we attempted to investigate this small difference and observed that it did not impact the results and interpretation. Because the activation of the digits occurs irrespective of the position value, we chose the simplest (most restrictive) model of feature overlap. Moreover, without taking into account the position value, we considered the commutative pairs as the same problem. This was in accordance with Campbell (1995) as well as with Rickard and Bourne (1996) who showed that commutative pairs are similar in difficulty. However, a difference in difficulty could potentially exist during the development. Unfortunately, we do not have data permitting us to test this hypothesis, which should be investigated in future studies. Finally, it has to be noted that we considered only the interference across multiplications, although interference could exist in a larger arithmetic facts network including other operation problems as simple additions and subtractions. It is however difficult to determine which problems the actual arithmetic facts network includes, because this depends on one's personal experience. Consequently, we focused on multiplications because they are specifically trained during primary school.

Second, we tested whether the individual differences in solving multiplications are partly determined by individual sensitivity to the interference parameter and/or the problem size. In Study 1, we tested this hypothesis through the arithmetic facts' development, with third-grade children, fifth-grade children, and undergraduates. We observed that the interference slope determined a substantial part of the individual differences in terms of speed in the third-grade children, fifth-grade children, and the undergraduate students, beyond the problem size slope.

Similarly, we showed in Study 2 that the interference parameter substantially determined the RT of the case DB, who was impaired in learning arithmetical facts, but the problem size was not significant. More important, compared to controls, DB showed a steeper interference slope, but her problem size slope did not differ from that of the controls.

Finally, the third study reported longitudinal data on fourth-grade children with poor versus normal arithmetic facts fluency, who are building their multiplications network during this period at school. The prediction of the interference parameter was studied after 1 year of development.

Results showed again that the children's interference slope determined a major part of the performance (in accuracy and speed) in multiplication in both the fourth and fifth grades. The interference slope of the first period of testing (in fourth grade) also predicted the performance (accuracy and speed) in multiplication 1 year later. Moreover, children who were more sensitive to the interference parameter also performed worse in the time-limited multiplication production task, where the retrieval strategy is the only successful strategy, again supporting the idea that this sensitivity disturbs the storage of multiplication facts and consequently disturbs the use of the retrieval strategy. Furthermore, the sensitivity to the interference parameter correlated with the speed in the table membership judgment task. This result supports the idea that children who are sensitive to the interference parameter build a weaker or smaller arithmetic facts network for multiplications, and they therefore need more time to judge whether a number belongs to the multiplication tables' answers. Interference therefore already plays a detrimental role in the encoding/learning phase. Nonetheless, the interference parameter could also impact on the retrieval process. Indeed, the interference parameter, representing the progressive feature overlap during learning multiplication, could raise competition between the potential responses of a problem during retrieval. In other words, after creation of a complete arithmetic fact network, if a problem is more interfering, numerous answers can be activated in parallel and compete because of similarity, whereas if a problem is less interfering, few competitors will be activated (Wickelgren, 1979). Some evidence of similarity interference during the retrieval stage has been reported in a retrieval-induced forgetting paradigm. In several experiments, Phenix and Campbell (2004) tested the effect of practice on the lure effect in a verification multiplication task. Of importance, they showed that after practice of specific multiplication facts, the performance for practiced product-related lures decreased and the performance for practiced product-unrelated lures was enhanced. This indicates that global similarity (operands with answer) across problems creates interference in a retrieval context. The detrimental effect of the interference parameter during the associative retrieval should be specifically tested in future studies.

This last study also aimed at refining the hypersensitivity-to-interference concept. First, we showed that sensitivity to the interference parameter was positively correlated with a measure of nonnumerical sensitivity to interference in associative memory. This result thus indicates that it is not a characteristic specific to the numerical domain but is a domain-general process.

Second, we tested whether sensitivity to interference reflects a lack of verbal memory capacity and measured verbal memory capacity with words list and paired-associates recall memory tasks. Neither of the verbal memory measures correlated with sensitivity to interference, sustaining the assumption of different processes. Finally, we tested whether the sensitivity to interference in memory resides in an inhibition deficit. However, results dismissed this assumption, revealing an independent relation between the sensitivity to interference in multiplication and inhibition capacities in children. Accordingly, the resistance to proactive interference has been convincingly demonstrated by Friedman and Miyake (2004) as being different from prepotent response inhibition and inhibition to distractors. According to Friedman and Miyake, the resistance to proactive interference is the ability to resist memory intrusions from irrelevant information that was previously relevant to the task. Some studies brought to light memory intrusions from irrelevant information in children with dyscalculia or in adults who are less performant in simple arithmetic (Barrouillet et al., 1997; Censabella & Noël, 2004; Geary et al., 2012; Passolunghi & Siegel, 2004). These studies interpreted the intrusions as an inhibition problem. These results could actually agree with the hypersensitivity-to-interference hypothesis.

The investigation of the individual difference in arithmetic facts effect (problem size effect) relative to the global performance in arithmetic facts was investigated by Barrouillet and Lépine (2005). This study compared third- and fourth-grade children with low versus high working memory capacities in single-digit additions. Barrouillet and Lépine assumed that working memory capacities represent the attentional resources that are required for processing and storing materials in the long-term memory and that are required for activating knowledge from the long-term memory. They predicted and showed that children with low working memory capacities use fewer retrieval strategies than children with high working memory capacities do. On the basis of Siegler's (1996) theory that predicts that as the difficulty of the problem increases the effect of working memory capacity increases, they predicted an interaction between the problem size effect and the group (children with low vs. high working memory capacities). However, results did not support this last assumption, showing no difference in problem size effect between groups. They wanted to test the interaction between groups and the problem difficulty, which is usually considered to be related to the problem size. Our studies showed, however, that the interference parameter substantially predicted performance across multiplications. Accordingly, the link between the retrieval and the working memory levels could potentially be explained by our interference parameter. Future studies on math learning disabilities should include a measure of sensitivity to interference in memory and/or should test the individual sensitivity to the interference parameter of the multiplication problems. According to our findings, one could imagine that the global math achievement is partly influenced by the sensitivity to interference in memory.

When evaluating sensitivity to interference in the multiplication problems, one alternative explanation could account for the results. In our hypothesis, the sensitivity to interference is viewed as an ability to resist or suppress irrelevant information during ongoing processing. We considered the difference in this ability between participants. However, this ability can be influenced by the individual representation of the material used. Because the interference comes from the feature overlap between the items to remember, the individual representation of these items will influence the feature overlap. The richer a representation is, the more features this representation has. When a representation has numerous features, it can be better distinguished from others (distinctiveness). One can therefore imagine that when someone has a poor representation of numbers, he or she might experience more sensitivity to the interference parameter. Consequently, the relationship between the interference parameter and global performance in solving multiplications could potentially be explained by poor representations of numbers. A weak magnitude representation (or a difficulty in accessing the representation from symbols) could make the multiplication associations fuzzy, less distinctive, and therefore more interference prone. This hypothesis is certainly worth testing. Nonetheless, the hypersensitivity to interference in memory hypothesis remains robust, because the case DB did not show any number representations deficit and also because people with an arithmetic facts deficit have been shown to have hypersensitivity to interference in nonnumerical tasks, which cannot be explained by the alternative assumption.

Perspectives and Summary

This hypothesis of hypersensitivity to interference responsible for arithmetic facts storage deficit has important implications for educational strategies as well as for the assessment and treatment of developmental dyscalculia. When a new cause of arithmetic facts deficit is discovered, the question of treatment is consequently raised. Despite the huge interest in finding a treatment, the question is not simple. Can we act on the ability to suppress irrelevant information? Could we train people with material that progressively increases the level of interference and decrease their sensitivity to interference in this manner? Could these persons suffering from hypersensitivity to interference be trained to use an explicit strategy for reducing the interference effect? Future studies should focus on such alternative possibilities for treatment.

Our hypothesis is currently sustained by behavioral data, with a case study and some group studies. Future studies should investigate this hypothesis with imaging studies allowing the neural correlates of this phenomenon to be explored. The activation of the medial temporal lobe, in particular the hippocampus, has been shown when children are learning arithmetic facts (De Smedt et al., 2011). Because the hippocampus is known to sustain declarative memory and more precisely relational memory, a structural or functional difference in the hippocampus could be observed in children with arithmetic facts deficit. Alternatively, the resolution of proactive interference has been shown to involve the left inferior frontal cortex (e.g., Jonides & Nee, 2006). A difference in this brain structure could potentially explain the hypersensitivity to interference of some people. These two assumptions should be the object of future studies.

Because the hypersensitivity to interference is not specific to numbers, other learning could be affected and should be investigated. Hypersensitivity to interference could potentially disturb the learning of grapheme–phoneme conversion during the learning of reading or maybe disturb the acquisition of homophones. This opens new avenues for research, especially given the observation that people suffering from dyslexia often have difficulties in learning arithmetic facts, in particular multiplication facts (De Smedt & Boets, 2010)

In summary, this work shows that the feature overlap in multiplications creates interference and determines part of the difficulty across multiplication problems, beyond the problem size. Moreover, it shows that being sensitive to this interference parameter of multiplications negatively influences performance in multiplication. People who are more sensitive to this feature overlap in multiplication problems show slower reaction times in all age groups, and in the fourth and fifth grade, these children are also less accurate. Furthermore, the sensitivity to the interference parameter has been shown to be directly linked to a deficit in retrieval strategy due to a weaker storage of the arithmetic facts. Finally, we found that the sensitivity to the interference parameter of multiplication problems is partly linked to sensitivity to interference in general but not with inhibition or verbal memory capacities. We conclude that the learning and storage of multiplications is particularly interference prone because of feature overlap and that people with hypersensitivity to interference in memory will therefore encounter difficulties in this learning. These new findings should be taken into consideration in education in schools and in the diagnosis and treatment of dyscalculia.

References

Albaret, J.-M., & Migliore, L. (1999). *Test d'attention sélective de Stroop* [Stroop test of selective attention]. Paris, France: Editions du Centre de Psychologie Appliquée.

Ashcraft, M. H. (1982). The development of mental arithmetic: A chronometric approach. *Developmental Review, 2,* 213–236. http://dx.doi.org/10.1016/0273-2297(82)90012-0

Ashcraft, M. H. (1987). Children's knowledge of simple arithmetic: A developmental model and simulation. In J. Bisanz, C. Brainerd, & R. Kail (Eds.), *Formal methods in developmental psychology* (pp. 302–338). New York, NY: Springer.

Ashcraft, M. H., & Christy, K. S. (1995). The frequency of arithmetic facts in elementary texts: Addition and multiplication in Grades 1–6. *Journal for Research in Mathematics Education, 26,* 396–421. http://dx.doi.org/10.2307/749430

Barrouillet, P., Fayol, M., & Lathuliere, E. (1997). Selecting between competitors in multiplication tasks: An explanation of the errors produced by adolescents with learning difficulties. *International Journal of Behavioral Development, 21,* 253–275.

Barrouillet, P., & Lépine, R. (2005). Working memory and children's use of retrieval to solve addition problems. *Journal of Experimental Child Psychology, 91,* 183–204. http://dx.doi.org/10.1016/j.jecp.2005.03.002

Barrouillet, P., Mignon, M., & Thevenot, C. (2008). Strategies in subtraction problem solving in children. *Journal of Experimental Child Psychology, 99,* 233–251. http://dx.doi.org/10.1016/j.jecp.2007.12.001

Campbell, J. I. D. (1987). Network interference and mental multiplication. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13,* 109–123. http://dx.doi.org/10.1037/0278-7393.13.1.109

Campbell, J. I. D. (1995). Mechanisms of simple addition and multiplication: A modified network-interference theory and simulation. *Mathematical Cognition, 1,* 121–164.

Campbell, J. I. D. (1997). On the relation between skilled performance of simple division and multiplication. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23,* 1140–1159. http://dx.doi.org/10.1037/0278-7393.23.5.1140

Campbell, J. I. D., & Graham, D. J. (1985). Mental multiplication skill: Structure, process, and acquisition. *Canadian Journal of Psychology/Revue Canadienne de Psychologie, 39,* 338–366. http://dx.doi.org/10.1037/h0080065

Censabella, S., & Noël, M. P. (2004). Interference in arithmetic facts: Are active suppression processes involved when performing simple mental arithmetic? *Cahiers de Psychologie Cognitive/Current Psychology of Cognition, 22,* 635–671.

Cohen, M. J. (2001). *Echelle de mémoire pour enfants* [Children's Memory Scale]. Paris, France: Editions du Centre de Psychologie Appliquée.

Crawford, J. R., & Garthwaite, P. H. (2004). Statistical methods for single-case studies in neuropsychology: Comparing the slope of a patient's regression line with those of a control sample. *Cortex, 40,* 533–548. http://dx.doi.org/10.1016/S0010-9452(08)70145-X

Crawford, J. R., & Howell, D. C. (1998). Comparing an individual's test score against norms derived from small samples. *Clinical Neuropsychologist, 12,* 482–486. http://dx.doi.org/10.1076/clin.12.4.482.7241

De Brauwer, J., Verguts, T., & Fias, W. (2006). The representation of multiplication facts: Developmental changes in the problem size, five, and tie effects. *Journal of Experimental Child Psychology, 94,* 43–56. http://dx.doi.org/10.1016/j.jecp.2005.11.004

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44,* 1–42.

De Smedt, B., & Boets, B. (2010). Phonological processing and arithmetic fact retrieval: Evidence from developmental dyslexia. *Neuropsychologia, 48,* 3973–3981. http://dx.doi.org/10.1016/j.neuropsychologia.2010.10.018

De Smedt, B., Holloway, I. D., & Ansari, D. (2011). Effects of problem size and arithmetic operation on brain activation during calculation in children with varying levels of arithmetical fluency. *NeuroImage, 57,* 771–781. http://dx.doi.org/10.1016/j.neuroimage.2010.12.037

De Visscher, A., & Noël, M. P. (2013). A case study of arithmetic facts dyscalculia caused by a hypersensitivity-to-interference in memory. *Cortex, 49,* 50–70. http://dx.doi.org/10.1016/j.cortex.2012.01.003

De Visscher, A., & Noël, M.-P. (2014). Arithmetic facts storage deficit: The hypersensitivity-to-interference in memory hypothesis. *Developmental Science, 17,* 434–442. http://dx.doi.org/10.1111/desc.12135

Farrel, S., & Lewandowsky, S. (2002). An endogenous distributed model of ordering in serial recall. *Psychonomic Bulletin & Review, 9,* 59–79.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General, 133,* 101–135. http://dx.doi.org/10.1037/0096-3445.133.1.101

Garnett, K., & Fleischner, J. E. (1983). Automatization and basic fact performance of normal and learning disabled children. *Learning Disability Quarterly, 6,* 223–230. http://dx.doi.org/10.2307/1510801

Geary, D. C., Brown, S. C., & Samaranayake, V. A. (1991). Cognitive addition: A short longitudinal study of strategy choice and speed-of-processing differences in normal and mathematically disabled children. *Developmental Psychology, 27,* 787–797. http://dx.doi.org/10.1037/0012-1649.27.5.787

Geary, D. C., Hoard, M. K., & Bailey, D. H. (2012). Fact retrieval deficits in low achieving children and children with mathematical learning disability. *Journal of Learning Disabilities, 45,* 291–307. http://dx.doi.org/10.1177/0022219410392046

Geary, D. C., Hoard, M. K., & Hamson, C. O. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for a mathematical disability. *Journal of Experimental Child Psychology, 74,* 213–239. http://dx.doi.org/10.1006/jecp.1999.2515

Graham, D. J., & Campbell, J. I. D. (1992). Network interference and number-fact retrieval: Evidence from children's alphaplication. *Canadian Journal of Psychology/Revue Canadienne de Psychologie, 46,* 65–91.

Griffiths, T. L., & Kalish, M. L. (2002). A multidimensional scaling approach to mental multiplication. *Memory & Cognition, 30,* 97–106. http://dx.doi.org/10.3758/BF03195269

Hall, J. F. (1971). Formal intralist response similarity: Its role in paired-associate learning. *American Journal of Psychology, 84,* 521–528.

Jonides, J., & Nee, D. E. (2006). Brain mechanisms of proactive interference in working memory. *Neuroscience, 139,* 181–193. http://dx.doi.org/10.1016/j.neuroscience.2005.06.042

Jordan, N. C., Hanich, L. B., & Kaplan, D. (2003). Arithmetic fact mastery in young children: A longitudinal investigation. *Journal of Experimental Child Psychology, 85,* 103–119. http://dx.doi.org/10.1016/s0022-0965(03)00032-8

Jordan, N. C., & Montani, T. O. (1997). Cognitive arithmetic and problem solving: A comparison of children with specific and general mathematics difficulties. *Journal of Learning Disabilities, 30,* 624–634.

Kaufmann, L. (2002). More evidence for the role of the central executive in retrieving arithmetic facts: A case study of severe developmental dyscalculia. *Journal of Clinical and Experimental Neuropsychology, 24,* 302–310. http://dx.doi.org/10.1076/jcen.24.3.302.976

LeFevre, J.-A., & Morris, J. (1999). More on the relation between division and multiplication in simple arithmetic: Evidence for mediation of division solutions via multiplication. *Memory & Cognition, 27,* 803–812. http://dx.doi.org/10.3758/BF03198533

LeFevre, J.-A., Sadesky, G. S., & Bisanz, J. (1996). Selection of procedures in mental addition: Reassessing the problem size effect in adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 216–230. http://dx.doi.org/10.1037/0278-7393.22.1.216

Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition, 18,* 251–269. http://dx.doi.org/10.3758/BF03213879

Noël, M.-P., Seron, X., & Trovarelli, F. (2004). Working memory as a predictor of addition skills and addition strategies in children. *Cahiers de Psychologie Cognitive/Current Psychology of Cognition, 22,* 3–25.

Oberauer, K., & Lange, E. B. (2008). Interference in verbal working memory: Distinguishing similarity-based confusion, feature overwriting, and feature migration. *Journal of Memory and Language, 58,* 730–745. http://dx.doi.org/10.1016/j.jml.2007.09.006

Passolunghi, M. C., Cornoldi, C., & De Liberto, S. (1999). Working memory and intrusions of irrelevant information in a group of specific poor problem solvers. *Memory & Cognition, 27,* 779–790. http://dx.doi.org/10.3758/BF03198531

Passolunghi, M. C., & Siegel, L. S. (2004). Working memory and access to numerical information in children with disability in mathematics. *Journal of Experimental Child Psychology, 88,* 348–367. http://dx.doi.org/10.1016/j.jecp.2004.04.002

Phenix, T. L., & Campbell, J. I. (2004). Effects of multiplication practice on product verification: Integrated structures model or retrieval-induced forgetting? *Memory & Cognition, 32,* 324–335. http://dx.doi.org/10.3758/BF03196862

Pirolli, P. L., & Anderson, J. R. (1985). The role of practice in fact retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 11,* 136–153. http://dx.doi.org/10.1037/0278-7393.11.1.136

Rickard, T. C., & Bourne, L. E. (1996). Some tests of an identical elements model of basic arithmetic skills. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 1281–1295. http://dx.doi.org/10.1037/0278-7393.22.5.1281

Roussel, J.-L., Fayol, M., & Barrouillet, P. (2002). Procedural vs. direct retrieval strategies in arithmetic: A comparison between additive and multiplicative problem solving. *European Journal of Cognitive Psychology, 14,* 61–104. http://dx.doi.org/10.1080/09541440042000115

Siegler, R. S. (1988). Strategy choice procedures and the development of multiplication skill. *Journal of Experimental Psychology: General, 117,* 258–275. http://dx.doi.org/10.1037/0096-3445.117.3.258

Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking*. Oxford, United Kingdom: Oxford University Press.

Slade, P. D., & Russel, G. F. M. (1971). Developmental dyscalculia: A brief report on four cases. *Psychological Medicine, 1,* 292–298. http://dx.doi.org/10.1017/S0033291700042252

Sokol, S. M., McCloskey, M., Cohen, N. J., & Aliminosa, D. (1991). Cognitive representations and processes in arithmetic: Inferences from the performance of brain-damaged subjects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 355–376. http://dx.doi.org/10.1037/0278-7393.17.3.355

Temple, C. M., & Sherwood, S. (2002). Representation and retrieval of arithmetical facts: Developmental difficulties. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 55*(A), 733–752. http://dx.doi.org/10.1080/02724980143000550

Verguts, T., & Fias, W. (2005). Interacting neighbors: A connectionist model of retrieval in single-digit multiplication. *Memory & Cognition, 33,* 1–16. http://dx.doi.org/10.3758/BF03195293

Wechsler, D. (2005). *Echelle d'intelligence de Wechsler pour enfants et adolescents—quatrième édition* [Wechsler Intelligence Scale for Children—Fourth Edition]. Paris, France: Editions du Centre de Psychologie Appliquée.

Wechsler, D. (2011). *Echelle d'intelligence de Wechsler pour adultes—quatrième edition* [Wechsler Intelligence Scale for Adults—Fourth Edition]. Paris, France: Editions du Centre de Psychologie Appliquée.

Wickelgren, W. A. (1979). *Cognitive psychology*. Englewood Cliffs, NJ: Prentice-Hall.

Yu, X., Chen, C., Pu, S., Wu, C., Li, Y., Jiang, T., & Zhou, X. (2011). Dissociation of subtraction and multiplication in the right parietal cortex: Evidence from intraoperative cortical electrostimulation. *Neuropsychologia, 49,* 2889–2895. http://dx.doi.org/10.1016/j.neuropsychologia.2011.06.015

Zbrodoff, N. J. (1995). Why is 9 +7 harder than 2 + 3? Strength and interference as explanations of the problem-size effect. *Memory & Cognition, 23,* 689–700. http://dx.doi.org/10.3758/BF03200922

Appendix A

Comparison of the Correlations Between the Performance (Mean Accuracy, Median RT) of the Third-Grade Children, Fifth-Grade Children, and Undergraduates, and the Two Problem Size Indices: Product and Maximum Operand

Variable	Mean accuracy			Median RT		
	3rd-grade children	5th-grade children	Undergraduates	3rd-grade children	5th-grade children	Undergraduates
Product	−.760	−.554	−.645	.507	.546	.695
Maximum operand	−.580	−.422	−.529	.444	.619	.679

Note. RT = reaction time.

(*Appendices continue*)

Appendix B

Stimuli of the Multiplication Task Used for Third-Grade Children, Fifth-Grade Children, and Undergraduate Students

Problem	Response	Condition	Problem	Response	Condition	Problem	Response	Condition
2 × 3 =	6	small first	4 × 2 =	8	large first	2 × 2	4	tie
2 × 5 =	10	small first	6 × 2 =	12	large first	3 × 3	9	tie
3 × 4 =	12	small first	7 × 2 =	14	large first	4 × 4	16	tie
2 × 8 =	16	small first	5 × 3 =	15	large first	5 × 5	25	tie
2 × 9 =	18	small first	6 × 3 =	18	large first	6 × 6	36	tie
4 × 5 =	20	small first	7 × 3 =	21	large first	7 × 7	49	tie
3 × 8 =	24	small first	6 × 4 =	24	large first	8 × 8	64	tie
4 × 7 =	28	small first	9 × 3 =	27	large first	9 × 9	81	tie
5 × 6 =	30	small first	8 × 4 =	32	large first			
4 × 9 =	36	small first	7 × 5 =	35	large first			
5 × 8 =	40	small first	7 × 6 =	42	large first			
6 × 8 =	48	small first	9 × 5 =	45	large first			
6 × 9 =	54	small first	8 × 7 =	56	large first			
8 × 9 =	72	small first	9 × 7 =	63	large first			

Appendix C

Mean of the Medians of Reaction Time and Mean Accuracy for Each Problem Separately for Third-Grade Children, Fifth-Grade Children, and Undergraduates

	Accuracy			Reaction time		
Problem	Grade 3	Grade 5	Undergraduates	Grade 3	Grade 5	Undergraduates
2 × 2 =	95	93	100	4,614.5	1,884	1,222.5
2 × 4 =	92	100	98	4,863	2,265.5	1,506
2 × 6 =	89	95	98	6,314.5	2,297	1,560
2 × 7 =	79	100	96	5,887.5	2,787	1,636.5
3 × 2 =	95	98	98	4,434	1,981	1,379
3 × 3 =	76	98	100	5,614	2,408	1,402.5
3 × 5 =	84	98	100	6,982	2,840	1,773
3 × 6 =	50	98	100	12,271	4,625	2,550.5
3 × 7 =	50	93	98	10,657	3,565	1,804
3 × 9 =	53	93	87	14,896.5	3,528	2,538.5
4 × 3 =	71	100	100	8,019	3,222	1,638.5
4 × 4 =	66	93	98	6,972	2,973	1,529
4 × 6 =	47	95	98	11,642	3,882	1,765
4 × 8 =	42	93	80	13,517	4,769	2,714
5 × 2 =	95	98	98	4,779	2,332	1,705
5 × 4 =	82	98	98	5,983	3,092	1,762
5 × 5 =	92	95	98	8,048	2,726	1,548
5 × 7 =	61	95	98	10,117	3,177.5	1,793
5 × 9 =	76	98	91	8,081	3,401	2,198
6 × 5 =	63	93	85	11,460.5	4,051	3,010
6 × 6 =	21	95	100	16,122	2,916	1,681.5
6 × 7 =	8	93	83	17,396	3,718	3,631
7 × 4 =	18	93	91	11,897	4,173	2,616.5
7 × 7 =	13	86	80	26,247	3,999	2,189
7 × 8 =	18	79	61	12,089	5,536	3,455.5
7 × 9 =	18	79	80	19,534	6,535	3,805
8 × 2 =	82	100	98	5,710	2,714	2,043

(*Appendices continue*)

Appendix C (*continued*)

Problem	Accuracy			Reaction time		
	Grade 3	Grade 5	Undergraduates	Grade 3	Grade 5	Undergraduates
8 × 3 =	53	86	98	11,262	5,263,5	2,640
8 × 5 =	68	95	93	10,280.5	4,345.5	2,459
8 × 6 =	18	86	67	8,351	4,392.5	2,701
8 × 8 =	21	83	83	10,260.5	3,053	2,338
9 × 2 =	79	100	98	6,299.5	2,538	1,746
9 × 4 =	39	74	89	11,901	6,051	3,263
9 × 6 =	18	95	65	16,414	5,132	4,204.5
9 × 8 =	37	79	85	9,083.5	4,421	3,969
9 × 9 =	29	100	96	7,500	2,886.5	2,172.5
M	55.5	92.97	91.28	10,152.76	3,596.67	2,276.38
SD	28.46	6.95	10.57	4,777	1,157	800

Appendix D

Performance Across Multiplications (Mean of Median Reaction Time and Mean Accuracy) of the Control Group and DB

Problem	Control group (N = 11)		DB
	RT (ms)	% CR	RT (ms) or errors
2 × 2	733	100	912
2 × 3	895	100	1,175
2 × 4	810	100	1,402
2 × 5	878,5	100	1,608
2 × 6	891	100	1,256
2 × 7	883	100	829
2 × 8	1,026	100	1,448
2 × 9	892	100	1,998
3 × 3	784	100	990
3 × 4	865	100	2,984
3 × 5	791	100	1,866
3 × 6	996.5	100	2,958
3 × 7	907	100	2,317
3 × 8	1,134	100	4,613
3 × 9	1,035	100	5,964
4 × 4	864	100	3,176
4 × 5	916	100	1,639
4 × 6	1,110	100	2,963
4 × 7	1,043	100	5,171
4 × 8	1,513.5	91	3,969
4 × 9	1,490	100	6,758
5 × 5	783	100	1,108
5 × 6	1,087	100	1,906
5 × 7	1,124	100	1,989
5 × 8	1,170	100	1,486
5 × 9	1,234	100	2,489
6 × 6	812	100	voice key problem
6 × 7	1,200	100	13,619
6 × 8	1,206	91	error (46)
6 × 9	1,856	91	11,773
7 × 7	1,044.5	100	15,217
7 × 8	1,456	91	4,895
7 × 9	1,319	100	7,678
8 × 8	1,157	100	1,837
8 × 9	1,891	91	error (71)
9 × 9	862	100	2,652
M	1,074	98.74	3,717
SD	283	3.19	3,621

Note. RT = reaction time; CR =correct responses.

(*Appedices continue*)

Appendix E

Stimuli of the Multiplication Table Membership Judgment Task

	Targets (true)	Lures (false)
	12	11
	14	13
	15	17
	16	19
	18	22
	21	23
	24	26
	25	29
	27	31
	28	37
	32	41
	35	34
	36	38
	42	44
	45	46
	48	52
	49	58
	54	62
	56	66
	63	68
	64	74
	72	76
	81	78
M	38.1	42
SD	20	21.2
No. odd	9	9
No. even	14	14

(*Appedices continue*)

Appendix F

Performance Across Multiplications (Mean of Medians Reaction Time and Mean Accuracy) of the Fourth-Grade Children in Period 1 and Period 2

	Period 1		Period 2	
Problem	% RC	RT (ms)	% CR	RT (ms)
2 × 2 =	100	1,520.5	100	1,294
2 × 4 =	95	1,604	98	1,600
2 × 6 =	100	1,782	100	1,555
2 × 7 =	100	1,730	100	1,328
3 × 2 =	100	2,176	99	1,932.5
3 × 3 =	99	2,009	98	1,491
3 × 5 =	99	1,784	100	1,434
3 × 6 =	91	3,656	87	2,594
3 × 7 =	93	3,627	93	2,155
3 × 9 =	89	3,236	83	3,582
4 × 3 =	98	3,617	96	2,050
4 × 4 =	88	2,195	96	1,774.5
4 × 6 =	82	4,550	90	3,431
4 × 8 =	78	4,018	80	3,887
5 × 2 =	100	1,755.5	100	1,507
5 × 4 =	99	2,930.5	98	2,027.5
5 × 5 =	98	1,790.5	98	1,520
5 × 7 =	93	3,211	98	3,017
5 × 9 =	91	3,197	97	2,489
6 × 5 =	93	2,446	95	2,402
6 × 6 =	97	1,707	98	1,302
6 × 7 =	75	3,553	85	2,567.5
7 × 4 =	95	3,740	80	3,246.5
7 × 7 =	75	1,882	72	1,474
7 × 8 =	61	5,190.5	53	3,564
7 × 9 =	71	3,627	74	3,973.5
8 × 2 =	99	2,263	100	1,810.5
8 × 3 =	78	4,199	83	3426
8 × 5 =	98	3,074	92	2,597
8 × 6 =	83	5,875	83	3,903
8 × 8 =	79	2,014	76	1,728
9 × 2 =	100	1,998	98	1,842.5
9 × 4 =	85	5,302	80	3,861
9 × 6 =	86	4,876.5	80	4,229
9 × 8 =	68	2,812	89	2,169
9 × 9 =	93	1,872	96	1,655
M	90	2,967	90	2,401
SD	11	1,200	11	930

Note. RT = reaction time; CR = correct responses.

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