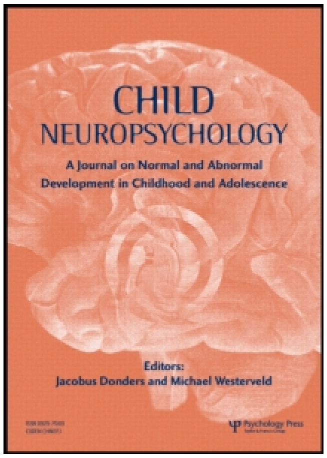

Child Neuropsychology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713657840

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First Published on: 20 December 2006
To cite this Article: Censabella, Sandrine and Noël, Marie-Pascale (2006) 'The Inhibition Capacities of Children with Mathematical Disabilities', Child Neuropsychology, 14:1, 1 - 20
To link to this article: DOI: 10.1080/09297040601052318
URL: http://dx.doi.org/10.1080/09297040601052318

Child Neuropsychology, 14: 1–20, 2008
http://www.psypress.com/childneuropsych
ISSN: 0929-7049 print / 1744-4136 online
DOI: 10.1080/09297040601052318

Psychology Press
Taylor & Francis Group

THE INHIBITION CAPACITIES OF CHILDREN WITH MATHEMATICAL DISABILITIES

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Several authors have argued that mathematical disabilities might result from difficulties in inhibiting irrelevant information. The present study addresses this issue by assessing three inhibition functions in 40 ten-year-old children: suppression of irrelevant information from working memory, inhibition of prepotent responses, and interference control. We found no significant differences between children with math disabilities and typically achieving controls, or between children with arithmetic facts disabilities and children with above-average arithmetic facts skills. These findings, along with other empirical evidence and with theoretical considerations, cast doubt on the inhibition deficit hypothesis.

INTRODUCTION

According to the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 1994), *mathematics disorders* are rather rare, with a prevalence of 1%. However, this prevalence is seriously underestimated and several studies have now shown that about 6% is a more realistic estimate (see Butterworth, 2005, for a review). Nevertheless, in contrast with reading disabilities, there is still much to know about arithmetic disabilities, especially about the underlying cognitive factors.

Beside more basic numerical deficits, two general cognitive factors have been related to math disabilities (Geary, 1993, 1994): working memory (more particularly, the phonological loop and the central executive, see Baddeley, 1997, for a description of working memory) and processing speed (more particularly, counting speed). Indeed, children with math disabilities (MD) have been reported to present working memory deficits (e.g., Geary, Brown, & Samaranayake, 1991; Geary, Hoard, & Hamson, 1999; Hitch & McAuley, 1991; McLean & Hitch, 1999; Passolunghi & Siegel, 2001, 2004) as well as a slowdown of processing speed (e.g., Censabella & Noël, 2005; Koontz & Berch, 1996).

Recently, another cognitive process, inhibition, has been put forward as a causal factor of MD, particularly of arithmetic facts retrieval difficulties. From a theoretical

Sandrine Censabella is supported by a grant from the Fond Special de Recherche of the Université Catholique de Louvain. Marie-Pascale Noël is supported by the National Research Fund of Belgium and by the Concerted Action Research of the Belgian French Community (grant 01/06-267). We are thankful to the anonymous reviewers for their useful comments on previous drafts of this paper.

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viewpoint, inhibition constitutes one of the functions of the central executive (Baddeley, 1996) that controls the content of working memory by suppressing activated but task-irrelevant information. Hence, inhibiting irrelevant information prevents working memory from being overloaded by this information (Bjorklund & Harnishfeger, 1990; Harnishfeger, 1995; Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). Because children with MD often present weak central executive capacities, it seems reasonable to suspect that they also present difficulties in suppressing irrelevant (or no-longer relevant) information from memory.

On empirical ground, the idea that children with MD might undergo inhibition impairment has been first suggested by Koontz and Berch (1996). They administered children with MD numerical and letter matching tasks and observed an interference effect only for children with MD: When judging if the names of the items in numerical pairs (e.g., 2 – • •) were different or not, children with MD, but not typically achieving controls, were slowed down by the irrelevant physical information. Considering this interference as a Stroop-like effect, the authors interpreted this as a result of inefficient inhibition processing in children with MD.

Thus, inhibition seemed an appealing candidate from both theoretical and empirical reasons. The hypothesis according to which MD was a consequence of an inhibition deficit henceforth gained grounds.

Inhibition: A Causal Factor of Math Disabilities?

In an attempt to test this inhibition deficit hypothesis, Barrouillet, Fayol, and Lathulière (1997, experiment 2) presented adolescents with learning disabilities simple multiplication problems with four answers each and asked them to indicate the correct one. They observed that the adolescents erred more often when the false answers were multiples of one of the operands (e.g., $4\times6=18$, 24, 28, or 30?) than when they were not (e.g., $4\times6=21$, 24, 25, or 27?) or when the false answers were not coming from multiplications tables (e.g., $4\times6=22$, 23, 24, or 26?). This associative confusion effect has been well documented in the arithmetic facts literature and is commonly assumed to reflect interference effects: As arithmetic problems are associated, in long-term memory, not only to their correct answers but also to associated incorrect ones, these incorrect answers constitute competitors that hinder retrieval of the correct answer (e.g., Campbell, 1987a, 1987b, 1995; Campbell & Tarling, 1996; Koshmider & Ashcraft, 1991; Stazyk, Ashcraft, & Hamann, 1982). Barrouillet et al. interpreted the confusion effect they observed as resulting from a failure, in adolescent with learning disabilities, in inhibiting the competitors.

In 2001, Bull and Scerif investigated whether several executive functions, including inhibition, were involved in mathematical skills. They found that arithmetic score correlated significantly with the interference score of a numerical version of the Stroop task, even when reading abilities were controlled ($r_{\text{partial}}=-.27$). Note, however, that there was no significant correlation with the classic color-word version of the task. The authors concluded that "children of lower mathematical ability do indeed show difficulties on tasks that measure the ability to inhibit … prepotent information (Stroop interference)" (p. 284).

The specific relationship between arithmetic disabilities and inhibition processes has been more thoroughly examined by Passolunghi and her colleagues. In a longitudinal study, Passolunghi, Cornoldi, and De Liberto (1999) reported that children with poor arithmetic problem-solving abilities showed lower performances than good problem-solvers in working memory tasks. More importantly, children with poor problem-solving skills also committed more intrusion errors (i.e., erroneously recalling nontarget information). For instance, poor problems-solvers made three times as many intrusions errors in the Listening Span task as good problems-solvers. These findings were replicated in two subsequent studies (Passolunghi & Siegel, 2001, 2004). According to the authors, the working memory deficits exhibited by children with poor arithmetic problem-solving abilities were related to the control of information available in memory. Indeed, this type of complex task requires inhibition to the extent that information contained in the sentences has to be processed in order to answer the true/false question but has afterwards to be suppressed from working memory in order to recall properly the target information (i.e., the final word of the sentences). Intrusion errors then indicate that processed information was maintained available in working memory instead of being suppressed. Thus, children with poor arithmetic problem-solving abilities exhibited difficulties in inhibiting task-irrelevant or no-longer relevant information. Because of these difficulties, more information remains in working memory, whether relevant or not, thereby overloading its capacity, accounting for the weaker performances in working memory tasks and for impairment in arithmetic word problem solving (e.g., Passolunghi et al., 1999, Passolunghi & Siegel, 2004).

Finally, Geary, Hamson, and Hoard (2000) reported that one of the most frequent error type committed by young children when solving simple addition consisted in stating the number following one of the addends (generally the larger one) in the counting string, as in $3+6=7$. They asked children to solve addition only by means of retrieval and observed that children with MD (with or without comorbid reading disabilities) committed more counting-string errors than the typically achieving control children. They attributed these counting-string errors to inefficient inhibition of irrelevant associations and concluded that retrieval difficulties of children with MD are related to this inefficient inhibition.

Altogether, these studies support the inhibition deficit hypothesis. However, some evidence coming from other studies of inhibition capacities in children with MD is inconsistent with this view. First, van der Sluis, de Jong, and van der Leij (2004) administered children with MD (with and without comordbid reading disabilities) and control children tasks involving only inhibition, tasks involving only shifting, and tasks involving both processes. They found that children with MD did not differ from the control group on the tasks involving only inhibition. Second, Censabella and Noël (2005) administered children with and without learning disabilities (i.e., MD and reading disabilities) four inhibition tasks. In these tasks, children with learning disabilities exhibited equivalent interference effects to control children. Interestingly, these two studies used a numerical Stroop of the same type as the one used by Bull and Scerif (2001), but both resulted in findings that challenge the conclusions of these latter authors.

To sum up, these studies reported contradictory evidence about inhibition deficits in children with MD. It might be possible, however, that the discrepancies between studies stemmed from the tasks used to assess inhibition, which could in fact involve different inhibition types.

Inhibition Process or Processes?

Inhibition refers to an active suppression mechanism that prevents irrelevant information from disrupting cognitive processing (Harnishfeger, 1995). Given the multiplicity and the diversity of phenomena and paradigms involving inhibition (e.g., Arbuthnott, 1995; Kok, 1999), it seems rather unlikely that one single kind of mechanism would be responsible for all of them. In fact, several studies have shown that inhibition is not a unitary construct. For instance, Kramer, Humphrey, Larish, Logan, and Strayer (1994) administered several tasks tapping inhibition functions to young and old adults and found only low and nonsignificant correlations between these tasks (ranging from .01 to .18), providing "evidence for independent varieties of inhibitory functions" (p. 508). In 2004, Friedman and Miyake administered nine inhibition tasks relating to three inhibition functions (see hereunder). Using a latent variable analysis, they demonstrated that common inhibition abilities are involved in some but not all inhibition tasks. Accordingly, inhibition is currently seen as a family of functions rather than a unitary construct (e.g., Dempster & Corkill, 1999; Harnishfeger, 1995; Hasher et al., 1999; Nigg, 2000; Shilling, Chetwynd, & Rabbitt, 2002; but see Perret, 2003, for an opposite standpoint).

Three functions have been commonly considered and described (e.g., Friedman & Miyake, 2004; Nigg, 2000): suppression of irrelevant information from working memory, inhibition of prepotent response, and interference control. As outlined above, suppression is the clearing of previously activated information that is irrelevant for the task at hand or has become irrelevant after a goal shift (i.e., the deletion of any task-irrelevant information). Prepotent response inhibition can be considered as a process that prevents predominant responses to be produced before being evaluated or before other less probable but potentially appropriate responses can be considered. The third function is anchored in the distinction, frequently overlooked, between inhibition and interference: The former refers to an active suppression *process* or an (active) activation-reducing mechanism (as opposed to the passive diminution or decay of activation), whereas interference stresses the competition among multiple stimuli, targets, or responses and describes a *performance decrement* caused by these competitors (Harnishfeger, 1995), an empirical effect that is opposite to facilitation. Interference does not always call for an active inhibition of the competitors (Anderson & Bjork, 1994), but when it does, it refers to the third inhibition function: interference control, the process by which interference is (actively) prevented, reduced, or resolved.

As Passolunghi and her colleagues indicated (e.g., Passolunghi et al., 1999), intrusions errors committed in memory tasks, such as the Listening Span, reflect suppression processes. Prepotent response inhibition can be assessed by the Stroop paradigm (Stroop, 1935) and interference control by Eriksen's Flanker task (Eriksen & Eriksen, 1974, see for example Friedman & Miyake, 2004).

However, no study has ever tested these three inhibition functions in the same sample of children. Indeed, the few studies that have directly compared inhibition capacities between children with MD and controls have considered only one or two inhibition functions. Passolunghi and her colleagues (e.g., Passolunghi et al., 1999) have focused on suppression in children with poor arithmetic problem-solving abilities. Bull and Scerif (2001) used the Stroop task and thereby investigated prepotent response inhibition in typically achieving children, as did van der Sluis et al. (2004) with children with reading and/or math disabilities. Finally, Censabella and Noël (2005) used the Stroop and Eriksen's Flanker paradigms, hereby assessing both prepotent response inhibition and resistance to interference in children with learning disabilities.

The Present Study

The aim of the present study was to test all three inhibition functions in one single sample of children with MD. Consequently, we administered three inhibition tasks assessing the three aforementioned inhibitory functions: 1) suppression of irrelevant information from working memory, 2) inhibition of prepotent responses, and 3) interference control. We used, respectively, the Listening Span, as used by Passolunghi and her colleagues (1999), the Stroop paradigm, and Eriksen's Flanker task, as used by Censabella and Noël (2005). We contrasted the performance of children with MD against that of typically achieving children of the same age. Furthermore, as it is assumed that children with MD have difficulties in the retrieval of arithmetic fact due to inefficient inhibition processes (Barrouillet et al., 1997; Geary et al., 2000), we subsequently selected only those children who had specific difficulties in the retrieval of arithmetic facts and examined inhibition capacities on this reduced subset of children. So we conducted two sets of analyses: one contrasting children presenting math disabilities and typically achieving children in the first part of the study, and the other contrasting children with arithmetic facts disabilities with above-average control children in the second part.

PART 1: CHILDREN WITH MATH DISABILITIES

Method

Participants. Four upper-middle-class public schools of the French part of Belgium (for a total of 154 fifth-graders) were solicited to participate in this study. Our classification of disabilities was similar to the one used by Swanson (1993), reflecting:

> (1) a learning problem that is specific, generally confined to one or two cognitive areas; (2) the child's achievement is not commensurate with his/her ability as measured by IQ or chronological age; and (3) the learning difficulty is not the result of retardation, poor teaching, or cultural depravation. (p. 90)

Therefore, identification of children with MD was based on arithmetic skills, reading skills, and standard intelligence.

Standardized Tests. Arithmetic skills were assessed using the first part of a standardized pedagogic test (Simonart, 1998) that evaluates the children's global academic level in arithmetic (the correlation between the score of the first part of the test and the total score is $r = .91$). This part, which contains 28 items to complete without time limit, evaluates children's abilities to solve simple calculations involving all four arithmetic operations and fractions, children's comprehension of the decimal, metric, and temporal systems, as well as comprehension of volume and masses (e.g., $23+35=?$; $132 : 4=?$; $1/6\times48=?$; 38.5 $dm^2=?$ m^3; 60 cl = ? l; how long is the duration between 13h45 and 14h15 in a same day?; in "28.5", how many units represent the digit "2"?; which is the smallest numeral: 8/10, 1, 75%, or 0.768?).

Arithmetic facts retrieval skills were also assessed by means of a speeded fluency task. Children were given a first sheet of paper with 80 single-digit additions (from $1+1$ to $9+9$) printed on it and they had 90 seconds to solve (correctly) as many problems as possible (with an emphasis on speed). Then, they received a second sheet of paper with 80 single-digit multiplications (from 1×1 to 9×9) with the same instructions and time limit. The number of correct responses of the two tasks was summed, yielding a fluency score (the correlation between the scores in the addition part and in the multiplication one was .57, $p < .0001$; and between the fluency score and the Simonart test was .26, $p < .001$, $N = 152$).

Reading skills were assessed by means of a subtest taken from a battery developed by Lobrot (1980) to assess reading and spelling. In this task (the L3 task), children have five minutes to read (silently) a maximum of 36 sentences and complete them with one of five given words, involving rapid reading and comprehension. These tasks were collectively administered at the children's schools, the examiner (and the teacher) taking care that children worked on their own tasks and did not copy each other.

Finally, intelligence was assessed by means of a short form of the Wechsler Intelligence Scale for Children-III (WISC-III, French version; Wechsler, 1996) comprising two subtests: Picture Completion and Information. Intelligence Quotients were estimated using Tellegen and Briggs' formula (1967, cited by Sattler, 1982). The correlation between the full-scale IQ and this short form is .81.[1] Note that we preferred this short form to other ones with higher correlations with the full-scale IQ (such as the one comprising the Block Design and Vocabulary subtests) because children with MD often encounter difficulties with the Block Design task due to visuospatial deficits (e.g., Rourke, 1993).

Classification Schemes. To be considered having MD, children had to meet the three following criteria: (1) presenting an arithmetic disability, (2) having a reading score above the 30th percentile (according to the new norms established by Piérart and Grégoire, 2004), and (3) showing an estimated IQ above 85 (which corresponds to one standard deviation below the mean IQ). Disability criterion was the one defined by the ICD-10 (World Health Organization, 1995) and that relates to a two-year delay or more in academic achievement. Thus, the average score of third grade children was taken as a reference ($M = 8.8$, $SD = 4.5$) and children with a score equal to or below 8 were considered as having math disabilities. This rather conservative criterion was chosen in order to reduce the number of false positives, hereby giving more priority to identify children with genuine difficulties than to obtain groups with large sample size. Children with average skills in both arithmetic (mean for the 5th grade $= 16.6$, $SD = 5.2$) and reading (i.e., above the 30th percentile) were considered as typically achieving controls. Moreover, the teacher was asked to confirm if the results of a child to the standardized arithmetic and reading tests reflected his/her skills throughout the year.

Testing Procedure. The selection phase comprised two testing sessions. In the first session, all children were assessed for arithmetic and reading skills with the standardized tests. Three out of the 154 tested were not considered because they did not complete one of these tests. Thirty-eight children were identified as having MD, but 11 of them presented low reading skills (below the 25th percentile) and were therefore excluded from further testing. For each child with MD, a child with average arithmetic score (range: 12–16) was matched as closely as possible for the reading score, the sex, the age, and the class. The remaining 27 children with MD as well as the 27 control children were selected for the second testing session, in which they were individually assessed for intelligence. This session resulted in the exclusion of six children with MD who had an IQ estimate below 85. Finally, one child with MD did not agree to continue the testing. Because the

[1]This value was recomputed because we used the WISC-III and not the WISC-R, as Sattler (1982) did. Therefore, calculation was based on Sattler's indication (see table note C-12, p. 573). IQ estimates were calculated following Sattler's instructions (p. 162) and the formula was based on the intercorrelations between tasks reported in the WISC-III manual.

Table 1 Descriptive Statistics for Children with Math Disabilities (MD) and Typically Achieving Control (TA) Children, and for Children with Arithmetic Facts Retrieval Disabilities (AFD) and Above-Average Controls

		Age (in months)	Arithmetic Score	Fluency Score	Reading Score	Estimated IQ
		Groups classified on the basis of arithmetic scores[a]				
MD	*M*	125.85	6.25	49.05	26.95	98.41
	SD	5.95	1.77	17.51	3.12	7.55
TA Controls	*M*	123.95	14.15	52.95	26.75	101.16
	SD	4.32	1.31	16.25	2.34	9.04
		Groups classified on the basis of fluency scores[b]				
AFD	*M*	125.00	8.83	34.58	25.58	102.66
	SD	4.84	3.59	4.83	2.35	7.96
Controls	*M*	126.83	10.25	72.50	27.17	100.00
	SD	5.18	5.05	11.56	3.04	8.01

[a]$N=20$ in each group. [b]Number of correct responses in the two arithmetic fluency tasks. $N=12$ in each group.

control children were matched on an individual basis, the corresponding seven controls were also excluded.

Finally, two groups of 20 children were selected for the experimental testing. The first group comprised 10 boys and 10 girls classified as children with MD. Ages ranged from 9 years 9 months to 10 years 11 months. The second group comprised 10 boys and 10 girls classified as typically achieving controls (age range: 9 years 7 months – 10 years 11 months). Note that all children had reading scores above the 50th percentile. Descriptive data and statistics for these groups are presented in Table 1. Compared to typically achieving children, children with MD had significantly lower arithmetic skills, $t(38)=16.03$, $p < .0001$, but equivalent fluency scores, $t(38)=0.73$, $p > .4$, reading skills, $t(38)=-0.23$, $p > .8$, and estimated IQs, $t(38)=1.04$, $p > .3$.

Tasks

Color-Word Stroop Test. The stimuli were four French color words (“jaune” - *yellow*, “bleu” - *blue*, “vert” - *green*, and “rouge” - *red*) and four squares of the corresponding colors. The task comprised 96 items, divided in three conditions of 32 items each: neutral (e.g., blue square), congruent (e.g., the word “blue” written in blue ink), and incongruent (e.g., “green” written in blue).

The items were administered in two blocks of 48 items separated by a self-paced pause. They were presented in mixed blocks in a fixed, pseudo-random order with the following constraints: 1) response or item on consecutive trials should not be identical, 2) no more than three consecutive trials should involve the same condition (neutral, congruent, or incongruent), and 3) no trial should involve negative priming (e.g., there was never the case that “blue” written in green was immediately followed by “yellow” written in blue), as the implication of inhibition mechanisms in negative priming has been controversial (for a review see Fox, 1995; or May, Kane, & Hasher, 1995). The response-stimuli interval was 1000 ms.

Children were asked to name the color of the squares or the ink-color of the words as quickly and accurately as possible. They had to answer orally in a microphone connected to a sound-activated relay that controlled a software clock accurate to 1 ms. They were informed about the functioning of the voice key and were asked to avoid making extraneous sounds to prevent premature triggering of the voice-activated relay. Ten practice trials involving other stimuli than the experimental ones (e.g., brown) were administered prior to the experimental items in order to ensure that the children fully understood the tasks instructions and to adjust the voice key sensitivity. Response times (RTs) and error rates were taken into account. Timing began with the presentation of the stimuli and ended when the microphone detected the child's response, causing the stimuli to disappear from the screen. The experimenter recorded the stated answer, and if the RT was spoiled due to the voice key malfunction. No feedback about accuracy or speed was provided.

Flanker Task. The procedure adopted here was simplified compared to the original task developed by Eriksen and Eriksen (1974). Seven aligned letters appeared at the center of the screen and the child was required to name the letter situated in the middle. Five visually dissimilar letters (according to Fisher, Monty, & Glucksberg, 1969) constituted the experimental stimuli (D, G, K, T, and V). The six flanker letters were all the same within each trial. Again, there were three conditions: neutral, in which there were no flankers (e.g., D); congruent, in which the flankers were identical to the target (e.g., D D D D D D D); and incongruent, in which the flanker letters were different from the target (e.g., G G G D G G G). The task consisted of two blocks of 45 mixed stimuli, for a total of 90 items. The pseudo-random order was fixed for all participants with the same constraints as for the Stroop task (the no-negative priming constraint implied that an item such as "G G G D G G G" could not be succeeded by an item as "T T T G T T T"). The procedure was as follow: (1) a fixation point appeared for 500 ms; (2) the stimulus was presented at the center of the screen, the target letter being 0.5 degree above the fixation point, and disappeared when the child answered; and (3) there was a 500 ms delay before the fixation point of the following trial. Response modality and measure were identical to the ones in the Stroop task.

Listening Span. In this test, adapted from Daneman and Carpenter (1980), the experimenter reads sets of sentences (from two to four) to the children. For each sentence, the child was required to indicate whether it was true or not. Then, at the end of the set, the child had to recall the last word of all the sentences included in this set.

The material consisted of 18 true (e.g., "la couronne est pour le roi" – *the crown is for the king*) and 18 false sentences (e.g., "les chevaux vivent dans des nids" – *horses live in nests*) counterbalanced within each set. Stimuli were reduced in length and complexity in order to be appropriate for the children. All the sentences were of simple syntactic structure and of the same syllabic length. Target items (i.e., the last word of each sentence) were all monosyllabic nouns. Within the sets, the sentences as well as the targets were phonologically and semantically dissimilar. A pilot study using this task indicated that the task procedure and sentences were understood by children as young as six years old and had no floor effect for older children.

The examiner read the first sentence of a set to the child who was instructed to determine the truth of the sentence as soon as possible. The child's answer was followed by the presentation of the next sentence. Immediately after the child's answer for the last sentence of the set, the child was required to recall the targets of the presented set (serial recall was not required in order to prevent floor effect). For example, in a two-sentences set composed of the examples noted in the preceding paragraph, the child had to answer "roi, nid" (*king, nest*). There were four sets of two sentences, four sets of three sentences, and four sets of four sentences administered to each child.

Two dependant measures were recorded: the span score, calculated as the number of correct sets (i.e., the number of sets for which all targets have been correctly recalled), and intrusion errors (Passolunghi et al., 1999). The span score is a measure of working memory capacity, and intrusion errors assess suppression skills.

General Procedure

Each child was tested individually in a quiet room at the child's school. The two WISC-III subtests required for the IQ estimation were administered in a preliminary session. The inhibition tasks were administered in a second session (along with other tasks not pertaining to this experiment) lasting about 40 minutes. For half of the children in each group, the tasks were administered in the following order: Flanker, Stroop, Listening Span; for the other half, the administration order was the reverse (Listening Span, Stroop, Flanker). Statistical analysis showed no effect of testing order on the test results.

Results and Discussion

For the computerized tasks (i.e., Stroop and Flanker), spoiled RTs (through failure of the voice key to detect an answer, premature triggering of the key, or multiple responses by the child) were excluded from the analyses. The qualitative nature qualitative nature of the responses was nonetheless taken into account as valid (e.g., when a child corrected himself/herself right away, the last stated answer was always taken into account, whether correct or not, but the RT was marked as spoiled). Latencies for incorrect responses were also eliminated. For each child, the median of correct RTs was calculated for each condition. RT data were analyzed by means of a mixed analysis of variance (ANOVA), with groups (MD vs. controls) as the between-subjects factor and conditions (neutral, congruent, or incongruent) as the within-subjects factor. Error rates and span scores were analyzed with nonparametric statistics, because they were not normally distributed.

Statistical analyses were carried out on raw but also on transformed data, using a logarithmic transformation (base-10) for latencies and an arc-sine transformation for error rates. However, as analyses on raw and on transformed data led to identical results, only statistics performed on raw data are reported in the following section.

Results (means and standard deviations by group) for the Stroop, Flanker, and Listening Span are reported in Table 2.

Color-Word Stroop Test. In total, out of the 3840 administered trials (32 items per condition per child), 9.56% of RTs were spoiled by a voice-key failure and further 2.14% of RTs from incorrect trials were eliminated. (Nevertheless, medians were computed on an average of 29.73 RTs per participant ($SD = 1.52$) for the neutral condition, of 29.73 RTs ($SD = 1.89$) for the congruent one, and of 26.50 RTs ($SD = 3.68$) for the incongruent condition.)

Latencies. The mixed ANOVA conducted on the RT data revealed a significant main effect of conditions, $F(2, 76) = 111.62$; $MSE = 5{,}864.81$; partial $\eta^2 = .75$; $p < .0001$. Paired comparisons with Bonferroni adjustment showed that incongruent items elicited significantly ($p < .0001$) longer RTs than neutral (+246.69 ms on average) and congruent

Table 2 Means (Standard Deviations) and effect sizes estimates (d) for Children with Math Disabilities (MD) and Typically Achieving (TA) Control Children

Measures	MD ($N=20$)	TA Controls ($N=20$)	d
	Color-Word Stroop (Latencies)		
Neutral	814.70 (88.72)	846.73 (106.40)	–0.30
Congruent	889.60 (129.06)	900.95 (146.19)	–0.08
Incongruent	1,055.15 (129.74)	1,099.65 (167.22)	–0.27
Stroop Effect (I – C)	240.45 (116.61)	252.93 (114.68)	–0.11
	Flanker (Latencies)		
Neutral	642.60 (65.82)	647.00 (69.17)	–0.06
Congruent	680.63 (72.70)	671.53 (72.45)	0.13
Incongruent	704.35 (68.02)	697.38 (80.39)	0.09
Interf. Effect (I – C)	61.75 (27.07)	50.38 (32.03)	0.36
	Listening Span		
Span Score	4.75 (1.52)	5.70 (1.22)	–0.78
Intrusions	2.45 (1.39)	1.95 (1)	0.50

Note. Interf. Effect=Interference effect. Latencies are reported in ms. Since the TA group was considered as the reference group, effect sizes (*d*) were calculated using the standard deviation of this group.

items (+182.12 ms on average, see Table 2 for corresponding means), which also differed significantly. Main effect of group and interaction between groups and conditions were not significant [group effect: $F(1, 38)=0.66$, partial $\eta^2=.02$; condition by group interaction: $F(2, 76)=0.48$, partial $\eta^2=.01$, ps > .4].

Despite the nonsignificant group by condition interaction, additional analyses were performed in order to directly compare the two groups on the inhibition abilities. For each child, we computed the difference between neutral and incongruent trials (i.e., the median RT for incongruent trials was subtracted from the median RT for neutral ones) divided by the child's median RT for neutral trials (this score was then multiplied by hundred so that it could be expressed in percent). This index reflected the increase in latencies in the congruent condition as compared to the neutral one (proportional scores were preferred in order to rule out processing speed bias, see for example Christ, White, Mandernach, & Keys, 2001). Independent t-tests conducted on this index showed no significant group difference, $t(38)=-0.01$, $p > .9$, $M=30.13\%$ for children with MD and 30.12% for control children, effect size $d=0.001$. It should finally be mentioned that this increase of latencies was significant in each group, as indicated by one-sample t-tests conducted separately for each group, $t(19)=8.85$ and 10.28 for children with MD and controls, respectively, ps < .0001.

Error Rates. Mean error rates for neutral, congruent, and incongruent items were, in order, 0.31%, 0%, and 7.36% for children with MD, and 0.16%, 0%, and 5.86% for control children. Friedman's ANOVA with conditions as the repeated measures were conducted in each group separately and showed a significant effect of condition in each group, $\chi^2(2, N=20)=31.39$, $p < .0001$, for both groups. In order to examine group differences, we computed a variable reflecting the Stroop effect: For each child, mean error rate for neutral items was subtracted from mean error rate for incongruent ones. Mann-Whitney U test applied on this variable (with group as the between-subjects factor) showed no significant group differences on this Stroop effect (U=180, $p > .5$, M=7.04 and 5.70 for children with MD and controls, respectively, $d = 0.20$). This interference effect was significant in each group, as demonstrated by nonparametric paired comparison between neutral and incongruent trials (Wilcoxon test, $Z = -3.52$ and -3.51 for children with MD and controls, respectively, ps < .0001).

Flanker Task. In total, 4.08% out of the 3600 possible RTs (30 trials per condition per child) were spoiled, and 0.47% of incorrect RTs were eliminated. The mean number of available RTs on which medians were computed were, per child, 28.58 ($SD = 1.47$), 28.53 ($SD = 1.60$), and 28.80 ($SD = 1.74$) for the neutral, congruent, and incongruent conditions, respectively. Errors were thus too infrequent to be statistically analyzed.

The mixed ANOVA performed on latencies revealed a significant main effect of condition, $F(2, 76) = 78.99$, $MSE = 399.67$, partial $\eta^2 = .68$, $p < .0001$. Overall, incongruent items elicited longer RTs than congruent ones (+24.79 ms on average) and neutral ones (+56.06 ms on average, see Table 2 for corresponding means). The group effect and the condition by group interaction were, however, not significant [group effect: $F(1, 38) = 0.03$, partial $\eta^2 = .001$, $p > .8$; condition×group: $F(2, 76) = 1.32$, partial $\eta^2 = .03$, $p > .2$].

Again, for each child, the median RT for incongruent trials was subtracted from the median RT for neutral ones, and the result was divided by the median RT for neutral trials. This increase of latencies in the incongruent compared to the neutral trials was significant in each group, as indicated by one-sample t-tests conducted separately for each group, $t(19) = 9.87$ and 7.03 for children with MD and controls, respectively, ps < .0001. Mean increases were 9.75% for children with MD, and 7.79% for control children. However, this difference was not statistically reliable, $t(38) = -1.32$, $p > .2$, $d = -0.44$.

Listening Span. When determining the truth of the sentences, children with MD did not err significantly more than their controls ($M = 0.40$ and 0.25, respectively, $U = 195$, $p > .8$).

When recalling the target, as shown in Table 2, children with MD had significantly lower span scores (i.e., number of correct sets) than the control children ($U = 126$, $p < .05$). However, they did not commit significantly more intrusion errors than their controls ($U = 172$, $p > .4$).

In summary, we found no differences between children with MD and control children on any of the inhibition measures. These results are in contradiction with the inhibition deficit hypothesis, which implies that children with MD also undergo inhibiting difficulties. Because this hypothesis concerns mainly difficulties in the learning and retrieving of basic arithmetic facts, we investigate, in the following section, inhibition in children with disabilities in the retrieval of arithmetical facts.

PART 2: CHILDREN WITH ARITHMETIC FACTS RETRIEVAL DISABILITIES

The children sampled in the present experiment were identified on the basis of a general math achievement test that encompasses a broad range of arithmetic skills. Because children with MD often have poor skills in some areas and average or better skills in others, averaging across these topics can overestimate their competencies in some areas and underestimate them in others (Geary, Hoard, Byrd-Craven, & DeSoto, 2004). It is then difficult to fully appreciate the extent of their disabilities and to isolate the faltering skills. Moreover, the pattern of difficulties may differ between children with MD, resulting in a nonhomogenous group.

It has been argued that children with MD present difficulties in the retrieval of arithmetic facts due to inefficient inhibition (Barrouillet et al., 1997, Geary et al., 2000). However, the children who were identified as having MD had no difficulties at all in the retrieval of arithmetic facts, as indicated by the fluency score that was equivalent in children with MD and control children. This might explain the absence of inhibition deficit. Indeed, it could be the case that inhibition is required to a great extent when retrieving the answer of arithmetic facts from memory, to suppress the incorrect answers associated to a problem, but to a much lesser extent when computing the answer to a multidigit problem (as 23+35) or other skills as the ones assessed in the Simonart test. In order to verify this possibility, we sampled the children with specific difficulties in the retrieval of arithmetic facts and examined their inhibition abilities.

Method and Participants

In order to determine the fact retrieval abilities of the 40 children who participated in part 1, we examined their scores in the arithmetic fluency task and compared these scores to the norms obtained from the whole sample of fifth graders collectively tested (N=152). Those children with a fluency score (i.e., total number of correct responses for the addition and the multiplication fluency tasks) at or below the 25th percentile were identified as having arithmetic facts retrieval disabilities, whereas children with a score above the 70th percentile were considered as above-average controls.[2] These cutoffs were chosen in order to enhance, in this small sample, the contrast between the children with and without difficulties, since control children with average skills might not be very much different, at a cognitive level, from children with MD, at least in this reduced subset of children.

Two groups of 12 children corresponded to these criteria. The disabled group was composed of eight children identified in the first part of this study as having MD and four typically achieving children. The control group was composed of six children identified as having MD and six typically achieving children. As can be seen from Table 1, these two groups differed significantly only on the fluency score t' $(14.73)=10.48$, $p < .0001$.[3] Arithmetic and reading scores, as well as estimated IQs, were equivalent, ts $(22)=0.79$, 1.43, and −0.82, respectively, all ps > .1.

Results

Results (means and standard deviations by group) for the Stroop, Flanker, and Listening Span are reported in Table 3.

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[2]It should be mentioned that, in order to check whether changing these criteria would have an effect on our findings, we performed a set of additional analyses. First, we compared children with disabilities to children with average retrieval skills (with fluency scores between the 50th and the 75th percentile) instead of above-average skills. Second, we compared two groups (children with disabilities and controls) selected on the basis of the children's scores in the addition fluency only, and then on the basis of their scores in the multiplication fluency only. All these additional analyses led to the same findings as the ones presented in the results section and are therefore not fully reported.

[3]Parametric statistics were used despite the heterogeneity of variance between groups following Howell's (1997/1998) indication that t-tests remain robust when the variables are normally distributed and the groups are of equal size (p. 229). This is why Welch-Satterthwaite solution was adopted (using t' and df'). However, a non-parametric statistic (the Mann-Whitney U Test) was also computed in order to verify that this could not have biased our results. Since both statistics lead to identical results, we limit our report to the parametric statistics.

Table 3 Means (Standard Deviations) and effect sizes estimates (d) for Children with Arithmetic Facts Disabilities (AFD) and Control Children

Measures	AFD (N=12)	Controls (N=12)	d
	Color-Word Stroop (Latencies)		
Neutral	859.54 (120.07)	824.04 (100.35)	0.35
Congruent	959.00 (143.76)	845.42 (133.76)	0.85
Incongruent	1,152.42 (122.53)	1,074.50 (170.19)	0.46
Stroop Effect (I – C)	292.87 (93.00)	250.46 (114.65)	0.37
	Flanker (Latencies)		
Neutral	654.92 (82.45)	650.67 (74.55)	0.06
Congruent	682.54 (82.14)	682.63 (85.71)	0.00
Incongruent	704.42 (90.26)	703.75 (83.83)	0.01
Interf. Effect (I – C)	49.50 (36.31)	53.08 (25.01)	–0.14
	Listening Span		
Span Score	4.67 (1.61)	4.67 (0.89)	0.00
Intrusions	1.75 (0.75)	2.58 (1.24)	–0.67

Note. Interf. Effect=Interference effect. Latencies are reported in ms. Since the control group was considered as the reference group, effect sizes (d) were calculated using the standard deviation of this group.

Color-Word Stroop Test

Latencies. The mixed ANOVA conducted on the RT data with groups (arithmetic facts retrieval disabilities vs. above-average controls) as the between-subjects factor and conditions as the within-subjects factor revealed a significant main effect of conditions, $F(2, 44)=107.18$; $MSE=4{,}556.20$; partial $\eta^2=.83$; $p < .0001$. Paired comparisons with Bonferroni adjustment indicated that incongruent items elicited significantly ($p < .0001$) longer RTs than neutral (+271.67 ms on average) and congruent ones (+211.25 ms on average, see Table 3 for corresponding means). Main effect of group and interaction between groups and conditions were not significant [group effect: $F(1, 22)=2.32$, partial $\eta^2=.09$, condition×group: $F(2, 44)=2.01$, partial $\eta^2=.08$, ps > .1].

Inhibition indices were computed for each child (i.e., [{median RT for incongruent trials - median RT for neutral ones}/median RT for neutral ones]×100). Statistical analyses showed that the increases of latencies were significant in each group (t [11]=9.49 and 7.59 for children with arithmetic fact retrieval disabilities and controls, respectively, ps < .0001), but, more importantly, equivalent between the two groups, $t(22)=-0.87$, $p > .3$, M=35.15% for children with fact retrieval disabilities and 30.42% for control children, d=0.34.

Error Rates. Mean error rates for neutral, congruent, and incongruent items were, in order, 0.52%, 0%, and 4.64% for children with MD, and 0.27%, 0%, and 11.03% for control children. For each child, Stroop effect was computed as in part 1 (mean error rate for incongruent items minus mean error rate for neutral ones). Statistical analysis (Mann-Whitney U test with group as the between-subjects factor) showed no significant group differences (U=58, $p > .4$, M=4.12 and 10.77 for children with facts retrieval disabilities and controls, respectively, $d=-0.42$).

Flanker Task. The significant main effect of condition found in the mixed ANOVA (with neutral, congruent, and incongruent condition as the within-subjects factor) indicated that, overall, incongruent items yielded longer latencies than congruent and neutral items (+21.50 ms and +51.29 ms, respectively, $F(2, 44) = 32.12$, $MSE = 495.74$, partial $\eta^2 = .59$, $p < .0001$, see Table 3 for corresponding means). Main effect of group and group by condition interaction were not significant (group effect: $F(1, 22) = 0.01$, partial $\eta^2 = .00$; condition×group: $F(2, 44) = 0.07$, partial $\eta^2 = .003$, ps > .9.

Indices reflecting the increase of latencies for incongruent compared to neutral trials were computed as for the Stroop task. Statistical analyses showed that these increases were significant in each group, $t(11) = 4.68$ and 7.40 for children with fact disabilities and controls, respectively, ps < .001, but equivalent between the two groups, $t(22) = 0.23$, $p > .8$, $M = 7.69\%$ for children with fact retrieval disabilities and 8.16% for control children, $d = -0.12$.

Listening Span. Children with poor or good arithmetic retrieval skills did not significantly differ from each other when determining the truth of the sentences ($M = 0.42$ and 0.25 for children with arithmetic facts disabilities and controls, respectively, $U = 67.50$, $p > .7$). Moreover, both groups had equivalent span scores ($U = 70$, $p > .9$). Finally, although the difference in the number of intrusion errors approached the significance level of .05 ($U = 172$, $p = .07$), this difference was in the unexpected, reverse direction: Control children made more intrusions than children with poor arithmetic facts retrieval skills (see Table 3).

GENERAL DISCUSSION

The major aim of the present study was to examine the inhibition deficit hypothesis, according to which math disabilities (and especially difficulties in retrieving basic arithmetic facts) are a consequence of inhibition deficits. Given that inhibition is currently conceived as encompassing several functions (e.g., Friedman & Miyake, 2004; Nigg, 2000), we investigated three such functions in children with MD and in children with arithmetic facts retrieval disabilities: suppression of irrelevant information from working memory, inhibition of prepotent responses, and interference control. But first, we would like to underline the discrepancy between children's results on the standardized math achievement test and on a test assessing specific skills. Indeed, children with disabilities as assessed by the general math test did not necessarily present arithmetic facts disabilities. As a matter of fact, these children did not differ from the typically achieving control children on the arithmetic fluency score. As Geary et al. (2004) already pointed out, this type of general achievement test is a compound of several skills and leads to an overestimation of some skills and an underestimation of others. Consequently, when putting forward specific hypothesis about the mechanisms involved in some particular math skills, it might be more appropriate to study children with difficulties restricted to the particular domains that have direct bearing on this hypothesis.

About inhibition processes, our findings are very clear: There were no significant differences between children with arithmetic disabilities and controls, whether those disabilities concerned general mathematics skills or, more specifically, arithmetic facts retrieval. The present findings are in opposition to the inhibition deficit hypothesis, but not necessarily in contradiction with the literature. As a matter of fact, although it may have looked convincing at first, this hypothesis is not really founded on robust evidence.

In the study of Barrouillet et al. (1997, experiment 2), when adolescents with learning difficulties had to choose the correct answer to simple multiplications among four answers, they erred more often when the three proposed false answers were multiples of one of the operands than when they were not. In fact, this study simply demonstrated the presence of an associative confusion effect, a well-known phenomenon in arithmetic facts, in adolescents with learning disabilities. But the authors did not include a control group in order to directly compare the performances of these adolescents with the ones of control children. If the adolescents with learning disabilities endured inhibition impairments, then we would expect them to show larger confusion effects; a prediction that was, however, not tested.

Bull and Scerif (2001) found a significant correlation between scores in a math test and interference effects in a numerical version of the Stroop task. Consequently, these authors inferred that children with poor arithmetic skills also undergo inhibition difficulties. But mathematical scores did not correlate significantly with the classical Color-Word Stroop task, even though both tasks are supposed to assess the same type of inhibition. This finding led Bull and Scerif to hypothesize that inhibition might be domain-specific and that children with MD might have inhibition problems restricted to numerical information.

This domain-specific hypothesis also accounts for Koontz and Berch (1996) findings. Indeed, these authors administered children with MD and control children a numerical-matching task and a letter-matching task. They observed interference effects in the numerical task only in children with MD (and interference effects in the letter task only in control children). The authors attributed the interference effect in children with MD to deficient inhibition processes. But if that was the case, then children with MD would also present interference effect in the letter-matching task, unless inhibition processes are distinct for numerical and nonnumerical information.

However, the domain-specific hypothesis was later refuted by the Censabella and Noël's study (2005). Indeed, these authors directly addressed this issue when investigating inhibition processes in children with reading and arithmetic disabilities. They administered the Stroop and Eriksen flanker paradigms once with numerical stimuli and once with nonnumerical stimuli. They observed that the pattern of results did not differ according the type of stimuli, which contradicts the domain-specific inhibition hypothesis. In the four tasks, children with disabilities displayed equivalent interference effects than the ones of control children. Then, the results of Bull and Scerif (a significant correlation between a global math score and Stroop interference in a numerical version only) as well as the ones of Koontz and Berch (interference effect in children with MD in a numerical- but not letter-matching task) cannot be interpreted in terms of inhibition impairments. However, they are consistent with a basic numerical deficit in MD, such as a deficit in accessing numerical semantic information (see for example Butterworth, 2005; Landerl, Bevan, & Butterworth, 2004; Rousselle & Noël, in press).

Another type of evidence put forward by Geary et al. (2000) in favor of the inhibition deficit hypothesis were the counting-string errors committed by children. When asked to solve simple additions by retrieving the answer, children with MD stated more often than control children the number following one of the addends in the counting string, leading the authors to conclude that their retrieval difficulties were related to inefficient inhibition. However, these errors seem to involve an inhibition process rather different from the one involved in the retrieval of arithmetic facts. Indeed, stating the counting-string associate of one of the addends hinges on the inhibition of prepotent response, given that counting represents a more familiar and automatic response than adding, especially in young children. In contrast, the inhibition deficits hypothesis put forward by Barrouillet et al.

(1997) implies the suppression of competitors, not the inhibition of prepotent responses. Arithmetic facts are organized in a network involving a spreading-of-activation process. When a problem is presented, not only the correct answer is activated but also incorrect, associated answers. Consequently, the set of associated but incorrect answers constitute competing answers that will interfere with the retrieval of the correct one. Although counting-string associates also constitute competing answers, it is likely that, in younger children, the competition between counting and adding is much stronger than the one between correct and incorrect associated answers during the solving process, since counting is much more automatic. Then, it is unclear how these counting-string errors substantiate the hypothesis according to which retrieval difficulties of children with MD are related to this inefficient inhibition. Furthermore, when testing the inhibition of predominant response in children with MD, van der Sluis et al. (2004) as well as Censabella and Noël (2005) did not find any deficit compared to control children.

Finally, other studies were more thorough and did actually show inhibition deficits in children with arithmetic difficulties. However, these difficulties were restricted to solving arithmetic word problems (Passolunghi et al., 1999). In fact, inclusion criteria in the Passolunghi and Siegel's studies (2001, 2004) was based on a standardized test for solving word problems and for manipulating Arabic and verbal numerals. Solving arithmetic word problems entails several competencies, not only arithmetic ones but also more linguistic ones, such as reading comprehension. It has been shown that suppression is an important skill in comprehension (e.g., De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; Gernsbacher, 1997; Gernsbacher & Faust, 1991; Gernsbacher, Varner, & Faust, 1990). Then, even if inhibition of irrelevant information is essential when solving word problems, it is not necessarily essential when solely carrying out arithmetic operations.

So, all in all, evidence in favor of the inhibition deficit hypothesis is not really compelling. Moreover, two studies examined the relationship between inhibition and mathematical skills by directly comparing children with MD and controls, but both yielded findings inconsistent with this hypothesis (Censabella & Noël, 2005; van der Sluis et al., 2004). In these two studies, there were no differences, in terms of inhibition, between children with MD and control children. However, both studies were limited to one or two inhibition functions. The present study not only extends their findings but, above all, it represents the first to study three inhibition functions in children with mathematics disabilities and with arithmetic facts disabilities, hereby, the first to test more thoroughly the inhibition deficit hypothesis.

In addition to these empiric data, a second line of evidence against the inhibition deficit hypothesis comes from theoretical models of arithmetic facts. Indeed, this hypothesis, as an explanation of arithmetic facts disabilities, implies an important assumption, namely, that the competitors (i.e., the incorrect answers that are activated by a problem) have to be actively inhibited. Although such active processes are involved under some particular conditions, such as negative priming (Arbuthnott & Campbell, 2000; Campbell, 1991; Campbell & Arbuthnott, 1996; Campbell & Clark, 1989; see also Phenix & Campbell, 2004, for a retrieval-induced forgetting paradigm in arithmetic), the involvement of active inhibition processes in arithmetic facts is far from being established. As outlined above, arithmetic facts are organized in an associative network in which retrieval occurs in the context of parallel activation of multiple associated facts (e.g., Campbell, 1995; Siegler, 2000). An important feature of these models is the strength of association between a problem and its associated answers, more particularly, the *relative* associative strength. The associative strength of the correct answer relative to the associative strengths of all answers is indeed the key determinant of performance and retrieval efficiency. This relative associative strength entails retrieval interference: The correct answer's relative associative strength is weaker as the number of associated but incorrect answers increases. This activation-based interference does not necessarily require active inhibitory mechanisms, as the reduced associative strength of the correct answer is sufficient to account for weaker performances. This interference is of a passive kind due to the "overfacilitation" of competitors (Anderson & Bjork, 1994; see also Logan, 1994). This passive interference account of interference in arithmetic facts has received empirical support from a recent study in which adults' performances when solving simple arithmetic facts were not related to scores in active inhibition tasks but to scores in a task involving activation-based interference (Censabella & Noël, 2004). Because we did not include such tasks of passive inhibition in our study, it might be the case that children with MD do also undergo inhibition deficits, but of a more passive kind, which is not part of the inhibition deficit hypothesis.

To conclude, in this study, children with math disabilities and with arithmetic facts retrieval disabilities were not found to exhibit inhibition deficits, whether concerning suppression of irrelevant information from working memory, inhibition of prepotent responses, or interference control. These findings are consistent with results from previous studies and contradict the inhibition deficits hypothesis, which states that inhibition might be a causal factor of MD. It might still be possible that inhibition is failing in MD, but that it is of a more passive inhibition kind, such as the one present in associative networks (Censabella & Noël, 2004). Furthermore, this study is also in line with the conception of developmental dyscalculia not resulting from deficits in general cognitive abilities (such as inhibition) but rather, from specific disabilities in basic numerical processing (e.g., Butterworth, 2005; Landerl et al., 2004; Rousselle & Noël, in press).

Original manuscript received August 19, 2006
Revised manuscript accepted October 2, 2006
First published online December 20, 2006

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