Serial-order learning impairment and hypersensitivity-to-interference in dyscalculia

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A B S T R A C T

In the context of heterogeneity, the different profiles of dyscalculia are still hypothetical. This study aims to link features of mathematical difficulties to certain potential etiologies. First, we wanted to test the hypothesis of a serial-order learning deficit in adults with dyscalculia. For this purpose we used a Hebb repetition learning task. Second, we wanted to explore a recent hypothesis according to which hypersensitivity-to-interference hampers the storage of arithmetic facts and leads to a particular profile of dyscalculia. We therefore used interfering and non-interfering repeated sequences in the Hebb paradigm. A final test was used to assess the memory trace of the non-interfering sequence and the capacity to manipulate it. In line with our predictions, we observed that people with dyscalculia who show good conceptual knowledge in mathematics but impaired arithmetic fluency suffer from increased sensitivity-to-interference compared to controls. Secondly, people with dyscalculia who show a deficit in a global mathematical test suffer from a serial-order learning deficit characterized by a slow learning and a quick degradation of the memory trace of the repeated sequence. A serial-order learning impairment could be one of the explanations for a basic numerical deficit, since it is necessary for the number-word sequence acquisition. Among the different profiles of dyscalculia, this study provides new evidence and refinement for two particular profiles.

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1. Introduction

The ability to calculate is, together with the ability to read, one of the major challenges that children are confronted with in primary school. Already from the earliest stage of mathematical learning, 3–6% of the children encounter difficulties (Shalev, Auerbach, Manor, & Cross-Tsur, 2000). When these difficulties can be objectivized by standardized arithmetic performance measures (during the early school years and for more than 6 months) and are not attributed to poor intelligence, developmental disorders, poor educational environment or sensory processing, children are diagnosed with mathematical learning disorder or developmental dyscalculia (D) (DSM-5, American Psychiatric Association, 2013). In the past 20 years, scientists have dedicated an increasing amount of studies to those children who show atypical development of numerical cognition (D children).

In terms of impaired numerical skills, D children are known to experience difficulties with reciting the number sequence (Landerl, Bevan, & Butterworth, 2004), transcoding (reading or spelling Arabic digits, Sullivan, Macaruso, & Sokol, 1996; Temple, 1989) but also in calculation strategies and procedures (Geary, 2004; Temple, 1992; Wilson & Dehaene, 2007). For instance, already in simple one-digit calculations, they make more errors, are slower and use immature strategies (Geary & Brown, 1991; Temple, 1992). In typical development, children progressively learn to retrieve the answers to arithmetic problems directly from long-term memory (such as $3 \times 5 = 15$). The arithmetic problems that are solved by retrieval are known as arithmetic facts. However, in D children, this typical transition from a procedural counting strategy to a memory-based retrieval strategy in learning arithmetic facts appears problematic (Geary & Brown, 1991; Geary, Brown, & Samarana, 1991; Jordan, Hanich, & Kaplan, 2003; Jordan & Montani, 1997). D children can show all these difficulties together or can suffer from one of these difficulties in particular. Indeed, the appellation “developmental dyscalculia” is used for heterogenic numerical disorders with different symptoms and different etiologies (Geary, 1993, 2004; Rubinsten & Henik, 2009; Temple, 1992; Wilson & Dehaene, 2007).
At the origin of the math disorder, it has been suggested that D persons have a basic deficit in numerical magnitude processing (of non-symbolic or symbolic numbers), tested for instance with magnitudes comparison tasks. Studies showed a numerical magnitude processing deficit in D participants that is assumed to disturb the acquisition of all future mathematics knowledge (Butterworth, 1999; Landerl et al., 2004; Mussolin, Mejias, & Noël, 2010; Piazza et al., 2010; Rousselle & Noël, 2007). The hypothesis of a magnitude processing deficit received lots of interest and is currently still debated (see De Smedt, Noël, Gilmore, & Ansari, 2013, for a review).

More recently, a number of researchers have questioned the quality of the ordinality processing in dyscalculia, which is another important characteristic of the number system. In a behavioral study with adults, Rubinsten and Sury (2011) tested D and control participants in two ordinality judgment tasks with non-symbolic (dots) and symbolic (digits) numerical stimuli. In these tasks, participants had to judge whether three stimuli (dots or digits) were correctly ordered or not. They found that D adults experienced difficulties with the processing of ordinal information. In the same vein, a brain imaging study by Kaufmann, Vogel, Starke, Kremer, and Schocke (2009) showed different brain activations during ordinal judgment tasks of numerical (digits) and non-numerical (physical size of symbols) stimuli between D and control children. More specifically, they found that in control children, the same (intra)parietal cortex supported both ordinal processing whereas in D children, there were stronger task specific activations. These two interesting studies suggest that at least some people with dyscalculia show impaired numerical ordinality processing.

Furthermore, Lyons and Beilock (2011) recently found that symbolic number-ordering may be a stepping stone from approximate number magnitude representation to mathematical competence. In this study, university students had to judge whether three Arabic digits were presented in increasing order (order processing measure), to compare the magnitude of two dot collections (magnitude processing measure) and to solve complex written calculation (arithmetical performance). Their results showed that number-ordering ability predicted 49.4% of the variance of the arithmetical ability and fully mediated the relation between number magnitude processing and arithmetic performance. However, in all these studies, ordinality processing is confounded with magnitude processing. Indeed, these three studies tested the well-established magnitude ordinality (from the smaller to the larger or vice versa) processing by using digits, amount of dots or physical size of items, all of these involving the magnitude aspect. A deficit in magnitude processing could in itself explain these results.

The first aim of the current study is to test the hypothesis of a serial-order learning deficit in dyscalculia, in a task that would not involve any processing of magnitude. We hypothesize that a deficit at that level would already impair the first numerical learning, in particular, learning the counting sequence. Around the age of 2 or 3 years, children recite by rote the sequence of number words as an unbreakable string. This learning requires children to remember the number words, that have no referents (meanings) yet at this time, in a specific order. This stage is necessary for acquiring counting and cardinal knowledge (Wynn, 1992). A serial-order learning deficit could hamper children to acquire the counting string and would therefore disturb the acquisition of counting and cardinal knowledge. Indeed, at the end, the cardinal meaning of a number word is fully determined by its position in the counting string. A difficulty in mapping symbols (number words) to numerical representations might also result from this and such disorder could disturb the entire subsequent development of numerical cognition (Rousselle & Noël, 2007). A serial-order learning deficit may therefore lead to the same math deficit profile as the aforementioned magnitude processing deficit.

Our hypothesis is that D people who show global conceptual math disorder might have a serial-order learning deficit. In order to test our hypothesis and distinguish it from the magnitude processing deficit hypothesis, we submitted adults with global dyscalculia and controls to a serial-order learning paradigm that does not contain any magnitude aspect, namely the Hebb repetition learning task (Hebb, 1961). In this task, participants are presented with sequences of stimuli (in this case syllables) for immediate serial recall. Concretely, nine syllables are successively displayed on the screen. Afterward, the same syllables are presented randomly on the screen and participants are required to indicate the nine syllables in the same order of presentation. Unbeknownst of the participants, one particular sequence is repeated every third trial while in the intermediate sequences, the stimuli are presented randomly (i.e. the non-repeated or filler sequences). Typically, performance on the repeated sequence gradually improves throughout the experiment, while performance on the filler trials remains relatively stable. The improved performance for the repeated trials, relative to the filler trials, is known as the Hebb repetition effect, which reflects the gradual transfer of serial-order information from short-term to long-term memory. This paradigm permits us to assess the ability to relate non-numerical stimuli (syllables) to a sequence in short-term memory and to measure the ability to consolidate repeated sequences in long-term memory. In addition, we developed a task to test the quality of the memorized sequence. In the beginning of the counting development, children treat the number words as an unbreakable string (Fuson, Richards, & Briars, 1982) and they cannot recite the sequence if they do not start with the first number word. Afterward, they are able to start anywhere in the sequence and move forward or backward within the sequence. This of course is very important for solving additions since doing 4 + 2 for instance, might require counting two steps away from 4. Akin to these developmental stages, we tested the capacity to start at any place in the memorized sequence and to go one or two steps forward. Therefore, after they learned the repeated sequence, participants were submitted to a computation-like task. In this task, a syllable (n) from the repeated memorized sequence was displayed and participants had to say the following syllable (n + 1) or the syllable thereafter (n + 2) within the learned sequence.

Beside the global math disability, some people show a profile with a quite specific difficulty regarding learning and/or retrieving arithmetical facts. Impaired fact retrieval has been suggested to be due to a central executive dysfunction or to a verbal deficit that could be associated with dyslexia (Geary, 2004; Kaufmann, 2002; Temple, 1992; Wilson & Dehaene, 2007). More recently, another hypothesis has been suggested according to which hypersensitivity to-interference would hamper someone to store arithmetical facts in long-term memory (De Visscher & Noël, 2013, 2014a,b). The second aim of this study was to investigate the recent hypothesis of hypersensitivity-to-interference in memory that hampers the memorization of arithmetical facts in dyscalculia. De Visscher and Noël (2013) reported a case study of dyscalculia that suffered from hypersensitivity-to-interference in memory hampering her to store arithmetical facts. Also in a group study with fourth-grade children, De Visscher and Noël (2014a,b) observed that children with low arithmetical facts fluency showed higher sensitivity-to-interference compared to children with typical arithmetical facts fluency. These findings suggest that at least some D people may have hypersensitivity-to-interference that prevents them from storing very similar items in memory and this would explain their difficulty in memorizing arithmetical facts. Because the repeated and filler sequences are usually constructed from the same, reduced set of stimuli (only the order changes), the Hebb paradigm is actually prone to proactive interference (Jonides & Nee, 2006; Page, Cumming, Norris, McNeil, & Hitch,
In order to test the sensitivity-to-interference and distinguish it from the serial-order learning impairment, the current study also included a non-interfering repeated learning condition in which the repeated sequence is constructed from different stimuli (syllables) than the filler sequences. The predictions we make are twofold. First, we predict that people with dyscalculia who show specific difficulties in arithmetic facts will experience higher sensitivity-to-interference compared to controls. More precisely, they are anticipated to show a deficit in learning the interfering repeated sequence while they should be able to learn the non-interfering repeated sequence well. By contrast, adults with dyscalculia who show global difficulties in all mathematical tests should have difficulties in the earliest stage of numerical development, as during the number word string recitation stage, and this would be related to serial-order learning deficit. Accordingly, they should therefore show a learning deficit for the two types of repeated sequences (both the interfering and non-interfering ones) and/or show a deficit in the manipulation of the memorized sequence.

In summary, our study aims at testing whether D adults with global math deficit have an impairment in long-term serial-order learning, using a Hebb repetition learning task. Second, we test whether D adults with selective arithmetic facts deficit are hypersensitive to interference during serial-order learning, by manipulating the overlap between stimuli in the non-repeated (filler) and repeated (Hebb) sequences. Since mathematical cognition is multi-determined, the different explanatory hypotheses of dyscalculia are not mutually exclusive, but should permit us to make different predictions about the impaired components depending on the math profile. In the present investigation, a deficit in serial-order learning is anticipated to disturb the learning of the ordinality aspect of numbers and should therefore impact on all mathematical abilities, leading to a global math deficit. Contrariwise, hypersensitivity-to-interference is predicted to specifically disturb arithmetic facts learning. This paper is aimed to contribute to the refinement of different profiles of dyscalculia and to put forward the importance of taking into account the particularities of the math profile when elaborating theoretical explanations.

2. Method

2.1. Participants and group descriptions

Participants were recruited either through announcements asking for people with dyscalculia (or with no calculation difficulties for the control group) around the Université catholique de Louvain (UCL) or via a registered pool of participants at the same university. The study was approved by the ethical committee of the Psychological Sciences Research Institute of UCL (Belgium). All participants signed a consent form and were paid 5 or 20 euros for their participation (for the selection phase or for the whole experiment, respectively). All participants were subjected to a short interview during which we collected various information about education history and potential problems faced during primary and secondary school, with particular focus on developmental or learning disabilities other than dyscalculia (e.g., attention deficit disorder with or without hyperactivity, dyslexia, specific language impairment, . . .) for which they received a diagnosis and perhaps also treatment.

2.1.1. Adults with dyscalculia

Among thirty-two volunteers complaining about math difficulties, twenty French-speaking participants with dyscalculia were selected according to three criteria. First, the criterion for participation was to be diagnosed with dyscalculia or to complain about difficulties in math since primary school. Second, the participants had to have sufficiently good reasoning capacities. To this aim, participants were tested with a computerized version of the advanced progressive matrices test (Raven, Raven, & Court, 1998) and they had to answer accurately to as many matrices as possible in 30 min. The overall level of intellectual functioning of participants should correspond to a score equal or superior to percentile 30. Third, because we were looking for two profiles of dyscalculia, the arithmetic disorders criterion was met using two types of tests: a global math test and an arithmetical fluency test. None of the adults with dyscalculia reported other developmental or learning disorders in addition to their diagnosis of dyscalculia or math learning difficulties since primary school.

On the one hand, we constituted a Global D group by selecting participants who produced a lot of errors in the global math test; i.e., they had less than −1.5 SD (corresponding to the percentile 7) in accuracy in the global math test initially created by Shalev et al. (2001, and modified by Rubinsten & Henik, 2005). This test includes 20 simple and 32 complex calculations using the four operations on integers, and 8 calculations on decimals (we did not use the part with fractions). Participants were asked to be as accurate and as fast as possible but there was no time limit. Before the present study was conducted, 43 university students from the Université catholique de Louvain completed this test. The participant’s results were compared to this sample.

On the other hand, we constituted an AF Only group by selecting participants who had a very specific problem with arithmetical facts. More precisely, participants in this group had to show normal accuracy on the global math test (≥ −1.5 SD) and impairment in retrieving AF from memory. To that aim, we used a measure of arithmetical fluency, the Tempo-Test Rekenen (TTR, De Vos, 1992). This test comprises five columns of very simple calculations, one for each operation and one with mixed operations. For each column, the participants had one minute to resolve correctly as many problems as possible. Participants who had at least two scores equal or inferior to the fifth-grade average in the arithmetical fluency task were included in the AF Only group.

In total twelve volunteers did not meet the criteria for dyscalculia. Among the selected participants, nine had impaired accuracy scores in the global math tests and constituted the Global D group (see Fig. 1) and eleven showed normal accuracy scores on the global math test but were impaired in the arithmetical fluency task; they constituted the AF Only D group.

Since people with dyslexia have been demonstrated to show a deficit in Hebb learning (Szmalec, Loncke, Page, & Duyck, 2011), we discarded participants with dyslexia. The reading skill was measured with the Alouette-R (Lefavrais, 2005), where the participants had to read a text as accurately and as quickly as possible in a maximum of 3 min. The number of errors and the time used to read the whole text was recorded. Two AF Only D participants were discarded because of comorbid reading impairment (less than −2 SD in accuracy in the reading test).

Because we were interested in serial-order learning deficits, we also decided to exclude people with a global verbal memory deficit. Verbal long-term memory (without order aspect) was assessed with the Words List subtest of the French version of the Wechsler Memory Scale (MEM-III, Wechsler, 2001). After listening to 12 words, participants had to recall as many words as possible in a free order. Four presentation and recall sessions were administered and provided a verbal memory measure. All participants with dyscalculia scored at or above the standard note 6 (corresponding to −1.3 SD as the mean is 10 ± 3). The first recall session of the 12 words in the MEM-III test can be seen as a measure of short-term memory without order (free recall). Therefore, performance on the first recall session will be used as a control variable in our
2.1.2. Control adults

Among twenty-six volunteers, twenty adults with no history of mathematical difficulties were selected to constitute the Control group, matched for gender, age and education. The participants were selected when they scored above – 1 SD in terms of accuracy in the global math test; had no reading impairment and performed above the fifth-grade level in all the columns of the arithmetic fluency task. One participant was discarded because of poor reading (accuracy < –2 SD) and three others because they performed weakly in one column of the arithmetic fluency task. The final Control group was composed of 16 participants.

2.1.3. Final group's comparison

We used Greenhouse-Geiser and Bonferroni correction when necessary.

The three groups were similar in age and showed similar reading and verbal long-term memory skills (without order aspect, see Table 1). However, a difference appeared with regard to the reasoning measure. Despite of a normal score on the Raven test (see participants section), the Global D group performed significantly worse compared to the Control group ($t(23) = −3.020, p = .009$). The AF Only D group performed at the same level as the Control group and the Global D group (respectively, $t(23) = −1.705, p = .276$; $t(16) = 1.499, p = .069$).

In the global math test, the two groups with dyscalculia scored below the Control group and they were also slower (Table 2). The Control group was more accurate than the AF only D group, who was more accurate than the Global D group (all $p < .001$). The two groups with dyscalculia were slower than the Control group ($p < .05$), without the groups with dyscalculia differing from each other.

Concerning the arithmetical fluency task, a repeated measures ANOVA was run with Group (AF Only D, Global D, and control) as between subjects factor and Operation (addition, subtraction multiplication, division, and mixed) as within subject factor. A main effect of Group ($F(2,31) = 45.268$, $p < .001$) revealed a significant difference between the Control group (all $p's < .001$) and the two groups with dyscalculia, the latter not differing from each other ($p = 1$). A main effect of Operation ($F(4,124) = 54.579$, $p < .001$) showed that additions led to better performance than all other operations, while division led to the lowest performance (all $p's < .01$ or .001). Subtraction, multiplication and the mixed column yielded similar results. An interaction was found between Group and Operation ($F(8,124) = 5.217, p < .001$) indicating an increasing gap between the Control group score and the two D groups' scores as a function of the difficulty of the Operation (all $p's < .001$, see Fig. 2).

The arithmetic difficulties of the two D groups were further confirmed in a computerized test including simple and complex subtractions as well as multiplications (see supplementary material for the results).

### Table 1
Mean performance, standard deviation (SD) and group's analysis ($F$) for Age, Reasoning, Reading, and Memory measures for the three groups (AF Only D, Global D and Control group).

<table>
<thead>
<tr>
<th>Variable</th>
<th>AF Only D group Mean (SD)</th>
<th>Global D group Mean (SD)</th>
<th>Control group Mean (SD)</th>
<th>$F(2,31)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>24.4 (6.6)</td>
<td>26.6 (6.7)</td>
<td>25.2 (5.4)</td>
<td>.300</td>
</tr>
<tr>
<td>Reasoning (Raven percentile)</td>
<td>55.3 (12.3)</td>
<td>45.8 (14.6)</td>
<td>66.6 (17.5)</td>
<td>5.352</td>
</tr>
<tr>
<td>Reading speed (s)</td>
<td>106 (18)</td>
<td>103 (19)</td>
<td>99 (16)</td>
<td>.398</td>
</tr>
<tr>
<td>Reading errors</td>
<td>4.1 (2.6)</td>
<td>3.9 (2.9)</td>
<td>2.4 (2.0)</td>
<td>1.783</td>
</tr>
<tr>
<td>Total words recalled (Words list, MEM III)</td>
<td>40.0 (1.7)</td>
<td>38.7 (4.4)</td>
<td>40.9 (3.5)</td>
<td>1.273</td>
</tr>
</tbody>
</table>

* $p < .05$.

### Table 2
Mean performance, standard deviation (SD) and group's analysis ($F$) in the global math test (accuracy and speed) for the three groups (AF Only D, Global D, and Control group).

<table>
<thead>
<tr>
<th>Variable</th>
<th>AF Only D group Mean (SD)</th>
<th>Global D group Mean (SD)</th>
<th>Control group Mean (SD)</th>
<th>$F(2,31)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global math test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of errors</td>
<td>10.67 (3.04)</td>
<td>19.78 (4.02)</td>
<td>4.63 (3.61)</td>
<td>51.426***</td>
</tr>
<tr>
<td>Total time (sec)</td>
<td>1071 (344)</td>
<td>1059 (313)</td>
<td>754 (168)</td>
<td>5.902**</td>
</tr>
</tbody>
</table>

*** $p < .01$.

** $p < .001$. 

---

**Fig. 1.** Mean and standard error (error bars) of z-score in the global math test accuracy for the two groups with dyscalculia: AF Only D group and Global D group.
In summary, both D groups show equally slow calculation as measured in the global math test and weak AF retrieval as measured in the arithmetical fluency test but the Global D group produce more errors in the global math test than the AF only D group.

2.2. Material and procedure

2.2.1. Hebb learning paradigm

During the Hebb learning task, participants were instructed to recall the order of presentation of nine syllables presented sequentially in the center of the screen for 1 s each (see Fig. 3). After a 500 ms inter-stimulus interval, all syllables were randomly positioned on a virtual circle around a question mark. The participants had to click the nine syllables in the same order of presentation with the computer mouse. When a syllable was clicked, it became blue. The question mark could be clicked by the participant to indicate an omission, at the position in the sequence where the omitted syllable occurred. This way, potential correct responses after an omission are still in the right serial position. As soon as the participants clicked nine times (on syllables or on the question mark), a pause screen appeared permitting the participant to have a small break. They were asked to press the space bar when they were ready to start the following trial.

Two sets of non-sense consonant–vowel syllable structures were constructed for the experiment. Both sets were composed of different consonants. Syllable frequency in French was matched between the two sets (using WordGen software; Duyck, Desmet, Verbeke, & Brysbaert, 2004). The task comprised of three types of sequences: interfering repeated sequences, non-interfering repeated sequences and filler sequences. The difference between the interfering and non-interfering repeated sequences is that interfering repeated sequences are made of the same syllables as the filler sequences, hence increasing proactive interference. Conversely, the non-interfering repeated sequences were constructed from different syllables than those involved in the filler sequences, hence reducing proactive interference. All types of sequences were mixed within one block. This means that a block started with a filler sequence, followed by a (interfering or non-interfering, in counterbalanced fashion across participants) repeated sequence, then another filler sequence, followed by a (non-interfering or interfering) repeated sequence, and so on. The experiment ended when the participant correctly reproduced two successive non-interfering repeated repetitions, with a maximum of 20 repetitions.

If a participant did not reach the stopping criterion after twenty repetitions, a learning phase started in which the participant was required to learn only the non-interfering repeated sequence until two consecutive correct repetitions. This procedure was used to stimulate all participants to acquire a long-term memory representation of the non-interfering repeated sequence, which was a prerequisite to proceed to the non-numerical computation task (described below). Based on each set of syllables, five different repeated sequences were created in a controlled way so that they never formed an existing word (see Table 3). For half of the participants, syllable set 1 was used for fillers and for the interfering repeated sequence and syllable set 2 was used for the non-interfering repeated sequence. For the other half of the participants, it was the reverse: set 2 was used for the fillers and interfering repeated sequence and set 1 for the non-interfering repeated sequence.

2.2.2. Non-numerical computation task

After the Hebb learning task, participants were subjected to a non-numerical computation task. In this task, one syllable from the non-interfering repeated sequence was displayed on the center of the screen. In one part of the task, the participants had to tell the syllable just following the one displayed according to the learned sequence (block 1, \( n + 1 \)). In another part of the task, they had to tell the second syllable following the one displayed (block 2, \( n + 2 \)). The participants were instructed to respond as fast and accurately as possible. The seven first syllables of the learned sequence were used three times per block resulting in twenty-one trials per block. For instance, for the learned sequence Mu–Pe–Co–Wu–Na–Fi–Ze–Li–Da, when “Mu” was displayed, participants had to say “Pe” in block 1, and “Co” in block 2. The order of blocks was counterbalanced between participants. Accuracy was hand-coded and reaction times were recorded with a voice-key.
3. Results

3.1. Hebb learning paradigm

We adopted a relative, rather than an absolute way of scoring serial ordering performance in the sense that one point was attributed for each correct binding or correct succession of two syllables (so the maximum score is 8 for a sequence of 9 syllables). For instance if a participant would omit the first syllable but recall the subsequent syllables in correct order, (e.g., 2–3–4–5–6–7–8–9), he would obtain a score of seven out of eight. In the traditional scoring method, which is derived from working memory capacity measurement (i.e. span), a point is only attributed if the stimulus is recalled in the same absolute position. In our example, the same participant would thus obtain a null score. Since our aim is not to measure span performance but rather to obtain a fine-grained view on serial-order learning performance, we estimated the relative score to be more sensitive and therefore better suited to the aims of this study. Besides, the two ways of scoring highly correlated between each other (r(1274) = .847, p < .001).

Since the number of repetitions was different between participants (depending on when they reached the stopping criterion) we decided to take the mean of correct bindings for each condition (interfering repeated, non-interfering repeated and fillers sequences) per participant. We used the first half of filler trials in order to have the same number of repetitions for each condition.

Because it allows the specification of random and fixed factors and it has many technical statistical advantages (Manning, 2007), we used the Generalized Linear Mixed Model (GLMM) for our analyses. The sequential Bonferroni correction was automatically used in the t-tests when necessary. The assumption of normality and sphericity were verified (Kolmogorov-Smirnov and Mauchly’s test). All p-values were calculated against a two-tailed test. The interaction between condition and reasoning (Raven score) was not significant (F(1,30) = 2.633, p = .138). No effect of reasoning (Raven score) was found (F(1,30) = 2.446, p = .138). Importantly, the interaction between Condition (fillers, non-interfering repeated sequence, interfering repeated sequence) and Group was significant (F(4,92) = 3.214, p = .016). This interaction, which is illustrated in Fig. 4, is analyzed below according to three main questions. First we evaluate whether the three groups have the same serial-order ability in short term memory (based on the filler trials). Second, we investigate the Hebb learning effect in the three groups by examining the difference between the filler and the non-interfering repeated conditions. Finally, the effect of interference in the three groups is analyzed by comparing the interfering and non-interfering repeated conditions.

Second, we analyzed the mean of correct binding by a GLMM that included Subjects as random factor, and Group, Condition, the interaction Group × Condition and the Raven score, as fixed factors. It revealed a main effect of Condition (F(2,92) = 10.922, p < .001), indicating that the interfering repeated condition (mean(SE): 4.076 (0.269)) led to a marginally lower mean than the non-interfering repeated condition (4.475 (0.269), t(92) = −1.788, p = .077) and that both repeated conditions led to better scores than the filler condition (mean(SE): 3.440 (0.269); interfering repeated versus fillers: t(92) = 2.846, p = .011, non-interfering repeated versus fillers: t(92) = 4.634, p < .001). Results thus confirm the implicit Hebb learning of both repeated sequences and show a marginal effect of interference (i.e., interfering repeated sequence led to lower recall than non-interfering repeated sequence). A marginal effect of Group (F(2,92) = 2.633, p = .077) was found showing that both D groups tended to have lower scores than the Control group (two p’s < .128; mean(SE): AF Only D: 3.702 (0.441), Global D: 3.503 (0.477), Controls: 4.786 (0.354)). No effect of reasoning (Raven score) was found (F(1,30) = 2.446, p = .138; mean(SE): AF Only D: 3.702 (0.441), Global D: 3.503 (0.477), Controls: 4.786 (0.354)).

Table 3

Syllables used as stimuli in the set 1 and the set 2.

<table>
<thead>
<tr>
<th>Order</th>
<th>Set of syllables 1</th>
<th>Set of syllables 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mu Pe Co Wu Na Fi Ze Da Pe Mu Co</td>
<td>Ti Ve Xu Ka Gu Be Ja Ri Se</td>
</tr>
<tr>
<td>2</td>
<td>Li Wu Na Fi Ze Da Pe Mu Co</td>
<td>Ve Ja Xu Ri Re So Gu Ka Ti</td>
</tr>
<tr>
<td>3</td>
<td>Fi Ze Mu Da Co Wu Li Pe Na</td>
<td>Gu Ri Be Ja Xu Ve Ti So Ka</td>
</tr>
<tr>
<td>4</td>
<td>Pe Co Na Wi Li Da Ze Fi Mu</td>
<td>Ja So Gu Be Ka Xu Ti Ve Ri</td>
</tr>
<tr>
<td>5</td>
<td>Na Wu Co Fi Ze Mu Pe Li Da</td>
<td>Ri Be So Ka Xu Ja Ti Ve Gu</td>
</tr>
</tbody>
</table>

Mean correct bindings for the three conditions according to the three groups (AF Only D, Global D, and Control). Error bars represent standard errors. **p < .01.
Beforehand, in order to rule out any potentially confounding effect of reading difficulties or general short term memory difficulties, we ran the same GLMM mentioned above with three additional fixed factors, namely the number of errors in the reading test (Alouette-R) as well as the RTs for this test and the score for the first recall of the Words list memory test (MEM III). The effects of the Raven score, the two reading measures and the first recall of the Words list memory test were not significant (all Fs < 1). The main effect of the condition remained significant (F(2,89) = 12.202, p < .001), as well as the interaction Group × Condition (F(4,89) = 3.045, p = .021). The main effect of Group was not significant (F(2,89) = 2.130, p = .125).

3.2. Serial-order capacity in short-term memory

Considering the filler condition first, the Global D group was significantly different from the Control group, while the AF Only D group did not reach the threshold for a significant difference but was marginally inferior to the Control group (see Table 4 and Fig. 4). To disentangle a general memory deficit from a specific deficit of serial order processing in short term memory we tested whether performance at the first recall of the Words list (MEM III) was different between groups. The results showed no effect of Group on performance for the first recall of the Words list (MEM III). To disentangle a general memory deficit from a specific deficit, we ran the same GLMM mentioned above with three additional fixed factors, namely the number of errors in the reading test and the score for the first recall of the Words list memory test (MEM III). The effects of the Raven score, the two reading measures and the first recall of the Words list memory test were not significant (all Fs < 1). The main effect of the condition remained significant (F(2,89) = 12.202, p < .001), as well as the interaction Group × Condition (F(4,89) = 3.045, p = .021). The main effect of Group was not significant (F(2,89) = 2.130, p = .125).

3.3. Hebb effect

No difference between groups was found in the non-interfering repeated condition (see Table 4). The Hebb effect (non-interfering repeated versus filler condition) was significant for the two D groups while not for the Control group, because of a low level of performance in the filler condition for the D groups (see Fig. 4 and Table 5). In other words, the D groups benefited more from the repetitions than the Control participants. The Control group showed a classic Hebb effect in a separate analysis (t(15) = -2.558, p = .022) but that dropped under the significant level in an omnibus GLMM. Besides, because we used an adaptive paradigm, the Hebb effect is expected to be smaller than in a classical Hebb paradigm. Indeed when the number of repetitions is fixed and above the strict necessary, the measure of the Hebb effect is increased artificially (when using the mean of correct responses).

3.4. Interference effect

Regarding the interfering repeated condition, the AF Only D group had a lower score compared to the Control group (see Table 4). The AF Only D group showed a substantial interference effect (non-interfering versus interfering repeated conditions) without the two other groups showing any interference effect (see Table 5 and Fig. 4).

3.5. Non-numerical computation task

One participant was excluded from this analysis because she accidentally had more trials (beyond the stopping criterion) and had therefore an advantage for this task. When the sphericity was violated, the GLMM was set to use robust estimation to handle violations of model assumptions (SPSS 20).

A GLMM with Subject as random factor, and Condition (plus 1, plus 2), Group (AF Only D, Global D and Control groups), the interaction between Condition and Group, and Raven score as fixed factors, was run on errors and reaction times.

Regarding the errors, a main effect of Condition (F(1,59) = 11.420, p = .001) indicated that going two steps further was more error-prone than going one step further (respectively, mean estimates (SE): 5.045 (0.752); 3.839 (0.752); t(59) = 3.379, p = .001). A main effect of Group (F(2,59) = 7.603, p = .001) indicated that the Global D group produced more errors than the AF Only D and Control groups (see Fig. 5, all p’s = .002), who did not differ from one another (t < 1). No interaction was found.

Table 4

<table>
<thead>
<tr>
<th>Condition</th>
<th>Pairwise comparisons</th>
<th>t(92)</th>
<th>Adjusted p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fillers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AF Only D – Control</td>
<td>-2.031</td>
<td>.090</td>
<td></td>
</tr>
<tr>
<td>Global D – Control</td>
<td>-2.397</td>
<td>.056</td>
<td></td>
</tr>
<tr>
<td>AF Only D – Global D</td>
<td>0.500</td>
<td>.618</td>
<td></td>
</tr>
<tr>
<td>Non-interfering repeated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AF Only D – Control</td>
<td>-0.251</td>
<td>.802</td>
<td></td>
</tr>
<tr>
<td>Global D – Control</td>
<td>-1.573</td>
<td>.357</td>
<td></td>
</tr>
<tr>
<td>AF Only D – Global D</td>
<td>1.304</td>
<td>.391</td>
<td></td>
</tr>
<tr>
<td>Interfering repeated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AF Only D – Control</td>
<td>-2.713</td>
<td>.024</td>
<td></td>
</tr>
<tr>
<td>Global D – Control</td>
<td>-1.511</td>
<td>.268</td>
<td></td>
</tr>
<tr>
<td>AF Only D – Global D</td>
<td>-0.978</td>
<td>.331</td>
<td></td>
</tr>
</tbody>
</table>

*p-values in bold are significant.

Table 5

<table>
<thead>
<tr>
<th>Interference effect</th>
<th>Interfering R mean (SE)</th>
<th>Non-interfering R mean (SE)</th>
<th>Pairwise comparison t(92)</th>
<th>Adjusted p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF Only D group</td>
<td>3.252 (0.503)</td>
<td>4.734 (0.503)</td>
<td>-3.340</td>
<td>.001</td>
</tr>
<tr>
<td>Global D group</td>
<td>3.957 (0.534)</td>
<td>3.793 (0.534)</td>
<td>0.391</td>
<td>.607</td>
</tr>
<tr>
<td>Control group</td>
<td>5.018 (0.398)</td>
<td>4.898 (0.398)</td>
<td>0.383</td>
<td>.703</td>
</tr>
<tr>
<td>Hebb effect</td>
<td>Fillers mean (SE)</td>
<td>Non-interfering R mean (SE)</td>
<td>Pairwise comparison t(92)</td>
<td>Adjusted p-value</td>
</tr>
<tr>
<td>AF Only D group</td>
<td>3.119 (0.503)</td>
<td>4.734 (0.503)</td>
<td>-3.857</td>
<td>.001</td>
</tr>
<tr>
<td>Global D group</td>
<td>2.758 (0.534)</td>
<td>3.793 (0.534)</td>
<td>-2.471</td>
<td>.031</td>
</tr>
<tr>
<td>Control group</td>
<td>4.442 (0.398)</td>
<td>4.898 (0.398)</td>
<td>-1.453</td>
<td>.299</td>
</tr>
</tbody>
</table>

*p-values in bold are significant.
Group, no effect of Raven score, nor interactions were found ($p = .159$; numerical computation task, for each group (AF Only D, Global D and Control). Error Mean number of errors per condition (1 step versus 2 steps) in the non-
figuress带来了新的证据，说明了算术事实表征的获取和检索之间的关系。特别是一个新的假设，即序列学习障碍会干扰算术事实的表征。由此，我们发现，AF Only D组在序列表征，特别是记忆任务中的表现明显高于其他两组。此外，AF Only D组在计算表现上也有显著的差异。

4. Discussion

This study aimed at testing two hypotheses regarding different profiles of dyscalculia: one profile characterized by specific AF difficulties would be due to hypersensitivity-to-interference in memory while another profile presenting global math difficulties would be associated with a serial-order learning deficit. We first summarize and discuss the findings of the first hypothesis, and then go on with the second hypothesis. Finally the limitations, considerations and future perspectives are set out.

First, in agreement with our predictions, the AF Only D group and the Global D group did not have the same cognitive profile in a Hebb paradigm, thus underlining the importance of taking into account the heterogeneity in dyscalculia. In particular, we found that the AF Only D group showed a larger sensitivity-to-interference compared to the Global D and the Control groups. Their performance in the interfering repeated condition was lower than the two other groups and they showed an interference effect while the two other groups did not. In the non-interfering condition, the AF Only D group showed similar serial-order learning skills as the Control group. Furthermore, the AF Only D participants showed a typical Hebb effect and reached the stopping criterion with the same number of repetitions as the Control participants, supporting the assumption of good serial-order learning skills. However, a relatively low performance in the filler condition is noticed in the AF Only D group. One possible interpretation might be that their weak performance in the filler and interfering conditions is due to the fact that the same set of syllables is used in both conditions which renders both conditions as interfering ones. We could therefore interpret that the AF Only D participants face difficulties with both conditions because of interference. In the non-interfering repeated condition the AF Only D participants showed similar performance to that of the controls. Besides, the quality of their memory trace for the non-interfering repeated sequence was similar to that of the controls, as evidenced by their performance in the computation-like task. Indeed, they could start the sequence from any position and go one or two steps further. In sum, their performance on the non-interfering repeated sequence and on the computation-like task bears witness to good serial long-term memory capacity. Contrariwise, in the interfering situation, the performance of the AF Only D group dropped drastically. These results corroborate previous findings showing that hypersensitivity-to-interference may hamper someone to store very similar items. Recently, De Visscher and Noël (2013) reported a case study with a circumscribed impairment of arithmetic facts storage (patient DB). While this person had perfect cognitive functioning (memory, executive functions, reasoning), she showed hypersensitivity-to-interference in memory. Furthermore, this recent hypothesis has been tested with fourth-grade children that are acquiring the multiplication tables (De Visscher & Noël, 2014a,b). Children with poor arithmetical fluency performance showed higher sensitivity-to-interference than control children. The present results bring new evidence for a link between an arithmetical facts deficit and hypersensitivity-to-interference in adults with AF dyscalculia, with another, totally different, paradigm.

Our second hypothesis was that the Global D group might suffer from impaired processing of serial-order sequences. We suggested that a serial-order learning impairment should already disturb the acquisition of the counting sequence at the age of 2 or 3 years. Since the acquisition of the ordered sequence of number words precedes the cardinal knowledge acquisition, a difficulty at the former stage should delay or disturb acquisition of the latter. An early disturbance in the acquisition of the symbolic numbers would consequently trigger difficulties in all future mathematical development since the symbolic number system is the basis of more complex arithmetical knowledge. In this study, we found that the Global D group did not differ from the controls in a words list memory task that did not involve any order constraint. However, the Global D group showed lower performance than the Control group, when a serial-order aspect was included in a short-term memory task (filler sequences). The Global D group needed more
repetitions than the Control group to learn a repeated sequence in long-term memory. Moreover, after learning the repeated sequence, when the task required them to travel within the sequence (non-numerical computation task), they produced much more errors than the Control and the AF Only D groups. The analysis of errors revealed that 59% of their mistakes concerned an order error (wrong syllable that belongs to the learned sequence), while the remaining 41% of their errors were syllables that did not belong to the learned sequence or non-responses. Thus, even though they reached the stopping criterion indicating that they had learnt the sequence, the long-term consolidation of the acquired sequential information was not as efficient as that of the controls. Furthermore, we tested whether Global D adults knew the repeated sequence as an unbreakable string (like during the number words acquisition) by comparing the amount of error when starting on the first versus second syllable. No interaction was found between the amounts of errors in the first versus second syllable across groups. The Global D group did not make more errors on the second syllable compared to the first syllable of the learned sequence. Altogether, the larger number of errors produced by the Global D group does not seem to reflect a deficit in manipulating the learned sequence but their memory trace of the non-interfering sequence seemed to degrade more rapidly. Such decline of the sequences’ memory trace could explain difficulties in symbolic numerical development since it is based on the number-word sequence recitation. A global math deficit (in strategies and procedures) could therefore be due to a serial order-learning deficit.

This deficit should not be due to general episodic memory deficit since the Global D participants had normal performance on the Words List recalling task, in which no serial-order information was required. One could possibly argue that the Global D profile is due to a more general (not necessarily serial) memory deficit, that has been frequently reported in D populations (see for instance the meta-analysis of Swanson and Jerman (2006)). This memory weakness is typically observed in tasks involving the central executive system (working memory) rather than merely the passive, temporary storage of information (short-term memory). In the former, the participant has to maintain sequences of information while simultaneously processing the same or other information (e.g., Baddeley & Logie, 1999; Engle, Kane, & Tuholski, 1999) while in the latter, sequences of items are just temporarily maintained by the participant who is then asked to reproduce the sequence in the same order of presentation. In the Hebb paradigm, the sequence has to be held in memory without any other concurrent processing demands, like in typical short-term memory span tasks, and the stress is put on the maintenance of serial order (the syllables are provided). Accordingly, the findings regarding the Global D group could potentially be interpreted in terms of a general (not necessarily serial) short term memory impairment. To investigate this potential confound, we used the Words List subtest in which 12 words were presented and participants had to recall as many words as they could, the order of recall being totally irrelevant. When comparing the first recall in the three groups, no significant difference was observed. This shows an important contrast between two short-term memory tasks, one taxing mainly the representation of order information (Hebb) and the other taxing only the maintenance of item information (Words List). It should however be noted that only one list of words was presented in the Words List subtest, providing an important source of evidence but not a definite conclusion.

Beyond the short term memory deficit, one could argue that the Hebb paradigm to some extent requires central executive resources, and that the Global D group deficit might be interpreted in terms of a working memory deficit. Nonetheless, the reverse interpretation is also valid. Nearly all the tasks that are commonly used to test working memory require processing of serial order. For instance, De Smedt et al. (2009) used a large battery of 7 tasks to measure each component of the short-term and working memory systems. Six of them involved processing of the serial order of the items (non-word repetition, digit span forward, block recall, listening span, counting span, backward digit span). Since the vast majority of WM tasks include order information, the association between dyscalculia and WM deficits could be explained by a serial-order processing deficit. Regarding our findings, one element is in disfavor of the interpretation in terms of a working memory deficit. While fluid intelligence has been shown to strongly correlate with working memory capacity (Kane, Hambrick, & Conway, 2005), the effects of the intelligence factor (Raven score) included in all Hebb analyses were never significant and did not change the significance of the Group × Condition interaction. Our findings seem therefore to support the interpretation of a serial order deficit in the Global D group. Currently, only one study has compared working memory tasks that tax the order information or not. Attout and Majerus (2014) reported that children with dyscalculia were impaired in a working memory task only when the processing of order information was required (but not for item information).

Nevertheless, further evidence is needed to disentangle a general working memory deficit from a more specific serial order deficit in dyscalculia. Our main contribution was to show that this serial-order processing deficit is characteristic of the Global D group and not of the AF Only D group, and that it appears in short-term memory and persists until storage in long-term memory. Finally, we extended the finding of previous studies reporting a deficit in ordinality processing (Rubinsten & Sury, 2011) and differences in brain activation during such processing (Kaufmann et al., 2009) in participants with dyscalculia. Indeed, by using a paradigm that does not confound the numerical magnitude processing with the serial order processing, we showed that the deficit in long-term serial-order learning also affects material that does not involve any magnitude dimension.

This work provides novel insights into two profiles of dyscalculia. First, people with a specific arithmetic facts deficit (and proper conceptual knowledge) were shown to experience hypersensitivity to-interference in memory. Second, people with a global math deficit were shown to encounter difficulties in learning and remembering serial-order information. These two profiles should be further investigated in future studies. First, since our samples were relatively small, these findings should be replicated. Second, the serial order deficit hypothesis should be distinguished from the approximate number system deficit (Piazza et al., 2010; Wilson & Dehaene, 2007) since a global math deficit is expected in both hypotheses. One could imagine that both deficits, the serial order and numerical representation deficit, could occur at the same time or could be related. Sustaining this idea, Lyons and Beilock (2011) showed that ordinal processing mediates the relation between the approximate number system and mathematical competence. Finally, since both our hypotheses are not specific to numbers, the question of comorbidity is of particular interest. The combined profile of dyslexia and dyscalculia could theoretically be explained by sensitivity to interference in memory as well as by a serial-order processing deficit. Because a deficit of serial-order learning has been shown in adults with dyslexia (Szmatec et al., 2011) we had to exclude people with dyslexia in order to test directly whether global math difficulty could be due to a serial order-learning deficit. It remains to be demonstrated how the two current hypothesis may be useful to shed light on the comorbidity. Similarly, the comorbidity of dyscalculia with the attention deficit disorder, with or without hyperactivity, deserves to be investigated as well. In our sample, none of our participants reported attention deficit during the pre-experimental


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