**Impaired Short-Term Memory for order in adults with dyslexia**

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Abstract

Verbal short-term memory (STM) deficits are consistently associated with dyslexia, but the nature of these deficits remains poorly understood. This study used the distinction between item and order retention processes to achieve a better understanding of STM deficits in adults with dyslexia. STM for item information has been shown to depend on the quality of underlying phonological representations, and hence should be impaired in dyslexia, which is characterized by poorly developed phonological representations. On the other hand, STM for order information is considered to reflect core STM processes, which are independent from language processing. Thirty adults with dyslexia and thirty control participants matched for age, education, vocabulary, and IQ were presented STM tasks, which distinguished item and order STM capacities. We observed not only impaired order STM in adults with dyslexia, but this impairment was independent of item STM impairment. This study shows that adults with dyslexia present a deficit in core verbal STM processes, a deficit which cannot be accounted for by the language processing difficulties that characterize dyslexia. Moreover, these results support recent theoretical accounts considering independent order STM and item STM processes, with a potentially causal involvement of order STM processes in reading acquisition.

*Keywords*: verbal short-term memory, serial order processing, dyslexia

**Introduction**

 Deficits in verbal short-term memory (STM) are well established in children and adults with dyslexia ([Brady, Shankweiler, & Mann, 1983](#_ENREF_8); [Martin et al., 2010](#_ENREF_53); [Pennington, Van Orden, Smith, Green, & Haith, 1990](#_ENREF_63); [Ramus et al., 2003](#_ENREF_67); [Snowling, Goulandris, & Defty, 1996](#_ENREF_78); [Tijms, 2004](#_ENREF_84)). However, the nature of these deficits currently raises many questions such as whether STM deficits in dyslexia are a basic impairment or whether they can be accounted for by the phonological processing difficulties that characterize this disorder (e.g., [Ramus & Szenkovits, 2008](#_ENREF_68); [Snowling, 2000](#_ENREF_77)). In most studies on dyslexia, verbal STM deficits have been highlighted via word list immediate serial recall tasks (i.e., digit or word span); these tasks require one to simultaneously store information about the phonological and lexico-semantic characteristics of the items of the memory list (item information) as well as information about the serial order in which the items are presented (order information). As we will show, the distinction between these two types of information to be maintained in STM may allow us to disentangle the question of STM deficits and their relation to language processing impairments in dyslexia.

 Many recent models of STM consider that serial order and item information are represented using distinct codes with only the codes for item information relying on the language network. Although these models differ in the way order information is represented, a common denominator of many models is that item information is maintained via temporary activation of underlying phonological, lexical, and semantic language representations ([Brown, Vousden, McCormack, & Hulme, 1999](#_ENREF_11); [Burgess & Hitch, 1999](#_ENREF_13); [Gupta, 2003](#_ENREF_28); [Henson, 1998](#_ENREF_31)). Another common denominator of these models is that order information is represented via specialized and language-independent codes. This module is either time-based ([Brown et al., 1999](#_ENREF_11)), context-based ([Burgess & Hitch, 1999](#_ENREF_13), [2006](#_ENREF_14)), or vector-based ([Gupta, 2003](#_ENREF_28); [Henson, 1998](#_ENREF_31)), and represents what one might consider as being the remaining specific property of STM processing. In support of these theoretical models, a number of studies have shown that item recall is more influenced by linguistic knowledge than order recall ([Nairne & Kelley, 2004](#_ENREF_60); [Saint-Aubin & Poirier, 1999](#_ENREF_71)). In particular, Saint-Aubin and Poirier ([1999](#_ENREF_71)) showed that lexical frequency, reflecting the intervention of phonological long-term memory, mainly affects item recall, relative to order recall. Majerus and D’Argembeau ([2011](#_ENREF_39)) also showed that immediate serial recall for words with rich and easy-to-activate lexico-semantic representations results in better item recall, but not better order recall, relative to words with poorer lexico-semantic content. Recent neuroimaging studies also show that while the retention of item information activates language processing regions in superior and inferior temporal gyri, the retention of order information activates a distinct network involving the right intraparietal sulcus ([Majerus, Belayachi, et al., 2008](#_ENREF_38); [Majerus et al., 2010](#_ENREF_40); [Majerus, Poncelet, Van der Linden, et al., 2006](#_ENREF_46)). Finally, in support for the proposed distinction between STM for item and STM for order information, selective impairment of either serial order or item retention abilities have been shown in participants with velocardiofacial syndrome ([Majerus, Van der Linden, Braissand, & Eliez, 2007](#_ENREF_48)), children with Down syndrome ([Brock & Jarrold, 2004](#_ENREF_9)), patients with semantic dementia ([Majerus, Norris, & Patterson, 2007](#_ENREF_43)), and patients with aphasia ([Attout, van der Kaa, George, & Majerus, in press](#_ENREF_2)). Attout et al. ([in press](#_ENREF_2)) recently showed a double dissociation between item and order STM deficits in two brain injured patients, patient MB showing poor item STM performance with associated phonological processing impairment but preserved order STM capacities, and patient CG showing poor serial order STM performance but preserved item STM capacities. This growing body of research supports the distinction between STM for item and STM for serial order information, and the independency of serial order information on the quality of the language network.

Given that typical verbal STM tasks do not distinguish between item and order retention abilities, poor performance in these tasks in participants with dyslexia could thus reflect deficits in item STM, order STM, or both. STM impairment in dyslexia has been mainly interpreted within the phonological core deficit hypothesis. According to this hypothesis, phonological representations in participants with dyslexia are impaired, hindering learning of the correspondence between letters and constituent sounds of speech, and more widely any task relying on activation of phonological representations ([Ramus et al., 2003](#_ENREF_67); [Snowling, 1981](#_ENREF_76)). This includes tasks involving nonword reading, phonological awareness, rapid lexical retrieval and verbal STM, for which participants with dyslexia show poor performance ([Wagner & Torgesen, 1987](#_ENREF_87)). Implicitly, this framework implies that the deficit in verbal STM is related to item impairment resulting from suboptimal activation of phonological representations, the latter being necessary for representing item information during STM tasks as we have noted before ([Burgess & Hitch, 1999](#_ENREF_13); [Majerus & D'Argembeau, 2011](#_ENREF_39)).

On the other hand, order STM abilities have rarely been considered in dyslexia. Some studies have considered STM for serial order and item information more closely in good and poor readers ([Mason, 1980](#_ENREF_55); [Mason, Katz, & Wicklund, 1975](#_ENREF_56)). In a study by Mason et al. ([1975](#_ENREF_56)), children had to recall eight digits or letters without regard to order in the item memory task, while in the order memory condition, they were given series of cards depicting the presented items and they had to place them in correct order of presentation. The results showed that poor readers showed inferior performance for both item and order memory conditions. However, the two groups were not matched for IQ, and the use of written stimuli could have penalized the poor readers in both the item and order STM conditions. More recently, Nithart et al. ([2009](#_ENREF_62)) investigated the linguistic and STM processes underlying reading impairment in children with specific language impairment or children with dyslexia. Among their tasks, they used a serial order digit recognition task, and they observed inferior performances in children with dyslexia, in comparison to a control group matched on chronological age but not on non-verbal IQ.

The present study aimed to explore item STM and order STM capacities in adults with dyslexia in order to determine whether dyslexia is characterized by a fundamental STM impairment. There is considerable evidence that dyslexia is a lifelong disability, and that reading, phonological processes, and verbal STM deficits persist into adulthood ([Elbro, Neilsen, & Petersen, 1994](#_ENREF_21); [Miller-Shaul, 2005](#_ENREF_58); [Pennington et al., 1990](#_ENREF_63); [Wilson & Lesaux, 2001](#_ENREF_88)). Hence, if dyslexia is characterized by an independent verbal STM impairment, which cannot be considered as being only the consequence of poor phonological processing abilities, then difficulties should still be observable in adult participants with dyslexia, and this most specifically for STM for serial order. We explored this hypothesis by administering tasks specifically designed to measure order and item retention abilities in a sample of university educated adults with developmental dyslexia. In Experiment 1, we used two STM tasks, serial order digit reconstruction and single nonword delayed repetition, which maximize either serial order or item STM capacities. In Experiments 2 and 3, we assessed item and serial order STM capacities within the same STM task, by distinguishing item and order errors in an immediate serial recall task (Experiment 2) or by distinguishing item and order probe conditions in a recognition STM task (Experiment 3).

**Experiment 1**

In contrast to STM tasks used in previous studies on dyslexia, which confounded item and order information, the present experiment used two tasks, adapted from previously published studies, which have been shown to be highly sensitive to either item processing capacities or serial order retention capacity ([Majerus, Poncelet, Greffe, & Van der Linden, 2006](#_ENREF_45); [Majerus, Poncelet, Van der Linden, & Weekes, 2008](#_ENREF_47); [Martinez Perez, Majerus, & Poncelet, 2011](#_ENREF_54)). The first task was a single nonword delayed repetition and consisted of the repetition of unfamiliar nonwords, which are especially challenging at the level of sublexical phonological processing. To maximize retention requirements for item information, the stimuli were new on any trial and the nonwords differed in phonotactic frequency (that is, the probability of the phoneme co-occurrence patterns defining the nonwords was variable), varying the processing demands at the level of phonological knowledge; this is further reflected by an expected advantage for maintaining nonwords with high phonotactic frequency patterns, reflecting the intervention of sublexical phonological knowledge at the item level ([Gathercole, Frankish, Pickering, & Peaker, 1999](#_ENREF_26); [Majerus, Van der Linden, Mulder, Meulemans, & Peters, 2004](#_ENREF_49); [Thorn & Frankish, 2005](#_ENREF_83)). In contrast, in order to reduce serial order requirements, only a single item had to be maintained for each trial and, at the sublexical level, all items had the same short monosyllabic structure. The second task was a serial order reconstruction task using highly familiar digit items. In order to decrease item processing requirements, the items were known in advance. Only order of presentation of the items changed across trials of the same sequence lengths, putting maximal weight on serial order retention mechanisms. For both tasks, the important point is that, relative to standard STM measures used in the dyslexia literature, retention requirements for either serial order or item information are maximized, whereas requirements for processing of either item or serial order information are minimized.

**Method**

**Participants.** Thirty young adults with developmental dyslexia (11 males; mean age = 24.3; SD = 3.4) and 30 control adults (11 males; mean age = 23.6; SD = 3.7) participated in the present study. The experimental and control groups were matched for gender, age, academic background (years of education), nonverbal IQ, and receptive vocabulary (see Table 1 for details on matching variables). The assessment was carried out by a graduate student in psychology. Participants were informed of their right to refuse consent and their right to withdraw consent or discontinue participation at any time without penalty. The participants signed an informed consent form prior to participation.

All participants were native French speakers with no history of neurological/psychiatric disorder or hearing impairment. All obtained a nonverbal IQ above 90 ([Raven, Raven, & Court, 1998](#_ENREF_70)) and all had high levels of education (university degree). None of the participants in the control group reported a history of reading or oral language difficulties; this was checked by administering a standardized orthography test, revealing scores at least equal to expected performance levels (see Table 1). The participants with dyslexia all had received a formal diagnosis of developmental dyslexia by a qualified professional during childhood; in addition, they scored at least two standard deviations below normal performance on an orthography test (see Table 1), in line with the criteria used in other studies with adults with dyslexia ([Everatt, 1997](#_ENREF_23); [Miles, 1993](#_ENREF_57); [Miller-Shaul, 2005](#_ENREF_58); [Ramus et al., 2003](#_ENREF_67)). Miles ([1993](#_ENREF_57)) showed that spelling performance is a valid indicator of dyslexia in adults; he observed that some adults with dyslexia can obtain high scores on a word recognition test, but will still show difficulties on measures of spelling performance. In addition to this measure of orthographic skills, we administered several reading and phonological processing tasks (phonological awareness and rapid naming measures) to further characterize reading and reading-related skills of the dyslexic group, in line with the literature ([Ben-Dror, Pollatsek, & Scarpati, 1991](#_ENREF_3); [Bruck, 1990](#_ENREF_12); [Ramus et al., 2003](#_ENREF_67)).

**Materials.**

***Background tasks.***

*Nonverbal intelligence.* The Standard Progressive Matrices ([Raven et al., 1998](#_ENREF_70)) were used as a measure of nonverbal intelligence.

*Receptive vocabulary.* Receptive vocabulary knowledge was estimated using the E.V.I.P. *(Echelle de vocabulaire en images Peabody)* scales ([Dunn, Thériault-Whalen, & Dunn, 1993](#_ENREF_17)), a French adaptation of the Peabody Picture Vocabulary Test ([Dunn & Dunn, 1981](#_ENREF_16)). As a dependent variable, we used standardized vocabulary scores.

*Reading abilities.* The standardized French reading test “Alouette-R” ([Lefavrais, 2005](#_ENREF_36)) was administered to estimate reading level. This text consists of 265 words containing many low frequency words. The participants were instructed to read the text as fast and as accurately as possible. A standardized reading score was computed by combining total reading time and errors.

To assess more precisely the reading procedures, we also administered 30 written words containing irregular orthography-to-phonology correspondences (that is, orthographic patterns that cannot correctly by using regular print-to-sound conversion rule), 30 written words containing only regular correspondences, and 30 nonwords developed by Poncelet ([1999](#_ENREF_65)). Irregular and regular words were matched on length (number of letters), lexical frequency, and imagery. Words and nonwords were matched on length. The 90 items were presented on cards, each card depicting 5 stimuli. For each condition, the experimenter presented the 6 cards in a fixed order, and participants were requested to read aloud the items of each card as quickly and accurately as possible. For each card, the experimenter engaged the chronometer when the participant started the pronunciation of the first item and stopped the chronometer at the end of its pronunciation of the fifth item. Accuracy of response for each item and reading time for each card of 5 items were measured. The proportion of correct responses and total reading times for each condition were used as dependent variables.

*Phonological awareness.* Phonological awareness abilities were first assessed using an adaptation of the phoneme identification task by Manis, Seidenberg, Doi, McBride-Chang, and Petersen ([1996](#_ENREF_51)). The participants listened to a nonword and had to produce the sound of the nonword that came immediately before or after a target phoneme indicated by the experimenter (e.g., which sound comes before “r” in “dreklan” ?). Twenty-four bi-syllabic nonwords were proposed, half of the items involved identifying the sound before and half after the target phoneme. The proportion of correct responses was determined.

We also administered a phoneme deletion task from EVALEC, a computerized battery of measures of reading and phonological processing skills ([Sprenger-Charolles, Colé, Béchennec, & Kipffer-Piquard, 2005](#_ENREF_79)). The participants listened to a nonword, and had to delete the first phoneme of the nonword and produce the remaining sound (e.g., which sound remained when you delete the first sound of “klo” ?). Twelve monosyllabic nonwords were proposed, and involved a consonant-consonant-vowel structure. The time taken to complete each item (delay between the end of the instruction and the onset of the response) was measured. Total response time was used as a dependent variable.

*Rapid Automatic Naming.* To assess the speed of lexical access, we used two tasks adapted from the Phonological Assessment Battery ([Frederickson, Frith, & Reason, 1997](#_ENREF_24)): automatic picture (ball, hat, door, table, box) naming and automatic digit naming. In each case, the participant was required to name two pseudorandom sequences of 50 stimuli (consisting either of line drawings of common objects or of single digit numbers) as quickly as possible. Each participant first named the five objects or a sequence of 8 digits to check familiarity with the items. According to Frederickson et al. ([1997](#_ENREF_24)), total naming times were recorded for each of the two tasks, irrespective of response accuracy.

***Experimental tasks.***

*Single nonword delayed repetition*. Item STM was assessed using an adaptation of the delayed item repetition task by Majerus, Poncelet, et al. ([2006](#_ENREF_45)). This task had been designed to maximize the processing demands of phonological item information while minimizing the contribution of serial order STM processes. A total of 60 single nonwords were presented via headphones for repetition after a filled delay. The stimuli were classified as containing high or low phonotactic frequency patterns, according to summed token frequencies of the CV(consonant-vowel)\* and \*VC(vowel-consonant) diphones obtained in the database of French phonology by Tubach and Boe ([1990](#_ENREF_85)). Each trial included the presentation of one nonword and an 8-s filled delay, during which the participants had to count backwards in steps of 3, starting at 95, in order to prevent sequential rehearsal. After the delay, the experimenter tapped sharply on the desk and the participants were asked to recall the nonword. To maximize retention requirements for item information, the stimuli were new on any trial. Furthermore, the nonwords differed in phonotactic frequency, varying the processing demands of phonological knowledge, the level which is considered to be impaired in adults with dyslexia. By contrast, several methodological precautions were taken to minimize order retention requirements: (a) only a single item had to be retained; (b) all nonwords had the same consonant–vowel–consonant monosyllabic structure, unlike traditional nonword repetition tasks using multisyllabic nonwords of unpredictable syllabic structure; hence the only order errors that could occur were inversions between the first and last consonant (these permutations are however infrequent, Leclercq and Majerus ([2010](#_ENREF_35)) only observed 0.4% of errors due to an inversion of initial and final consonants in the performance of children of 4 and 5 years old); (c) nonwords were recalled after a filled delay, which prevented sequential rehearsal of the to-be-stored information. The proportion of items correctly repeated, as a function of phonotactic frequency, was determined.

*Digit serial order reconstruction.* The digit serial order reconstruction task ([adapted from Majerus, Glaser, Van der Linden, & Eliez, 2006](#_ENREF_41)) was designed to maximize requirements for processing serial order information while minimizing requirements for processing item information. This task consisted of the auditory presentation, via headphones, of digit lists by increasing length (6 to 9 digits), with 6 trials for each length. At the end of each trial, the participants were given cards, on which the digits presented during the trial were printed (cards were giving in numerical order), and they sorted the cards according to their order of presentation. In this task, processing of phonological item information is minimized since the stimuli are known in advance – the participants are told which item information will be presented in each trial (for sequences of length 6, only the first six numerals were used) – and are provided at recall through cards to the participants who simply had to arrange them in correct serial position. The proportion of correctly placed items, by pooling over all sequence lengths, was determined.

**Results**

**Background tasks.** Table 1 presents the results of the dyslexic and control groups in the reading, phonological awareness, and rapid automatized naming tasks. For the standardized French reading test “Alouette-R”, the dyslexic group performed more poorly than the control group, *F*(1,58) = 49.3, *p* < .001, = .46. In the word and nonword reading task, for response accuracy, significant main effects of group, *F*(1,58) = 31.9, *p* < .001, = .35, and stimulus type, *F*(2,116) = 65.4, *p* < .001, = .53, with a significant interaction, *F*(2,116) = 16.2, *p* < .001, = .21, were observed. Newman-Keuls post-hoc comparisons (*p* < .05) indicated significantly poorer performance for the dyslexic group relative to the control group in the nonword reading condition only. For reading time, significant main effects of group, *F*(1,58) = 41.2, *p* < .001, = .41, and stimulus type, *F*(2,116) = 349.7, *p* < .001, = .85, were also observed, with again a significant interaction, *F*(2,116) = 9.4, *p* < .01, = .14. Reading latencies were longer in the dyslexic group relative to the control group for all stimulus types (Newman-Keuls post-hoc comparisons).

For the phoneme identification task, the dyslexic group also showed poorer performance relative to the control group, *F*(1,58) = 21.1, *p* < .001, = .26. The same results were observed for the phoneme deletion task, *F*(1,47) = 47.6, *p* < .001, = .50, consistent with previous reports. Finally, in the rapid automatic naming task, we observed main effects of group, *F*(1,58) = 30.0, *p* < .00, = .34, and stimulus type, *F*(1,58) = 537.7, *p* < .001, =.90, with no interaction, *F*(1,58) = 0.22, *ns*, < .01; naming times were higher for all stimulus types in the dyslexic group (Newman-Keuls post-hoc comparisons, *p* < .05). In sum, all these results are consistent with previous reports of reading and phonological processing impairments in adults with dyslexia.

< INSERT TABLE 1 about here >

**Experimental tasks.** For the item delayed repetition task (see Table 2), we observed a main effect of group, *F*(1,58) = 49.4, *p* < .001; = .46, as well as a main effect of phonotactic frequency nonword condition, *F*(1,58) = 7.5, *p* < .01; = .12, with no significant interaction, *F*(1,58) = .00, *ns*; < .01. The dyslexic group obtained poorer performance than the control group in both conditions, and both groups performed better in the high phonotactic frequency condition than in the low phonotactic frequency condition. In order to check that serial order STM requirements were minimized in this task, we computed the number of order errors, i.e. inversions of the first and last consonant. As predicted, there were virtually no phoneme ordering errors, with order error rates ranging between 0.012 in the control group and 0.014 in the dyslexic group.

For the digit serial order reconstruction task (see Table 2), a mixed ANOVA revealed significantly poorer performance in the dyslexic group than the control group, *F*(1,58) = 27.9, *p* < .001, = .32. We further performed an analysis on performance as a function of serial position. In order to increase the reliability of this analysis, we restricted our analysis to list lengths 7 to 9, and combined serial positions 5 and 6 of list length 8, and serial positions 3 and 4, as well as 5 and 6 of list length 9[[1]](#footnote-1). This allowed us to obtain 18 estimates for each of the seven serial positions entering into the analysis. Figure 1 shows the proportion of correct responses as a function of group and serial position. A mixed ANOVA revealed significant main effects of group, *F*(1,58) = 28.8, *p* < .001, = .34, serial position, *F*(6,348) = 38.3, *p* < .001, = .40, with furthermore a significant interaction, *F*(6,348) = 4.4, *p* < .001, = .08. The interaction was explored via planned comparisons, with Bonferroni corrections for multiple comparisons (*p* < .007): the dyslexic group showed the same performance levels as the control group for the recency portion of the serial position curve, but the group effect was most pronounced for the primacy portion (effect significant for positions 1, 2, 3, and 4). This indicates that the dyslexic group had pronounced difficulties for maintaining early serial positions.

< INSERT TABLE 2 about here >

< INSERT FIGURE 1 about here >

These analyses confirm that adult participants with dyslexia present poor STM for item information, as would be expected given their difficulties at the level of processing phonological item information. At the same time, the dyslexic and control groups showed a similar phonotactic frequency effect, suggesting preserved access to sublexical phonological representations. Importantly, for the serial order reconstruction, these results clearly highlight impairment for the storage of order information in the dyslexic group, and this both in terms of overall performance as well as in terms of serial position effects, with an abnormally increased primacy effect.

**Experiment 2**

Experiment 1 showed item and serial order STM deficits in the dyslexic group. However, the tasks used in that experiment did not allow us to directly compare both types of deficits since they were measured by tasks having distinct experimental procedures. In Experiment 2, we assessed item and order STM abilities within the same STM task, by determining the rate of item errors (omissions, intrusions, paraphasias) and order errors (items recalled in an incorrect serial position) via an immediate serial recall task (e.g., [Nairne & Kelley, 2004](#_ENREF_60); [Poirier & Saint-Aubin, 1996](#_ENREF_64)). This task involved the auditory presentation of verbal sequences of increasing list length. After the auditory presentation of each list, the participants were given nine cards illustrating the nine possible stimuli that could occur in each sequence. They first had to select the cards that had been presented (item errors), and then they had to arrange them following their order in the auditory sequence (order errors). Majerus et al. ([2009](#_ENREF_42)) successfully used this type of task to dissociate item and order retention capacities in young healthy children. Majerus, Poncelet, Elsen, and Van der Linden ([2006](#_ENREF_44)) showed that these estimates of item and order STM abilities based on error types show good correlations with other measures of item STM and order STM, respectively, and which were similar or identical to those used in Experiment 1.

**Method**

**Participants.** The participants were the same as in the previous experiment.

**Materials.**

***Experimental task.***An adaptation from the task of Majerus et al. ([2009](#_ENREF_42)) was used to assess order and item STM abilities within a single task based on the number of item and order error types. The stimuli used for this task were nine monosyllabic animal names: *chien, chat, loup, ours, lion, coq, singe, rat, mouche* (dog, cat, wolf, bear, lion, cock, monkey, rat, and fly respectively). These nine stimuli were used to form lists with lengths ranging from 5 to 9 items, and there were 6 trials for each list length. The stimuli were presented auditorily, via headphones, by increasing list length. After the presentation of each list, the participants were given nine cards (in alphabetical order) depicting the nine possible stimuli that could occur in each sequence. The participants then needed to select the cards that had been presented (possibility for making item errors) and to arrange these cards following the order of presentation of the auditory sequence (possibility for order errors). To measure both item and order retention capacities, we computed the proportion of item (omissions and confusions) and order (a target animal is reconstructed in the wrong serial position) errors over all trials. The proportion of order errors was relative to all items recalled, taking into account differences in overall item recall performance.

**Results**

**Experimental task.** For the item and order reconstruction task (Table 3), a mixed ANOVA showed significant main effects of group, *F*(1,58) = 38.8,  *p* < .001, = .40, and error type, *F*(1,58) = 35.8, *p* < .001, = .38, with furthermore a significant interaction, *F*(1,58) = 5.2,  *p* < .05, = .09. Although Newman-Keuls post-hoc comparisons (*p* < .05) revealed that the dyslexic group presented significantly higher error rates for both item and order errors relative to the control group, the group effect was more pronounced for order errors ( = .48) than for item errors ( = .15) (see Figure 2).

We further conducted further analyses of covariance (ANCOVA) in order to show that the group differences for item and order error types are independent. For the item error type, the effect of group remained significant when order STM performance was entered as a covariate, *F*(1,57) = 5.4, *p* < .05; = .08. Likewise, for the order error type, the effect of group remained significant when item STM performance was entered as a covariate, *F*(1,57) = 37.6, *p* < .001; = .40. The control group obtained again higher performance levels relative to the dyslexic group for both analyses. In order to further demonstrate the independence of item and order STM abilities, we performed correlation analyses between item and order STM measures. For the control group (*n* = 30), performance for the two STM performances did not significantly correlate after controlling for general cognitive efficiency (Raven’s matrices, EVIP verbal comprehension), *r* = .27, *ns*. The same was observed in the dyslexic group (*n* = 30), partial *r* = -.07, *ns*.

< INSERT TABLE 3 about here >

< INSERT FIGURE 2 about here >

The results of Experiment 2 show a particularly strong impairment at the level of order retention capacities in the dyslexic group. This impairment remained significant after taking into account group differences at the level of item STM, further showing that item and order STM deficits are independent. Furthermore, we computed order errors by proportionalizing order errors relative to the overall amount of items correctly recalled; hence order errors reflect order maintenance difficulties, independently of initial item processing difficulties. The results of Experiment 2 also suggest that the differences in task design for item and order STM measures in Experiment 1 cannot explain the deficits observed for item and order STM in the dyslexic group. At the same time, as can be seen in Table 3, the proportion of item and order errors in Experiment 2 differed to some extent in the control group, with slightly fewer item errors than order errors. This raises the question whether the disproportionate deficit for order STM in the dyslexic group may have been biased by task sensitivity, the task being potentially more sensitive to order STM than item STM abilities.

**Experiment 3**

To further explore order STM abilities in adult participants with dyslexia, we constructed a new item and order STM task by controlling more closely of task sensitivity towards both order and item STM abilities. This new task was a serial order and item probe recognition STM paradigm, already successfully used in previous studies of item and order STM components ([Attout et al., in press](#_ENREF_2); [Henson, Hartley, Burgess, Hitch, & Flude, 2003](#_ENREF_32); [Majerus, Bastin, et al., 2007](#_ENREF_37); [Majerus, Belayachi, et al., 2008](#_ENREF_38); [Majerus et al., 2010](#_ENREF_40); [Majerus, Poncelet, Van der Linden, et al., 2006](#_ENREF_46); [Marshuetz, Smith, Jonides, DeGutis, & Chenevert, 2000](#_ENREF_52)). In order to increase sensitivity for item STM components relative to Experiment 2, we chose nonword stimuli, which require the creation of detailed item representations, with the additional difficulty that the phonological material is unfamiliar. In the item STM condition of this task, four nonwords were presented auditorily, followed by an item corresponding to one of the items in the list or differing from one of the items by a single phoneme. Negative probes differing from the target by a minimal amount were used in order to further increase retention demands at the item level. The order STM condition was identical to the item probe recognition task, except for the probe trials that consisted of the presentation of two probe items of the memory list: The participants had to decide whether the first probe item had occurred before the second probe item in the memory list. This task has already been used in other neuropsychological studies demonstrating a dissociation between order and item STM capacities in neurodevelopmental populations such as 22q11.2 microdeletion syndrome ([Majerus, Van der Linden, et al., 2007](#_ENREF_48)) and recently in aphasic patients ([Attout et al., in press](#_ENREF_2)).

**Method**

**Participants.** The dyslexic and control groups both included 24 participants[[2]](#footnote-2), and were a subsample of the participants in Experiments 1 and 2. As in previous experiments, both groups were matched for gender, age, academic background (years of education), nonverbal IQ, and receptive vocabulary.

**Materials.**

***Experimental task.*** The memory lists were sampled from a pool of 30 pairs of mono-or dissyllabic nonwords that differed by a single phoneme (e.g., /korv-korb/, /cherille-chetille/). The nonwords respected French phonotactic rules and the stimuli of each pair were matched on diphone frequency, following the Lexique database (2409.5 vs. 2346.5, *F*(1,48) = .01, *ns*) ([New, Pallier, Brysbaert, & Ferrand, 2004](#_ENREF_61)). The use of nonwords and minimal pairs enabled us to increase reliance on phonological item processes: (a) the temporary representation of nonwords required access to sublexical phonological knowledge, and minimized access to lexico-semantic long-term memory support; (b) the use of minimal pairs allowed us to increase the phonological proximity between the probe and the target stimuli, requiring the maintenance of detailed item representations for accurate STM recognition. The stimuli were presented auditorily by lists of four (one item per second). In the item condition, after each list, a probe nonword was presented and the participants had to judge whether the nonword had been in the list or not. Negative probe trials consisted in the presentation of one member of the minimal pair in the memory list and the other member in the probe array. In the serial order condition, the participants heard two adjacent nonwords of the memory list and had to judge whether their order of presentation was the same as in the memory list or reversed. For the different trials, the stimuli were pseudorandomly sampled from a pool of 60 nonwords. There were 30 trials for each STM condition and an equal number of positive and negative probe trials, probing equally all item positions, in each condition. The task was programmed and presented on a laptop computer using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA, USA). The stimuli were presented via headphones and the participants responded by pressing the “O” key for “yes” responses or the “I” key for “no” responses. The proportion of correct responses, for each condition, was determined.

**Results**

**Experimental task.** Table 4 shows the proportion of correct responses as a function of group and STM condition. A mixed ANOVA revealed significant main effects of group, *F*(1,46) = 7.8, *p* < .01; = .15, and STM condition, *F*(1,46) = 11.9, *p* < .01; = .20, with a significant interaction, *F*(1,46) = 4.1, *p* < .05; = .08. Newman-Keuls post-hoc comparisons (*p* < .05) showed that the control group obtained similar performance for both STM conditions and that the dyslexic group performed poorer than the control group, and this only for the serial order STM condition (see Figure 3).

We further conducted further analyses of covariance (ANCOVA) in order to show that the group difference in order STM condition was independent from item STM performance. The effect of group remained significant when item STM performance was entered as a covariate, *F*(1,45) = 8.7, *p* < .01; = .16 : The dyslexic group obtained again lower performance levels relative to the control group on the serial order STM condition. Finally, we performed correlation analyses between item and order STM performances as in Experiment 2. For the control group (*n* = 24), performance in the item and order STM conditions did not significantly correlate, partial *r* = .16, *ns*, (after control of Raven’s matrices and EVIP verbal comprehension). The same was also true for the dyslexic group (*n* = 24), partial *r* = .26, *ns.*

< INSERT TABLE 4 about here >

< INSERT FIGURE 3 about here >

As in Experiment 2, we observe more severe difficulties in the dyslexic group for retaining serial order information in STM than for retaining phonological item information. Furthermore, in Experiment 3, task sensitivity was perfectly matched for item and order STM, as reflected by identical performance levels in the control participants for item and order probe recognition conditions.

**General discussion**

This study applied the distinction of item STM *versus* order STM to the exploration of verbal STM deficits in adult participants with dyslexia. The central question is whether verbal STM deficits in dyslexia reflect a fundamental deficit and are not only the consequence of poor phonological processing abilities. Experiment 1 showed that the adults with dyslexia obtained poorer performance than the control group in tasks maximizing either item STM (supposed to depend on the quality of phonological representations) or serial order STM (supposed to reflect the intervention of a language-independent serial order processing system). Importantly, Experiments 2 and 3 showed that the serial order STM impairment in the dyslexic group was even more severe than the item STM deficit. In all three experiments, the order STM deficit was independent from item STM deficits.

**Item STM and phonological processes in dyslexia**

On the one hand, this study shows that dyslexia is associated with impairment at the level of item STM. This is a less surprising result, since this is to be expected if we consider that participants with dyslexia suffer from degraded phonological representations and that the activation of these representations underlies representation of item information during verbal STM tasks ([Burgess & Hitch, 1999](#_ENREF_13); [Majerus & D'Argembeau, 2011](#_ENREF_39)). Many authors postulate a core phonological deficit in dyslexia; that is, phonological representations of children and adults with dyslexia are underspecified, poorly activated or not sufficiently categorical (e.g., [Elbro, 1998](#_ENREF_19); [Manis et al., 1997](#_ENREF_50); [Ramus & Szenkovits, 2008](#_ENREF_68); [Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004](#_ENREF_72); [Snowling, 2000](#_ENREF_77)). This impairment appears in phonological awareness, rapid automatized naming, and nonword reading tasks, which all recruit phonological processes. In the present study, all these tasks were also poorly performed by the dyslexic group in agreement with previous reports of phonological deficits in dyslexia (e.g., [Martin et al., 2010](#_ENREF_53); [Pennington et al., 1990](#_ENREF_63); [Szenkovits & Ramus, 2005](#_ENREF_81); [Wilson & Lesaux, 2001](#_ENREF_88)). Given that several models assume that verbal item information is stored via temporary activation of phonological and lexico-semantic representations of the language network, and strongly depend upon the quality of phonological long-term knowledge ([Brown, Preece, & Hulme, 2000](#_ENREF_10); [Burgess & Hitch, 1999](#_ENREF_13); [Gupta, 2003](#_ENREF_28); [Henson, 1998](#_ENREF_31)), the item STM impairment observed in the group of adults with dyslexia in this study can be easily explained by this phonological core deficit hypothesis. In this sense, impaired item STM in dyslexia can be considered to be a consequence of the core phonological impairment, rather than being a causal factor of dyslexia.

At the same time, this raises the question why no deficit was observed for the item STM condition in Experiment 3. This could have been related to the recognition procedure used in Experiment 3: a partial or degraded STM trace could, in some cases, have been sufficient for leading to a correct response given that recognition procedures do not require the full output of target information but probe recognition of parts of the target information; probe items also provide cues that can help reconstruct partially degraded STM cases. It is important to note here that this does not mean that the task used in Experiment was less sensitive to item STM processes as opposed to order STM processed: the arguments invoked here are valid for retention at *both* the order and item STM level. Hence it is remarkable to note that the order STM impairment was still apparent, even by using a recognition probe experiment, which may facilitate retrieval of information, further supporting our main findings of a robust and severe order STM impairment in adult participants with dyslexia. Finally, the phonological impairment in dyslexia may not be a universal characteristic of dyslexia. Ramus and Szenkovits ([2008](#_ENREF_68)) encountered a similar problem and noted: “there is good evidence that our participants with dyslexia did present a phonological deficit. But this deficit surfaces in some tasks and not in others […]” (pp.137). They proposed that a core phonological deficit may affect not all persons with dyslexia.

**Order STM, dyslexia and theoretical implications**

 The more novel finding of this study is the clear impairment at the level of short-term maintenance for order information in adults with dyslexia. This deficit was observed not only to be robust and severe, but also to be independent from item STM impairment. Item and serial order STM tasks remain of course STM measures, and thus share some common processes, such as attentional focalization, resistance to interference and more strategic processes such as overt or covert rehearsal. Nevertheless, after controlling for common factor via ANCOVAs or partial correlation analyses, no evidence for an association between order STM and item STM deficits was observed.

The observation of order STM impairment in adults with dyslexia is an important finding because this demonstrates that verbal STM deficits in dyslexia are not just the consequence of associated language impairment. According to several STM models (e.g., [Burgess & Hitch, 1999](#_ENREF_13); [Henson, 1998](#_ENREF_31)), item information and order information are processed by distinct mechanisms and serial order STM capacities are independent from language processes. Studies have established that STM for order is processed by neural networks distinct from the language network (which supports item STM), and is much less impacted by psycholinguistic variables such as lexical or phonotactic frequency, as opposed to item STM ([Majerus & D'Argembeau, 2011](#_ENREF_39); [Majerus et al., 2010](#_ENREF_40); [Saint-Aubin & Poirier, 1999](#_ENREF_71)). Moreover, Attout and colleagues ([in press](#_ENREF_2)) recently showed a double dissociation between item and order STM capacities in aphasic patients.

These data also have wider theoretical implication, since they are in direct contradiction with the predictions of some recent models of STM that consider that representations for item and order information in STM are intimately related, and that item and order STM deficits should co-occur. Both Botvinick and Plaut ([2006](#_ENREF_4), [2009](#_ENREF_5)) as well as Gupta and Tisdale ([2009](#_ENREF_29)) proposed computational models of STM where item and order information are maintained using distributed representations, which code for items and order conjunctively, arguing for a strict association of item and order STM performance. However, we should note here that, while linking representations of item and order information at some processing stage (which, by the way, is also the case for models such as Burgess and Hitch, 1999), order information is nevertheless encoded ([Botvinick & Watanabe, 2007](#_ENREF_6)) or updated ([Gupta & Tisdale, 2009](#_ENREF_29)) via specific mechanisms. In the Botvinick and Watanabe ([2007](#_ENREF_6)) model, two kinds of units are distinguished at the input level: units representing item information and units representing ordinal position or rank information. It is only at a subsequent step of the model that rank information, coding order information, is integrated with item information in conjunctive representations. Hence, if order information is encoded incorrectly, then it should still be possible to observe specific order STM impairment even in this more integrated model of order and item STM representations. In the Gupta and Tisdale ([2009](#_ENREF_29)) framework, the production of serially ordered sequences depends upon a *context updating* mechanism, which changes the activation pattern at each time step and provides the basis for the recall of stimuli in an ordered succession. Even if authors emphasize that this mechanism refers to a more abstract functionality than the mechanism postulated by Burgess and Hitch ([1999](#_ENREF_13)), Gupta ([2003](#_ENREF_28)) or Brown et al. ([1999](#_ENREF_11)), this theoretical model still includes a distinct system for allowing for sequence level processing, and hence dissociations between item and order processing should still be possible. Our data provide strong support for the existence of separate processes for encoding / maintaining item information on the one hand, and order information on the other hand, even in the light of more integrated models of item and order STM representations.

Our results also have potential theoretical implications for the association STM deficits and reading acquisition difficulties. Our results suggest that order STM impairment reflects a fundamental deficit in dyslexia, and could even be an important contributing factor to dyslexia. As such, the present data offer interesting opportunities for future research given that existing studies have focused mainly on impairments at the item level rather than at the sequence level ([Brady, 1986](#_ENREF_7); [Kibby, Marks, Morgan, & Long, 2004](#_ENREF_34); [Rapala & Brady, 1990](#_ENREF_69); [Snowling, 2000](#_ENREF_77); [Tijms, 2004](#_ENREF_84)). The present results raise the question about the functional role of order STM deficits in dyslexia and reading acquisition. Many authors argue that decoding processes are the central mechanism of reading acquisition, necessary for the acquisition of long-term orthographic knowledge and for reading progress more generally ([Ehri, 1998](#_ENREF_18); [Share, 1995](#_ENREF_73), [1999](#_ENREF_74); [Stanovich & Stanovich, 1995](#_ENREF_80)). Likewise, children and adults with dyslexia show a severe impairment in the use of decoding processes and a lack of automaticity of this procedure ([Rack, Snowling, & Olson, 1992](#_ENREF_66); [Snowling, 2000](#_ENREF_77); [Vellutino, Fletcher, Snowling, & Scanlon, 2004](#_ENREF_86)). During the application of grapheme-to-phoneme correspondences during unfamiliar word reading, not only the phonemes have to be maintained before speech output, but they have to be maintained and updated in ordered succession while corresponding speech motor output programs are gradually activated. Gathercole and colleagues ([Gathercole & Baddeley, 1993](#_ENREF_25); [Gathercole, Willis, Emslie, & Baddeley, 1992](#_ENREF_27)) suggested that verbal STM may be used to temporarily store the products of the letter-to-sound conversion. Their study design, however, did not allow for identification of the core STM processes that explain this association. Our study suggests that the ability to maintain an ordered representation of the succession of letter-to-sound conversions may be the critical factor here. This is also in line with recent data by Szmalec and colleagues, showing that children with dyslexia present difficulties in learning new verbal sequence information in a Hebb learning paradigm ([Szmalec, Loncke, Page, & Duyck, 2011](#_ENREF_82)). Finally, in a recent longitudinal study, we showed that order STM capacity, but not item STM capacity, predicted later print-to-sound decoding abilities in kindergarten children ([Martinez Perez et al., 2011](#_ENREF_54)). These data also fit with more general implications of order STM in sequence learning, such as learning of new oral lexical representations ([Gupta, 2003](#_ENREF_28); [Jarrold, Thorn, & Stephens, 2009](#_ENREF_33); [Majerus, Poncelet, Elsen, et al., 2006](#_ENREF_44); [Mosse & Jarrold, 2008](#_ENREF_59)). Majerus and colleagues showed that order STM is a strong predictor of vocabulary knowledge and new vocabulary acquisition, and this in both children and adults ([Leclercq & Majerus, 2010](#_ENREF_35); [Majerus et al., 2009](#_ENREF_42); [Majerus, Poncelet, Greffe, et al., 2006](#_ENREF_45); [Majerus, Poncelet, et al., 2008](#_ENREF_47)). Gupta ([2003](#_ENREF_28)) proposed that order STM mechanisms allow for the maintenance of an ordered representation of new phoneme sequences, and their ordered reactivation in the language system, thereby contributing to long-term learning of the new phoneme sequences via Hebbian learning processes ([see also Burgess & Hitch, 2006, for a similar account](#_ENREF_14)). By extension, we suggest that a similar mechanism could apply during the acquisition of new written word representations, order STM allowing for the maintenance, and reactivation of an ordered sequence of grapheme-phoneme associations. The fact that people with dyslexia have been shown to present also difficulties in the acquisition of new phonological lexical representation, as for example assessed via word-nonword paired associate learning tasks, further supports our hypothesis of a fundamental order STM deficit contributing to both phonological and orthographic learning deficits in adults with dyslexia ([Aguiar & Brady, 1991](#_ENREF_1); [Elbro & Jensen, 2005](#_ENREF_20)).

**Conclusions**

The study we report here is the first to apply the distinction between item and order information in verbal short-term memory (STM) to the exploration of verbal STM deficits in dyslexia, and to show a severe and persisting impairment in core order STM processes in adults with dyslexia, providing a clear answer to the long-standing debate over the specificity versus non-specificity of STM disorders in dyslexia. Future studies will need to investigate the precise, potentially causal mechanisms that link order STM impairment to reading acquisition and efficiency in dyslexia.Acknowledgments

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Table 1

Background cognitive skills of the dyslexic and control groups

Variable Dyslexic group Control group

 Mean SD Mean SD

Age (years) 24.3 3.4 23.6 3.7

Academic background (years of education) 15.3 2.2 14.7 2.1

Nonverbal reasoning (max = 60) 52.5 3.5 53.1 3.4

Receptive vocabulary a  122 7.2 122.7 5.7

Orthography skills b (max = 60) 43.1\*\*\* 6.0 57.2 2.7

Text “Alouette-R” reading c 362.2\*\*\* 66.2 521.3 104.9

Single word and nonword reading

Irregular words (proportion) 0.95 0.05 0.97 0.03

Regular words (proportion) 0.98 0.04 0.99 0.01

 Nonwords (proportion) 0.84\*\*\* 0.14 0.95 0.15

 Irregular words (s) 18.9\*\* 3.8 13.9 2.5

 Regular words (s) 18.5\*\* 3.2 13.9 2.4 Nonwords (s) 40.2\*\*\* 9.8 29.6 5.9

Phonological awareness

 Phoneme identification (proportion) 0.83\*\*\* 0.23 0.95 0.09

 Phoneme deletion (s) d 12.3\*\*\* 3.5 7.04 1.4

Rapid Automatic Naming

 Objects (s) 35.3\*\*\* 5.8 30.5 3.2

 Digits (s) 20.5\*\*\* 3.6 16.3 2.2

\*\* *p* < .01 \*\*\* *p* < .001

a Standardized score on the EVIP scales ([Dunn et al., 1993](#_ENREF_17));b As noted before, we ensured that the dyslexic and control groups differed on orthographic skills. These were estimated using a spelling task of 60 words, each containing one or more segments known to represent various French spelling difficulties. Items varied in French lexical frequency ([Content, Mousty, & Radeau, 1990](#_ENREF_15)). There was no time-limit to complete the task, and if necessary the participant could ask to have the stimulus presented a second time. The number of correct responses was calculated. Norms for this test (mean = 55.9; SD = 3.7) had been previously obtained on 139 university students, all French native speakers with no history of reading or oral language difficulties (mean age = 21.2; SD = 2.8); c Score combining total reading time and errors; d Data obtained on 24 adults with dyslexia and 24 control adults.

Table 2

Means and standard deviations for performance (proportions of correct responses) on the experimental STM tasks in Experiment 1

Task Dyslexic group Control group

 Mean SD Mean SD Effect size

Single nonword delayed repetition

 High phonotactic frequency 0.50\*\*\* 0.13 0.73 0.12 0.45

 Low phonotactic frequency 0.45\*\*\* 0.17 0.68 0.14 0.35

Digit serial order reconstruction 0.76\*\*\* 0.15 0.87 0.15 0.32

\*\*\* *p* < .001

Table 3

Means and standard deviations for performance (proportions of errors) on the experimental STM task in Experiment 2

Task Dyslexic group Control group

 Mean SD Mean SD Effect size

Item and order reconstruction task

 Item errors 0.24\*\*\* 0.14 0.19 0.13 0.15

 Order errors 0.39\*\*\* 0.17 0.28 0.19 0.48

\*\*\* *p* < .001

Table 4

Means and standard deviations for performance (proportions of correct responses) on the experimental STM task in Experiment 3

Task Dyslexic group Control group

 Mean SD Mean SD Effect size

Item and order probe STM task

 Item condition 0.83 0.07 0.86 0.06 0.02

 Order condition 0.76\*\* 0.07 0.84 0.08 0.17

\*\* *p* < .01

Figure 1

Response accuracy on the digit serial order reconstruction task (Experiment 1) as a function of group and serial position. Error bars represent standard errors.



Figure 2

Mean error proportions (and standard errors) in the item and order reconstruction task (Experiment 2) as a function of error type and group.



Figure 3

Mean correct responses proportions (and standard errors) in the item and order probe STM task (Experiment 3) as a function of STM condition and group.



1. When collapsing serial positions for list length 8 and 9, we chose mid-of-list positions for which performance levels were similar, leading to no significant changes in the overall shape of the serial position curve. [↑](#footnote-ref-1)
2. Experiment 3 was conducted a few months after Experiments 1 and 2. Six participants with dyslexia were unavailable at that time; in order to ensure that the experimental and control groups were still matched, their six 6 control peers were also excluded from the sample [↑](#footnote-ref-2)