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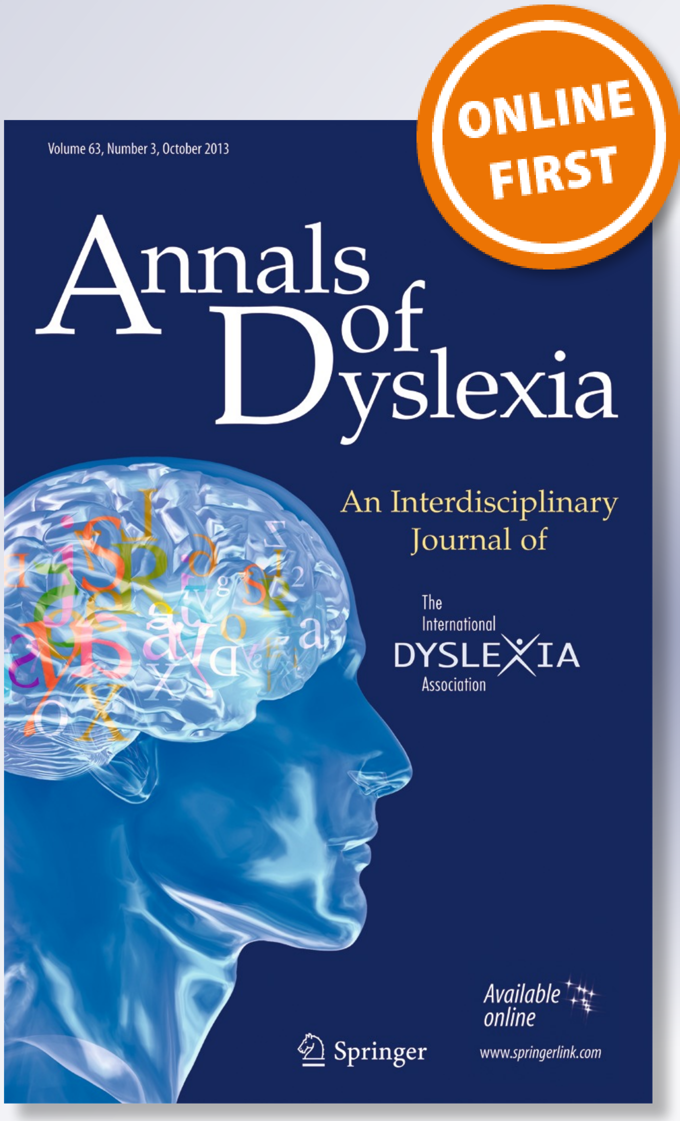

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Abstract Recent findings suggest that people with dyslexia experience difficulties with the learning of serial order information during the transition from short- to long-term memory (Szmalec et al. Journal of Experimental Psychology: Learning, Memory, & Cognition 37(5): 1270-1279, 2011). At the same time, models of short-term memory increasingly incorporate a distinction of order and item processing (Majerus et al. Cognition 107: 395-419, 2008). The current study is aimed to investigate whether serial order processing deficiencies in dyslexia can be traced back to a selective impairment of short-term memory for serial order and whether this impairment also affects processing beyond the verbal domain. A sample of 26 adults with dyslexia and a group of age and IQ-matched controls participated in a 2×2×2 experiment in which we assessed short-term recognition performance for order and item information, using both verbal and nonverbal material. Our findings indicate that, irrespective of the type of material, participants with dyslexia recalled the individual items with the same accuracy as the matched control group, whereas the ability to recognize the serial order in which those items were presented appeared to be affected in the dyslexia group. We conclude that dyslexia is characterized by a selective impairment of short-term memory for serial order, but not for item information, and discuss the integration of these findings into current theoretical views on dyslexia and its associated dysfunctions.

Highlights • Adult dyslexics were tested on short-term memory (STM) tasks for order and item
• Both conditions were run with verbal and nonverbal material, respectively
• Dyslexics compared to controls performed worse in order tasks but not in item tasks
• Data suggest a domain-general problem with serial order in STM to underlie dyslexia

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Introduction

The term dyslexia as defined by international standards (DSM-IV and ICD-10) encloses various degrees of phenomena that can be described as a gradual transition from rather moderate variations in literacy to almost complete illiteracy despite adequate schooling in a modern literate society.

One of the most debated questions is whether the causes of dyslexia are of a specifically linguistic nature—such as a phonological deficit (Katz et al. 1981; Ramus and Szenkovits 2008; Swan and Goswami 1997; Ziegler and Goswami 2005, but see also Castles and Coltheart 2004; Morais and Kolinsky 1994)—or instead related to a more general dysfunction, such as perceptual problems (Bosse et al. 2007; Romani et al. 2011), working memory and executive impairments (Brosnan et al. 2002; Kibby et al. 2004; Smith-Spark and Fisk 2007), or implicit learning difficulties (Pavlidou et al. 2010; Vicari et al. 2003).

Recently, Szmalec et al. (2011) renewed the claim that many of the experimental tasks that show impaired performance in participants with dyslexia involve sequentiality, i.e., the processing of serial order information. Cognitive tasks that do not rely on sequentiality often appear unaffected in dyslexia. When this claim was launched about 40 years ago, the question of domain specificity[1] remained open and, consecutively, the debate centered around the more predominant verbal impairments in support of the phonological deficit hypothesis (for a summary see Beaton 2004, p. 115ff; Katz et al. 1981; and more recently Nithart et al. 2009). Focusing on problems that people with dyslexia demonstrated in the visual domain, the most influential theories reported magnocellular impairments, visual attention, and attention span deficits (Facoetti et al. 2009; Lallier et al. 2010; Lobier et al. 2012; Romani et al. 2011; Vidyasagar and Pammer 2009). Convincing evidence in support of a serial order impairment was reported by Howard et al. (2006) in the field of implicit learning. They observed that people with dyslexia experienced difficulties with implicit learning tasks only when tasks involved complex sequential stimulus presentation. Howard et al. concluded that not all types of implicit learning are affected in dyslexia but only those that address the learning of sequential information in "higher order cognitive functions" (see also Waber et al. 2003 and Roodenrys and Dunn 2008 for findings of unaffected serial reaction times in dyslexia). Based on those findings, Szmalec et al. (2011) formulated the hypothesis that "dyslexia, and its associated cognitive dysfunctions, may be traced back specifically to the learning of serial order" during the gradual transition from short- to long-term memory (Szmalec et al. 2011, p. 1271). They tested this hypothesis using the Hebb paradigm, a short-term serial recall procedure in which one particular sequence of items is repeated regularly without announcement throughout the experiment (Hebb 1961). In the verbal recall task of Szmalec et al., for example, sequences of nine nonsense syllables were presented for immediate serial recall (i.e., da–fi–ke–mo–pu–sa–ti–vo–zu), with one particular sequence repeated on every third trial (called *Hebb trials*), while all other sequences contained the same nonsense syllables, but in a randomized order (*Filler trials*). Participants typically show a

[1] To avoid confusion with the distinction between sensory *modalities* like the visual versus auditory modality, we will use the term *domain* here to dissociate processing of verbal from that of nonverbal material. Most of our stimulus material was presented visually, in which one experimental factor, labeled *domain*, varied verbal versus nonverbal content.

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Hebb learning effect, i.e., gradually improved serial recall of the repeated sequences. Interestingly, Szmalec et al. found that adults with dyslexia showed impaired Hebb repetition learning relative to matched controls, not only for sequences of verbal material (i.e., syllables), but also for visuospatial sequences of dots presented on a computer screen.

Within the computational models of Hitch et al. (2009) and of Page and Norris (2009), a Hebb learning sequence is committed to long-term memory through repeated reactivation of the primacy gradient of activations representing the order among individual items in a short-term serial recall sequence. In this view, Hebb repetition learning relies on the same mechanisms as those responsible for representing a sequence of items in short-term serial recall. This converges with the finding of Howard et al. (2006) in two ways: impaired performance by participants with dyslexia seems to be related (a) to serial order processing and (b) to higher order cognitive functions (such as short-term memory), rather than peripheral (i.e., perceptual) deficiencies.

The role of short-term memory in dyslexia has indeed been demonstrated by several earlier studies who reported a reduced memory span in dyslexia, mostly constraining it as a specifically verbal impairment (Kibby et al. 2004; Nithart et al. 2009; Pennington et al. 1991; Ramus and Szenkovits 2008; but see also Smith-Spark and Fisk 2007). Serial recall tasks however, which are the most widely used measure for short-term memory performance, require to remember the respective items (i.e., the identity of digits) together with the serial order of the same items, therewith confounding two different functions: item and order processing. This is important because current models of short-term memory make a strong dissociation between sequential order processing and item processing (Brown et al. 2000; Burgess and Hitch 1999; Farrell and Lewandowsky 2002; Majerus et al. 2009; Page and Norris 2009). Item information in these models is a short-term activation of long-term memory, while order processing is a function of short-term memory that operates on those items. Because item information consists of long-term content, it is supposed to be domain specific, while the order process is generally available for all memory content of different domains.

The distinction between short-term memory for item and order information has been used in a number of studies (Majerus et al. 2006, 2008, 2009; Nairne and Kelley 2004; Saint-Aubin and Poirier 1999) in order to understand the role of short-term memory in various aspects of language learning and processing. The results of these studies showed that these two short-term memory components make independent and specific predictions for new word learning and language skills. Serial order memory appears to be a better predictor for the speed and quality of new word learning (Majerus et al. 2006), whereas item retention rather predicts language-specific long-term knowledge, phonological skill (i.e., previous exposure to the phonology of a foreign language, Majerus et al. 2008), or lexical frequency and semantic neighborhood (Saint-Aubin and Poirier 1999). Also at the neural level, these two functions of short-term memory have been dissociated. Majerus et al. (2009) showed that a network of domain-general executive and attentional functions responded to order tasks, whereas regions specific to sensory input and long-term content reacted to item task requirements. Specifically, a whole network including dorsolateral prefrontal cortex (DLPFC), inferior parietal lobe (IPL), intraparietal sulcus, and cerebellar regions corresponded to encoding and storage of serial order information. For the storage of item information, all three temporal gyri, the fusiform gyrus, hippocampus, and precuneus, were active. Supporting this domain-general nature of serial order processing, Mosse and Jarrold (2008) demonstrated that individual differences in visuospatial and in verbal serial order learning performance (i.e., verbal and visuospatial Hebb repetition learning) both predicted novel word-form acquisition equally well. These studies emphasize the difference between a domain-general order function and its domain-specific item counterpart and describe short-term memory processing as an emergent function of serial order or other context processing requirements operating on long-term item content.

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The current study investigates the precise locus of impaired short-term memory in people with dyslexia by making an explicit distinction between the representation of item and order information in different tasks (Majerus et al. 2006; 2008; 2009). In item tasks, participants were instructed to recognize whether a certain stimulus had been in the list, irrespective of its position. In the serial order task conditions, participants were asked to recognize whether two sequences made of the same stimuli matched in terms of the order in which the stimuli were presented. Each task condition was constructed in two versions, one with verbal material (nameable images, words, and digits) and one with nonverbal material (nonsense drawings), to directly address the theoretical assumption of a domain-general serial order function as discussed above. This way, we aim to provide a detailed insight into the short-term memory functions that can account for the language problems as well as other associated cognitive dysfunctions in dyslexia.

To summarize, the earlier claim of Szmalec et al. (2011) that a serial order learning deficit underlies dyslexia is based on the computational model of Page and Norris (2009), which provides a link between short-term memory for order and sequence learning. The model proposes that in addition to a sequence learning mechanism, the "quality of a short-term representation of the stimulus list" realized in the model's order layer determines learning of serial information (ibid., p. 3741). We therefore hypothesize that dyslexia is characterized by an impairment of short-term memory that is selective for serial order and that this impairment generalizes across the verbal and the nonverbal domain. In this view, short-term memory for items is basically activation of long-term memory content and therefore should be unaffected in dyslexia.

Interestingly, an assessment of short-term memory for order and item processing in a population with dyslexia was also recently reported by Martinez Perez et al. (2012). To address serial order memory, they administered a verbal order reconstruction task with animal names and pictures. Their results show inferior performance in children with dyslexia compared to both reading age- and chronological age-matched controls. This part of their finding is consistent with our hypothesis. It is also the case, however, that Martinez Perez et al. (2012) found inferior performance of children with dyslexia also for verbal item information, when compared to a chronological age-matched control group. To address item processing in short-term memory, they used a delayed repetition task of single three-phoneme nonwords. In our view, though, this task may not be optimally suited to tap selectively into item processing irrespective of serial order. The drop in performance of the dyslexia group might still be due to an underlying order requirement in the nonword repetition (item) task because all lexical items and combined phonological entities by definition imply sequences of phonemes (i.e., words, but also nonwords, see Page and Norris 2009; Szmalec et al. 2012). In the present study, we therefore carefully selected verbal material for the item task that can be processed without serial decoding, i.e., nameable images in visual presentation and existing words in auditory presentation. Well-known words mainly elicit semantic processing, while nonwords require both item and serial order processing (Mosse and Jarrold 2008; Page and Norris 2009). Under these assumptions, we hypothesize that the temporary representation of item information is spared in dyslexia, provided that processing of these item representations neither involves sequentiality nor addresses verbal skills that are untrained as a consequence of having dyslexia.

The study

In order to dissociate item from order memory, we used a simple recognition task similar to the tasks of Martinez Perez, Majerus, and Mahot (2012), Majerus, Poncelet, Elsen, and van der

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Linden (2006), and Majerus, Poncelet, Van der Linden, and Weekes 2008. Nithart, Demont, Majerus, Leybaert, Poncelet, and Metz-Lutz (2009) and Majerus et al. (2006, 2008) used span tasks to assess order memory. For two reasons, we used recognition tasks with fixed list length instead. Recognition tasks specifically address the storage function of short-term memory without imposing further demands on working memory's executive functions that are usually related to recall as in span procedures or Hebb learning (see Pennington et al. 1996 for task distinction or Smith-Spark and Fisk 2007 for both storage and executive functions investigated separately in dyslexia). Furthermore, fixed list lengths provided a measure that avoided an over- or underestimation of serial order processing capacity due to interference levels that rise and fall in a nonlinear fashion in span tasks (May et al. 1999).

To test our hypothesis, we aimed to design item and order tasks that dissociate the item and order processing in short-term memory as strictly as possible, in the sense that item tasks rely as little on order storage as possible, and vice versa (see Majerus et al. 2008, for specific task constraints). As introduced above, this distinction was orthogonal to the one between different domains, such that each task condition was designed once with verbal and once with nonverbal material, creating four memory tasks. For the verbal item task, we used nameable pictures during list encoding and auditorily presented words in the subsequent item recognition phase. Participants saw a list of pictures, then heard a word and had to decide whether the corresponding picture had been in the list or not. This procedure was meant to foster central verbal processing instead of mere visual picture matching as verbal items were addressed both through the visual and the auditory modality. The other verbal condition, the verbal order task, was conducted with digits instead of pictures, to reduce load on item recognition and focus on serial order combinations of recurring, semantically poor verbal stimuli (as used by Nithart et al. 2009). Here, participants saw two consecutive lists of digits and had been instructed to decide whether the order of both lists was the same or not.

For the nonverbal conditions, we created 175 black and white nonsense drawings, 171 drawings for the nonverbal item task, and a set of four drawings for the nonverbal order task. To discourage the participants to verbalize the nonsense drawings, we added a verbal suppression task, in line with the procedure for visual working memory tasks described by Luck and Vogel (1997).

This approach resulted in a 2×2×2 design with the factors group (control/dyslexia), task (order/item), and domain (verbal/nonverbal). According to our hypothesis of an impaired short-term memory function for order, we predicted an interaction of group and task, in which participants with dyslexia would perform worse in order tasks than controls, irrespective of verbal or nonverbal material. Contrastingly, we expected no difference between groups for item tasks.

Method

Participants

Fifty-two students, all native Dutch speakers, with a mean age of 21 years (standard deviation (SD)=1.5 years, range 18.3 to 25.5, 30 males) from all faculties of Ghent University and four university colleges in Ghent volunteered for the study, resulting in two groups of 26 participants each.

All of the 26 participants of the experimental group (16 males) had a history of dyslexia that dated back to childhood. To be sure that the dyslexic participants were not merely "garden variety poor readers" (Goswami 2003, p. 535), we recruited only participants who had

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obtained a certificate of dyslexia through a government-approved diagnostic center, Cursief, which is the support center for students with disabilities in Ghent (diagnostic standard: *Gletschr*, De Pessemier and Andries 2009). They had received their most recent full evaluation of a formal dyslexia diagnosis from Cursief no longer than 2 years ago to qualify for special support during their studies. Criteria for diagnosis implied that they all scored below the 10th percentile on diagnostic reading or spelling tests and that this impairment had persisted through therapeutic remediation that had lasted at least 6 months. Comorbidities with other disorders as well as low intelligence and sensory dysfunctions had been excluded and none of the participants had a history of neurological health problems.

To match groups, all participants were administered the same standardized tests, two reading tests including a 1-min word reading task in Dutch ("Éen Minuut Test" (EMT), Brus and Voeten 1979) and a Dutch nonword reading task ("Klepel", Van den Bos et al. 1994), and IQ testing (short version of the Kaufman Adolescent and Adult Intelligence Test (KAIT) in Flemish, see Dekker et al. 2004), either less than 2 years before or during participation. The cutoff criteria of the reading tests had been recently evaluated for adults with dyslexia by Callens et al. (2012) and Tops et al. (2012). In each reading test, the participant was asked to correctly read aloud as many words and respectively nonwords as possible in 1 min.

Four participants were removed due to methodological reasons: one female and one male in each group were removed due to self-reported sleep deprivation, medication that impaired attention, unrelated language problems, and insufficient grouping criteria, in this case mild dysorthography but no dyslexia. Furthermore, we applied an outlier analysis to each group that controls for sample size and diverging skew, using group mean values and variance by condition with a cutoff criterion of at least 2.4 SD below their group's mean performance in the same task (Van Selst and Jolicoeur 1994). Three participants of the dyslexia group performed below this cutoff criterion in one of the item tasks, which corresponded to performance at chance level. The dyslexia group showed 14.27 correct answers per 18 trials (SD=1.83) in item tasks, which corresponds to 80 % correct answers and little variance within group (SD=10 %). The three participants mentioned above presented 9, 10, and 10 correct answers, a ratio of 50–55 % correct responses. The data of these participants was removed. No participant in the control group showed performance at 2.4 SD below group mean in any condition.

The impact of overall data reduction was approximately equal in each group (before versus after data elimination in group C: $\chi^2=960$, simulated $p<0.001$; and in group D: $\chi^2=924$, simulated $p<0.001$). The sample then consisted of 24 participants in the control group and 21 participants in the dyslexia group.

Table 1 shows a comparison of the two groups by demographic data, reading performance, and KAIT scores. Group differences were evident in reading performance both for word (EMT) and nonword reading (Klepel) and in the subtest *word definitions* of the KAIT, which can directly be related to the dyslexia diagnosis.

Measures

Task demand varied to address item or order processing. In addition, set size made an important difference between tasks. In item tasks, new items were displayed in each trial, and the order in which stimuli appeared was completely irrelevant to the task. In order tasks, only a closed set of the same items was used, so that demands for item memory were as minimal as possible. Using open sets for item tasks (i.e., new items for every trial) and closed sets for order tasks (i.e., using the same items in different order) has been an important

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Table 1 Sample characteristics

	Dyslexia group		Control group		t test (paired, 2-sided)
n	21		24		
Gender, f/m	10/11		10/14		
Handedness r/l	19/2		19/5		
	Mean	SD	Mean	SD	*p* value
Age (years)	20.8	1.4	21.4	1.6	0.207
KAIT total IQ	107.5	9.4	111.4	8.7	0.152
Fluid measure (IQ)	107.2	11.3	108.5	12.0	0.701
Symbol learning[a]	81.8	9.3	84.6	14.8	0.449
Logic thinking[a]	12.2	3.4	11.3	3.6	0.392
Hidden code[a]	27.6	4.6	28.7	4.6	0.432
Crystallized measure (IQ)	106.4	8.2	112.3	7.3	0.014
Word definitions[a]	21.0	1.9	23.2	2.5	0.002
Auditory comprehension[a]	12.5	3.1	13.9	2.9	0.126
Double meaning[a]	15.8	3.3	16.6	3.3	0.435
Word reading (EMT)	84.9	18.3	101.6	10.1	<0.001
Nonword reading (Klepel)	46.4	13.1	64.6	11.0	<0.0001

[a] Test scores

prerequisite in previous work to address order and item processing in short-term memory in the purest manner possible (Majerus et al. 2006, 2008).

In summary, the orthogonal and simultaneous dissociations between order versus item information on the one hand and verbal versus nonverbal information on the other hand necessarily implied constraints on task design. Note, however, that these differences across tasks allow the targeted theoretical dissociations, while the crucial comparisons of the study remain the differences between participants with dyslexia and controls within tasks.

Pilot

Our tasks with fixed list length, other than in span procedures, are not adaptive to difficulty levels. Successively, to balance difficulty levels and beware of ceiling effects in item tasks and bottom effects in order tasks, all four tasks were set to a specific list length by piloting with 18 non-dyslexic volunteers who were found among our research colleagues. Each volunteer performed every condition only once, consisting of 18 trials each. Adequate list length was determined by an educated guess aimed to prevent bottom and ceiling effects. After two volunteers had participated, list length in each condition was adapted to one more or less items per list according to their performance. If performance was below 70 %, the list of this condition was reduced by one item, and if it was above 80 %, one item was added. This procedure was repeated a second time. The final list length was fixated if at least 10 out of 18 volunteers of the pilot sample performed at around 75 % correct with that number of items per list in the specific condition.

Verbal item task

A subset of 234 pictures from the set of colored object drawings by Rossion and Pourtois (2004) formed 18 lists of 13 pictures each. As targets, we chose those word–picture combinations that

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were represented by disyllabic Dutch words within a restricted frequency range (2 to 52 counts per million words of the underlying corpus (Celex), log frequency range=0.3–1.7, mean (*M*)=0.982, SD=0.408). Mean age of acquisition for target words was 4.8 years (SD=2.4; see Severens et al. 2005 for all picture and word norm characteristics). The most and least frequent words were *vliegtuig* (*airplane*) and *sleutel* (*key*), respectively. All words had a name agreement with the respective picture of 100 %. No picture or target word was ever repeated across the experiment, so that load was focused entirely on the retention of new items in every trial.

After single presentation of a list of object drawings, a word was presented auditorily, followed by a question mark on the screen. Participants were asked to respond *yes* or *no* with buttons on a response box indicating whether the target word named one of the pictures in the list or not.

The list encoding phase was the same in all tasks and proceeded as follows: List selection per trial was randomized and each trial started with a fixation cross that was displayed for 1,000 milliseconds (msec) in the position in which the first item would appear. Then, the list items—here 13 pictures—were displayed in consecutive single presentation at a rate of 1,000 msec next to each other, positioned along a horizontal axis in the upper third of the computer screen. Each list was followed by an inter-stimulus interval of 1,000 msec. In the following recognition phase, a word was presented auditorily and the participant was asked to make a binary decision. In 50 % of the cases, the word required a yes response as it referred to one of the objects depicted in the list before. In all tasks, each trial was followed by a question mark providing the option to respond for a maximum of 10 s, provided that the trial was not terminated by a response before. To familiarize participants with the task, one probe trial with different items was used before the beginning of the experiment proper.

Nonverbal item task

The procedure was the same as in the verbal item task, but the material consisted of 171 nonsense drawings. We refer to Fig. 2 in the Appendix for stimuli examples. Of the 200 drawings initially created, 25 were eliminated due to their resemblance to existing characters. Of the remaining 175 drawings, we used 171 for this task and four drawings for the nonverbal order task. The task was the same as for the verbal item task, namely to decide by button press whether the target had been in the presented list or not.

During the recognition phase of this task, no word was presented but a central fixation cross indicated the target item position at the center of the screen and consecutively, one drawing was displayed for 1,000 msec. Also here, none of the drawings were ever displayed again in a new trial. List selection was randomized and counterbalanced across participants. Two familiarization trials using different items were administered before the beginning of the task.

Verbal order task

The digits 1 to 9 were rotated in 9 list positions to form 18 lists, each of which was therefore made of all digits from 1 to 9. List presentation at encoding was the same as in the other memory tasks. It was followed by the same list, but in 50 % of the cases, items in two adjacent positions had been swapped. Participants were instructed to answer yes or no by pressing the green or red button, respectively, according to whether the order of the encoding and recognition list was the same or not. For the cases of a no response, they were instructed to press the red button as soon as they recognized the difference. Responses during presentation of the recognition list terminated that trial.

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The encoding list was presented in the upper third of the computer screen as in all four memory tasks. To control for after images at the same screen location, the recognition list in order tasks was presented centrally on the screen, with each item being shown for 1,000 msec in single presentation, one by one. A second fixation cross in the center of the screen announced the position of the first list item. Swaps in serial order were counterbalanced across all list positions. To familiarize participants with the procedure, one trial of the same length and material preceded the experimental trials.

Nonverbal order task

Rotating four nonsense drawings in four list positions, we formed 18 stimuli lists. To make this task perceptually easy at the item level, the drawings were developed in such a way that they were easy to distinguish while maintaining their nonverbal character.

The procedure was identical to that of the verbal order task. Also here, participants were asked to decide whether the order of the two lists was the same by pressing the no button as soon as they noticed a difference in the serial order and by pressing the yes button if the order of the two lists was the same. As described in the "Introduction," participants additionally were instructed to continuously utter "de de de" ("the the the" in English) at their own pace and volume throughout the whole task to prevent verbalization of the repeating nonsense drawings. Of the two nonverbal tasks, the order task was much more vulnerable to a verbal strategy because, here, a set of four items was constantly repeated throughout the whole task, whereas in the nonverbal item task, items were new on every trial. Figure 1 shows the procedure of the task giving an example of a mismatch trial. The items shown here were the same throughout the whole task.

As in the verbal order task, two neighboring positions were swapped in half of the target lists, counterbalanced across all list positions.

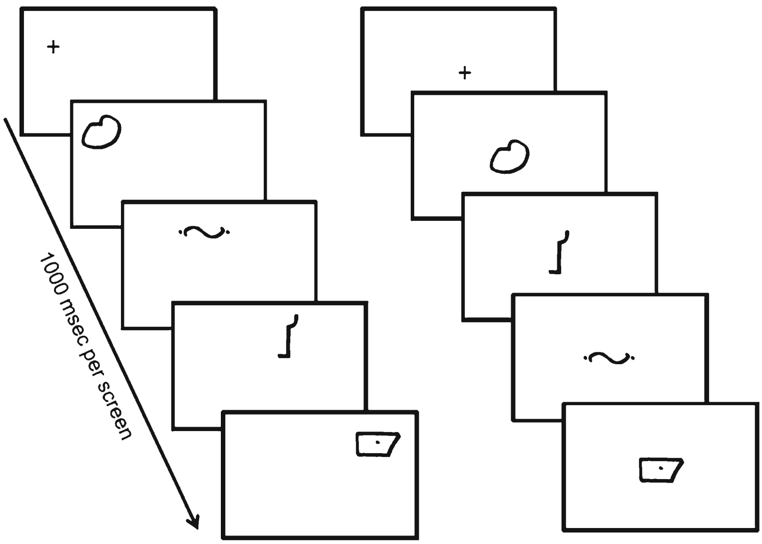

Fig. 1 Procedure of the nonverbal order task, example of a mismatch trial. Participants could press a response key during presentation of the second list; in this case, a fast and correct response would be no during the second screen of the second list

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Two familiarization trials with the same material were presented before the experiment proper began. Other than in the item conditions that were constructed with an open set of stimuli, in both order conditions, the trials used for familiarization contained the same material as the experimental trials.

Procedure

The experiment was conducted in two sessions held 1 day apart. In session 1, the participants performed the four memory tasks, and 1 day later, they returned to fulfill the reading and IQ tests. The order of the four memory tasks was counterbalanced between tasks and groups.

Results

Data of the four memory tasks were analyzed in R, free software for statistical analysis and mathematical models. Raw accuracy data were summed to form the number of correct responses across all 18 trials per condition for each participant. The number of correct responses is presented in Table 2, showing mean values and standard deviations for each group and condition. All tasks presented adequate accuracy without strong ceiling or floor effects.

The number of correct responses was submitted to a mixed effects ANOVA with the fixed factors group, task and domain, and the random factor participant. The ANOVA revealed a main effect of task ($F(1, 43)=61.351$, MSE=3.69, $f=1.193$, $\eta_p^2=0.5879$, $p<0.001$) and an interaction of task and domain ($F(1, 43)=25.435$, MSE=4.04, $f=0.848$, $\eta_p^2=0.3717$, $p<0.001$), indicating an advantage of item tasks in the verbal domain and of order tasks in the nonverbal domain. Crucially, the main effect of task was further qualified by an interaction of task and group ($F(1, 43)=7.288$, MSE=3.69, $f=0.497$, $\eta_p^2=0.1449$, $p<0.01$) showing that in order tasks, performance was significantly lower for participants with dyslexia compared with controls.

Item task accuracy was analyzed in a mixed effects ANOVA on group and domain with the random factor participant. The ANOVA on item tasks showed a main effect of domain ($F(1, 43)=24.264$, $MSE=2.06$, $f=0.998$, $\eta_p^2=0.3607$, $p<0.001$), indicating that the verbal item task was easier than the nonverbal item task.

The same model for correct responses in order tasks revealed two effects, a main effect of domain ($F(1, 43)=9.376$, MSE=5.64, $f=0.649$, $\eta_p^2=0.1790$, $p<0.01$) and a main effect of group ($F(1, 43)=6.386$, MSE=6.21, $f=0.540$, $\eta_p^2=0.1293$, $p<0.05$) and no interactions. The effect of domain indicated the opposite pattern of the item tasks: the verbal order task was more difficult than the nonverbal order task. This change in pattern between tasks

Table 2 Number of correct responses (max. possible 18) by group and condition

	Item tasks		Order tasks	
	Verbal	Nonverbal	Verbal	Nonverbal
Group	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Control	14.917 (1.586)	13.833 (1.786)	12.083 (2.062)	13.625 (2.700)
Dyslexia	15.571 (1.399)	13.619 (1.396)	10.762 (2.488)	12.286 (2.452)

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corresponds to the interaction of domain and task in the omnibus ANOVA described above. The main effect of group supports the hypothesis that participants with dyslexia performed worse than matched controls in serial order tasks. There were no more effects or interactions.

Discussion

The aim of this study was to investigate whether dyslexia is characterized by a problem in the processing of serial order, but not item information in short-term memory, generalizing across verbal and nonverbal stimulus domains. We observed that participants with dyslexia only performed worse in serial order memory tasks, but in both tasks with verbal and nonverbal material. We conclude that the dyslexic short-term memory impairment indeed specifically concerns domain-general serial order processing.

The results of serial order memory impairments reported here converge with the current findings of Martinez Perez et al. (2012) in school children and generalize the impairment in serial order short-term memory to adults with dyslexia. From the present findings, we suggest that the serial order impairment can persist through development for many years and is apparently not remedied through instructional therapy that almost all of our participants with dyslexia had followed in the past.

In the verbal item task however, our findings are not in line with the results of Martinez Perez et al., who showed inferior performance for children with dyslexia also in this task. As suggested in the "Introduction," there are three possible reasons for these inconsistent findings. The first reason could be that we used existing words in our verbal item task, whereas Martinez Perez et al. used nonwords (consonant–vowel–consonant structure) in their item task. Because nonword or new word reading taps into both order and item processing (Mosse and Jarrold 2008; Page and Norris 2009), nonword recall may be less suitable to investigate dissociations between order and item memory. Therefore, the finding of impaired item task performance of Martinez Perez et al. may have been caused by serial order processing requirements of their stimuli. Existing words may be recalled through semantic codes and require less serial order processing, so that they constitute a purer measure of item information. Second, the delayed recall task that Martinez Perez et al. used might have elicited more executive function requirements that are usually related to working memory processing, than our recognition task (Pennington et al. 1996 and Smith-Spark and Fisk 2007, as mentioned in "The study"). And third, unlike Martinez Perez et al., we replicated the absence of a dyslexia disadvantage for item information also with visual stimuli. Visual stimulus materials in the form of nonsense drawings allow a pure measure of item memory that is not confounded by the necessity to memorize order information, which is almost inevitable for verbal material. Short-term recognition of nonverbal stimuli was also unimpaired in the dyslexia group, which further supports the conclusion that the cognitive basis of item short-term memory seems to be relatively unaffected in dyslexia.

The relation between serial order processing and nonword or new word reading might play an important role especially for beginning and poor readers. Recent models about the relation between short-term memory and lexical learning (Gupta et al. 2005; Hitch et al. 2009; Page and Norris 2009) assume that a novel word form is initially an unfamiliar sequence of sublexical items (phonemes or syllables) that is gradually committed to long-term memory where it acquires the status of a unitary lexical representation (Szmalec et al. 2009; Szmalec et al. 2009; 2012). The unity of this long-term representation, according to Page and Norris (2009),

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implies that recall of the entire representation can be achieved by activation of merely one single sublexical entity, rather than by the activation of all individual items in the sequence. This situates problems with serial order memory at the core between new word encoding and the acquisition of stable orthographic representations, i.e., the transition from phonemic reading to lexical recognition.

Indeed, Barca et al. (2006) suggest that bad readers and people with dyslexia rely longer on grapheme–phoneme conversion (and therefore serial order processing) in nonword reading, while experienced readers recognize letter groups or even entire nonwords at once. This skill is based on transition frequencies and highly trained visual familiarity of co-occurrences in letter patterns that are derived from experience with word reading (McCandliss et al. 2003). Also, phonological awareness and the skill to segment speech into phonological elements develop in interaction with reading (Morais et al. 1979; Morais and Kolinsky 1994). In this view, word reading entrains linguistic long-term knowledge that in turn is used to encode nonwords or new words. This not only means that recall of a nonword demands more serial order processing relative to a word, but also that it relies partly on linguistic item knowledge derived from reading exposure. With less reading exposure, there arguably is a lack of support from newly acquired item knowledge during development. Hence, despite the dyslexic disadvantage in serial order processing, people with dyslexia have to rely longer on reading strategies that require exactly that kind of processing, further delaying reading development. Dyslexia might therefore initially be a condition that is not specific to language, but that impairs mostly the acquisition of serially ordered information, i.e., of written language, and in a second step affects the acquisition of linguistic skills that usually develop along with reading. Support for this idea also comes from the work of Martinez Perez et al. (2012), who report that the impairment in nonword repetition of the group of children with dyslexia disappeared in comparison with the reading age-matched control group.

Therapeutic intervention should in this view benefit from techniques that explicitly strengthen serial order memory. An example for such a technique can be found in common therapeutic memory strategies: walking a step for each letter position or for each word forward, naming the letter or word, and then repeating it backwards. Another, more recent but not yet very widespread technique uses visualization of written words in detail, letter by letter, and reading the letters aloud for- and backwards, making sure how many letters there are and in which order they are written (Davis 2010). This certainly does not imply that teaching linguistic skills should be disregarded. On the contrary, phonological awareness, word form learning, and consecutive vocabulary knowledge will be more accessible in early intervention if they are taught together with the cognitive prerequisites such as memory for serial order that are needed to master and automatize these skills. The inherent serial nature of language becomes most evident in its most formal setting, in reading and writing. This is why developing fast and efficient processing of serial information is most important at the stage of written language acquisition.

The error pattern described by Friedmann and Rahamim (2007) might directly link the problems of order processing that we report here to typical problems that people with dyslexia face with written language. Friedmann and her group identified a subgroup of children with dyslexia who predominantly show letter position errors within words. Investigating exactly such error patterns from the perspective of the current serial order account remains an interesting project, being conscious of the fact that dyslexia can be associated with a wide variety of heterogeneous causes across studies (Pennington 2006; Zoccolotti and Friedmann 2010).

Neurologically, order memory is essentially related to a network based on IPL and additionally on DLPFC in conjunction with intraparietal sulcus and cerebellar regions

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(Majerus et al. 2009), as described in the "Introduction." Especially the IPL has been recently identified as the relevant locus for expert readers to map graphemes and phonemes, as investigated with transcranial magnetic stimulation during nonword reading (Costanzo et al. 2012). According to our findings, people with dyslexia would be expected to show an alteration both in DLPFC and IPL due to impaired short-term memory for order that should emerge during nonword reading but also while carrying out nonverbal order tasks that tap into short-term memory. But for item memory tasks, the corresponding temporoparietal regions that respond to single phonemes or visual shapes should be unaffected in dyslexia, in as far as these do not correspond to changes acquired by extensive training in reading as for example changes in the visual word form area (McCandliss et al. 2003).

Conclusion

Our results indicate that dyslexia is related to a specific impairment in short-term memory for sequential order, but not item information. While participants with dyslexia performed worse than controls in serial order tasks across verbal or nonverbal material, they showed no impairment in item tasks relative to controls. We propose that this specific impairment may lead to the language problems that are characteristic for dyslexia: Assuming that a deficit in serial order processing and sequence learning leads to impaired acquisition of orthographical as well as phonological word form representations, the integration of written language as a format for representing linguistic knowledge that is characteristic for a normal development is hindered. Unstable encoding and consolidation of long-term knowledge will in turn result in a lack of automatization and a delay in reading development and subsequently lead to insecurity about orthographic word forms to individually varying degrees.

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Appendix

Example stimuli of the nonverbal item task

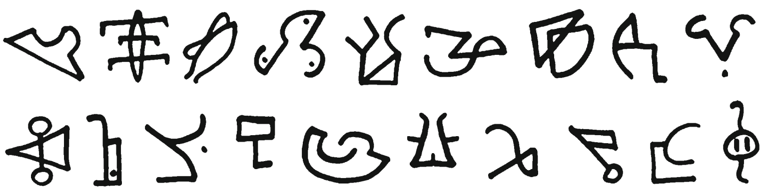

Fig. 2 Nineteen example stimuli of a total of 171 drawings from the nonverbal item task

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