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Order or dis-order?

Impaired Hebb learning in dyslexia

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Abstract

The present study offers an integrative account which proposes that dyslexia and its various associated cognitive impairments reflect an underlying deficit in the long-term learning of serial-order information, here operationalized as Hebb repetition learning. In non-dyslexic individuals, improved immediate serial recall is typically observed when one particular sequence of items is repeated across an experimental session, a phenomenon known as the Hebb repetition effect. Starting from the critical observation that individuals with dyslexia seem to be selectively impaired in cognitive tasks that involve processing of serial order, the present study is the first to test and confirm the hypothesis that the Hebb repetition effect is affected in dyslexia, also in non-verbal modalities. We present a theoretical framework in which the Hebb repetition effect is assumed to be a laboratory analogue of naturalistic word learning, on the basis of which we argue that dyslexia is characterized by an impairment of serial-order learning that affects language learning and processing.

Keywords: dyslexia, Hebb sequence learning, serial-order information, language learning, reading, verbal short-term memory, working memory

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Developmental dyslexia is a reading disability of neurological origin that persists throughout life despite adequate intelligence, education and socioeconomic background (Snowling, Bishop, & Stothard, 2000). It affects about 5 – 10% of the population (Shaywitz, 1996), and it has been found in many people with impressive achievements, from Leonardo Da Vinci and Albert Einstein to Agatha Christie and Walt Disney. Several decades of research have shown that dyslexia strongly impinges on cognitive functioning, even beyond reading: associated problems have been reported in sensory functioning (Stein, 2001), working memory (Smith-Spark & Fisk, 2007) and motor learning (Howard, Howard, Japikse, & Eden, 2006; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003). Because different areas of cognitive functioning are affected in dyslexia, it has proven particularly difficult to put forward a unified theoretical framework that is able to provide a satisfactory explanation for this complex picture of cognitive impairments (Ramus, Rosen, Dakin, Day, Castellote, White, & Frith, 2003; Vidyasagar & Pammer, 2010). Instead, influential accounts of dyslexia have focused on key aspects of impaired language processing, such as *phonological awareness*, (e.g., Vellutino, Fletcher, Snowling, & Scanlon, 2004), or on associated *visual-sensory* problems (e.g., the magnocellular deficit theory, Stein, 2001; but see also Vidyasagar & Pammer, 2010) and *perceptual* problems (e.g., the perceptual anchor theory, Ahissar, 2007), or even on *motor learning* dysfunctions (e.g., the automaticity/cerebellar deficit theory, Nicolson & Fawcett, 1990).

The present study approaches dyslexia and its associated impairments from a new, memory-based perspective. We put forward an integrative account which proposes that the various cognitive problems described in the literature can be attributed to the fact that dyslexic individuals experience particular difficulties when it comes to representing information relating to *serial order*. However, unlike previous accounts, our main focus is not on the *processing* of verbal (and other) material. Instead, we put forward a *learning* account, in which the various difficulties experienced by people with dyslexia are assumed to originate from an impairment that affects the *learning* of serial-order information in memory, of which Hebb repetition learning (defined below) is a paradigmatic example.

It is well known that the processing and learning of serial order plays a crucial role in cognition because many aspects of human behavior are sequential in nature. But the ability to manage complex sequential structures is probably most evident in language learning and processing (e.g., Conway & Christiansen, 2001). The precise nature of the relationship between serial-order learning and language learning has been debated for many years (e.g., Conway & Pisoni, 2008). Recently, Page and Norris (2008, 2009) clarified this relation by demonstrating, through computational modeling work, how the Hebb repetition effect can be seen as a laboratory analogue of naturalistic word-form acquisition. Hebb (1961) asked participants to perform an immediate verbal serial-recall task in which one particular sequence of digits was repeated every third trial. He observed that recall for repeating sequences increased substantially compared to non-repeating sequences, a phenomenon which became known as the Hebb repetition effect. In essence, the Hebb repetition effect is a serial-order learning effect which shows how information relating to a sequence in short-term memory (STM) gradually develops into a stable long-term memory trace. The idea that the Hebb repetition effect is a laboratory analogue of novel word-form learning has been further elaborated by Szmalec, Duyck, Vandierendonck, Barbera-Mata and Page (2009). In their study, participants saw sequences of nonsense syllables, following a standard Hebb learning procedure. They then performed an auditory lexical decision task on nonwords that were constructed from the syllables included in the repeated Hebb sequence. These Hebb-based nonwords yielded slower lexical decisions than control nonwords, which indicated that the repeated sequences of syllables, learned in the Hebb procedure, had established stable, long-term lexical representations, similar to the way children implicitly develop lexical representations based on sequence regularities in the phonological input from their environment (see also Mosse & Jarrold, 2008, for converging correlational evidence).

The above theoretical and empirical lines of research within the domain of STM suggest that Hebb sequence learning mimics naturalistic word learning. In other words, the Hebb paradigm is believed to draw upon those STM processes responsible for representing serial order information in the service of language learning and processing. The fact that the latter are the primary locus of impairment in dyslexia (e.g., Di Betta & Romani, 2006) raises the question of whether Hebb learning is also impaired in dyslexia. Although to the best of our knowledge, the Hebb repetition effect has never been studied in relation to dyslexia, we believe that a majority of the findings and observations in the literature are in line with the hypothesis of impaired Hebb sequence learning in dyslexia.

First, the idea that dyslexia involves difficulties with the sequencing of information is consistent with the high prevalence of letter reversals during misreading (e.g., reading "was" as "saw"; Whitney & Cornelissen, 2005). Second, our own review of the literature made apparent that virtually every working memory, motor learning or sensory functioning task that has yielded difficulties for persons with dyslexia appears to involve processing of serial order to some extent. In the learning literature for example, it has been observed that individuals with dyslexia experience difficulties with tasks that require implicit learning. Howard et al. (2006) further elaborated on this impairment and specified that people with dyslexia seem to be impaired on implicit higher-order sequence learning, but not on implicit spatial context learning, which led these authors to conclude that only "some kinds of implicit learning" (pp. 1131) are impaired in dyslexia. A closer inspection of the implicit learning tasks that were administered in this study led us to observe that people with dyslexia experience problems only when the task requires processing of *serial information*, in line with our serial-order learning account of dyslexia. Third, a number of studies have shown that persons with dyslexia have problems in discriminating or processing stimuli when they are presented serially, but not when they are presented simultaneously. Ben-Yehudah, Sackett, Malchi-Ginzberg and Ahissar (2001), for example, used a psychophysical procedure, called the temporal forced-choice paradigm, in which participants are required to judge in which one of two time intervals a target stimulus occurs. Interestingly, their results indicate that with a *spatial* forced-choice paradigm, in which stimuli are presented simultaneously, controls and people with dyslexia showed similar sensitivity, whereas in the *temporal* variant (i.e. under sequential presentation) the dyslexic sample performed worse. Consistent with our account, the Ben-Yehudah et al. (2001) findings also illustrate that people with dyslexia experience difficulties with processing serial information, although seriality was not identified by the authors as the key feauture of the dyslexic disadvantage. By contrast, other researchers have argued that serial-order processing seems to be intact in dyslexia (e.g., Lassus-Sangosse, N'Guyen-Morel & Valdois, 2008), based on results obtained with a letter-string processing procedure that requires the oral recall of visually presented sequences of letters. One crucial feature of the letter-string processing procedure however, is that the letters are recalled randomly which means that participants are not required to remember the serial order in which the letters were presented; for this reason, this method does not allow to dissociate between item-processing and serial-order processing like the Hebb repetition effect does. Fourth, Ramus and Szenkovits (2008) recently argued that individual phonological representations seem to be intact in dyslexia, but that the dyslexic problems become particularly prominent when a load is imposed on working memory. From this, they formulated the broad conclusion that the observed difficulties originate from "the short-term memory processes operating on phonological representations" (p. 133). While Ramus and Szenkovits believe that the phonological deficits in dyslexia reflects *some* memory deficiency, the present study is the first to build upon this suggestion by making the hypothesis explicit that dyslexia, and its associated cognitive dysfunctions, may be traced back specifically to the learning of *serial order* in LTM.

In summary, we hypothesize that dyslexia reflects an impairment in serial-order learning that manifests itself in various cognitive functions that are sequential in nature, amongst which the acquisition and processing of language are the most obvious ones. If language impairment in dyslexia reflects difficulties not only with concurrent language *processing*, but also in an earlier stage, with the *learning* of serial order information, then the Hebb effect should be affected in individuals with dyslexia compared with non-dyslexic controls.

There is an accumulation of evidence for the view that serial order is represented at a somewhat abstract level (e.g., Couture & Tremblay, 2006; Depoorter & Vandierendonck, 2009; Guérard & Tremblay, 2008; see also Parmentier, in press, for a review on this matter), meaning that similar serial-position mechanisms operate across different modalities . This idea also finds support in recent neuroscientific findings (e.g., Jensen & Lisman, 2005) which show that order memory is consolidated through synaptic changes that reflect the same functional characteristics regardless of which type of stimuli are being processed. From this, we conclude that Hebb learning with nonverbal materials might also be affected in people with dyslexia. Such an impairment across modalities would offer strong support that dyslexia does not only imply processing difficulties of specific (e.g., phonological) materials, but instead originates from problems with the abstract representation of order.

Our hypothesis was tested in a three-part experiment that measured Hebb learning across different modalities: one using verbal materials presented visually, one using verbal materials presented auditorily, and one using visuospatial materials. We predicted a reduction of the Hebb effect in the group with dyslexia, compared with matched controls, across the different item and presentation modalities involved in our procedure.

Method

Participants

Sixteen adults with dyslexia (13 females, 3 males) and 16 matched controls, all native Dutch speakers, volunteered in the study. They were all enrolled in higher education at Bachelor or Master level. In order to secure that the dyslexic participants were not merely "garden variety poor readers" (see Goswami, 2003, p. 535), we only used participants who had a history of dyslexia during childhood and who had also obtained a certificate of dyslexia through a government-approved diagnostic centre ("vzw Begeleiding Studenten met een Handicap", Ghent, Belgium) in order to receive support and benefits during their study (e.g., extra time for exams). This diagnosis of dyslexia was based on the most complete and recently validated instrument for assessing reading and writing abilities in Dutch, which is called the *Gletschr* (De Pessemier & Andries, 2009). The *Gletschr* is constructed around three criteria: Impairment (≤ 10th percentile on reading and/or spelling batteries), Exclusion (the reading and/or spelling problems cannot be attributed to a lower intelligence, nor to any sensory dysfunction, inefficient education or any other developmental or behavioral disorder) and Defective Response To Instruction (difficulties persist despite additional therapeutic remediation during minimum 6 months). For further validation, our experimental procedure also contained two established Dutch reading tests that are diagnostic for the disorder. The first test was the Eén Minuut Test (Brus & Voeten, 1979), a test of technical reading proficiency in which participants are required to read aloud as many words as possible within one minute. The second test, the Klepel (Van den Bos, lutje Spelberg, Scheepsma, & de Vries, 1994), requires participants to read aloud as many pseudo-words as possible within two minutes. Knowing that IQ matching is essential in adult dyslexia research (Goswami, 2003), groups were matched using a short-form IQ measure (Turner, 1997) including the Similarities, Comprehension, Block Design, and Picture Completion subtests of the WAIS-III (Wechsler, 1998). Table 1 shows that individuals with dyslexia and controls only differed on the two measures that are diagnostic for dyslexia, and not with respect to IQ.

Materials and Procedure

The order of the Hebb, IQ and dyslexia measures was counterbalanced across participants and matched between the control and dyslexic group. The experiment lasted approximately 2 hours. Each participant received a fee of 20 Euros.

Verbal-Visual Hebb condition. Two lists of 9 nonsense syllables were constructed: "da-fi-ke-mo-pu-sa-ti-vo-zu" and "ba-du-ki-le-mu-so-to-vi-za". One list was used in the verbal-visual Hebb experiment, and the other one was used in the verbal-auditory Hebb experiment described below. This means that we had 9 different syllables in total per experiment and that only the order between those syllables varied across trials. The use of both lists in the visual and auditory presentation modalities was counterbalanced across participants. All syllables were consonant-vowel (CV) structures that are clearly discriminable from each other, have no meaning in the participants' native language, and do not combine into existing words. Sequences of 9 nonsense syllables were presented to the participants for immediate serial recall. Each participant completed 30 sequences, including 20 non-repeated sequences (or filler sequences) and 1 sequence that was repeated 10 times (i.e., the Hebb sequence). The same Hebb sequences were used for both groups, but to prevent stimulus-specific effects, the Hebb sequence was different for each participant within a given group. The Hebb procedure was identical to that of Page, Cumming, Norris, Hitch, and McNeil (2006): the CVs were presented serially on a 15" monitor and remained on the screen for one second. At recall, the 9 stimuli were distributed in a "noisy" circle around a question mark ("?") that was centered on the computer screen. The participants were instructed to tap the stimuli with the computer mouse, and to tap the question mark for any omitted stimulus.

Verbal-Auditory Hebb condition. The CVs were digitally recorded in WAV format by a female speaker and presented auditorily through closed headphones (Sennheizer HD 265-1) at 60 dB. At recall, the participants were required to reconstruct the sequence from memory by naming the syllables aloud to the experimenter and saying "blank" for any omitted item. The syllables were not presented on the screen like in the verbal-visual condition. The reason why we used this procedure is that we also needed a "purely auditory" condition where the participants with dyslexia would not have to read the syllables on the screen, so that any serial order learning disadvantage would not merely be due to difficulties reading the syllables.

Visuospatial Hebb condition. To study visuospatial Hebb learning, we used the dots task, a Corsi-like (Corsi, 1972) visuospatial immediate serial recall task. The procedure was identical to the one described by Couture and Tremblay (2006). We used sequences of 9 black dots presented on a white background. Because visuospatial working memory performance is known to be sensitive to the characteristics of the dot configurations (Parmentier, Elford, & Maybery, 2005), we used different dot locations on the screen for each individual participant within one group, in order to minimize stimulus-driven effects, but the dot configurations were matched between groups. The dots were presented serially, at a rate of one per second. At recall, the nine dots were presented on the screen and the participants used the mouse to indicate order in which the dots had occurred.

Results

An item was scored as correct if it was recalled in its correct serial position. Figure 1 shows the mean proportion of correctly recalled Hebb and filler items as a function of group and item/presentation modality. The Hebb repetition effect was measured using the common technique of taking the gradient of the regression line through points representing the performance on successive Hebb repetitions and comparing it with the gradient for corresponding filler lists, for each individual participant (e.g., Page et al., 2006). The individual data are depicted in Appendix. It shows that the number of dyslexic participants who performed worse than 1.65 standard deviations below the mean of the control group was 5 in the Verbal-Visual modality, 8 in the Verbal-Auditory modality and 5 in the Visuospatial modality. Overall, 14 out of the 16 participants with dyslexia fell below normal performance on at least one of the three Hebb learning modalities. The gradient values were entered into an ANOVA with Group (controls vs. dyslexics), Sequence Type (filler vs. Hebb) and Modality (Verbal-Visual vs. Verbal-Auditory vs. Visuospatial) as the independent variables. We observed significant main effects of Group, $F(1,30) = 17.94$, $n_p^2 = .37$, $p < .001$ and Sequence Type, $F(1,30) = 65.97$, $n_p^2 = .69$, $p < .001$, while the main effect of Modality was not significant, $F(1,30) = 1.08$, $n_p^2 = .03$, $p > .35$. The crucial interaction effect between Group and Sequence Type was significant, $F(1, 30) = 23.22$, $n_p^2 = .44$, $p < .001$, indicating a stronger Hebb effect for the control group. Further planned comparisons, which are summarized in Table 2, demonstrate that the persons with dyslexia showed reduced Hebb learning for all stimulus and presentation modalities.

Discussion

The present study is the first to show that up to 50% of individuals with dyslexia are impaired in Hebb sequence learning across modalities[1]. This pattern is consistent with the dysfunctions associated with dyslexia described above, from which it becomes apparent that primarily functions that require the processing of serial-order information are affected. In order to establish the link between impaired Hebb learning and impaired language processing it is necessary to make the STM mechanisms explicit that are assumed to underlie both the Hebb repetition effect and language learning. According to Page and Norris (2008, 2009), a temporally grouped list of phonemes or syllables is likely to be learned as a single representation in memory that gets activated when its constituent phonemes are presented in the correct order. From this perspective, a newly learned word-form is simply a grouped sequence of sublexical items, and impairment in learning the order of the items within such a sequence is likely to result in problematic word-form learning. Consequently, if the order of the lexical representation's constituent elements is not optimally consolidated as a single lexical entry in long-term memory, the lexical representation will be poorly specified. Lexical access for that entry during reading will be impaired and normal procedures for mapping grapheme sequences to phoneme sequences will be disrupted (Whitney & Cornelissen, 2005) compared with normal readers who may accurately access a consolidated lexical representation from a letter string. This rationale is also supported by earlier findings from Di Betta and Romani (2006), who observed that adult dyslexics are impaired in their ability to learn new words, both in spoken as well as in written format.

The present serial-order learning account of dyslexia is an attempt to present a unifying framework in the sense that it accounts for the language learning and reading problems observed in dyslexia, but also for the associated dysfunctions that have been reported. First, the many dyslexic disadvantages for measures of working memory or STM (Smith-Spark & Fisk, 2007) have implied tasks that require the temporary sequencing of discrete elements in memory, by which processing of serial order is implicitly also involved. Our results show that, whereas improvement on the Hebb sequences is worse for people with dyslexia, performance on the filler trials is comparable for the dyslexic and control groups. Hence, memory capacity as such is not lower in dyslexia. Therefore, the current results show that it is selectively the *long-term learning* of serial-order information that appears to be problematic (i.e. smaller improvement in recall of the Hebb sequences) in people with dyslexia. Within the Page and Norris (2008, 2009) framework, it is particularly this form of learning that is crucial when children learn words from sequence regularities in the phonological (and, by extension when learning to read, orthographic) input from their environment. Crucially, learning in the Page and Norris model depends both on the quality of the short-term representation of a to-be-recalled list and on an independent weight-change process governed by a variable learning rate. Mosse and Jarrold (2008) suggested, on the basis of their data, a similar demarcation between the contributions of STM and a general learning process. Indeed, they went further in suggesting that a common learning process and learning rate applies, at least to some extent, across modalities.

Second, it has often been debated whether or not implicit learning is impaired in dyslexia (e.g., Vicari et al., 2003). In this context, the present Hebb learning results should not be interpreted as a mere demonstration of an implicit learning deficit in dyslexia. Although the Hebb effect was originally believed to be a manifestation of purely implicit learning (Hebb, 1961), subsequent research has demonstrated that the question is more complex. An important issue related to the Hebb effect in the context of implicit learning is whether participants are aware of the Hebb repetitions and whether the awareness has any consequence for the degree of learning (McKelvie, 1987; Page & Norris, 2008). Hebb learning studies have demonstrated that participants are mostly aware of the Hebb repetitions, though a minority of participants do not become aware. Data suggest that awareness has no impact on learning performance at all (e.g., Stadler, 1993) – in other words Hebb learning is implicit in some, and explicit in others. In the present study, 87% of the controls and 81% of the dyslexic participants reported being aware of the repetitions. By contrast, in implicit learning research, tests of explicit knowledge are used to confirm that a majority of the participants remain unaware of what they are learning (e.g., Howard et al., 2006). As a consequence, the Hebb effect is less and less regarded as a measure of pure implicit learning, and certainly not one within the tradition of the implicit learning studies in the domain of dyslexia. Accordingly, we propose that people with dyslexia experience difficulties with the consolidation of serial-order information in memory, rather than with implicit learning per se. This theoretical standpoint accommodates the earlier observation that not all implicit learning tasks are affected by dyslexia, but only those involving sequencing of information (Howard, et al., 2006). Furthermore, it is also important to note that the current serial-order learning account can accommodate the earlier findings that have led towards the formulation of the automaticity/cerebellar deficit hypothesis of dyslexia (e.g., Nicolson & Fawcett, 1990), which states that people with dyslexia display difficulties with automatization in various areas of skill. Because the latter hypothesis defines automatization as the ability to execute previously overlearned sequences, it can be assumed that overlearning serial information in a Hebb task, overlearning sequences of sublexical items during naturalistic word learning, and overlearning motor sequences in serial reaction time tasks, all represent the ability to consolidate serial-order information.

Third, also in the large body of evidence pointing to sensory dysfunctions in dyslexia, it appears to be the case that the discrimination of both auditory and visual stimulus materials (cfr. magnocellular deficit hypothesis of dyslexia, Stein, 2001) is only problematic when the experimental context involves sequencing, and not when the stimuli are presented simultaneously or in isolation (Ramus & Szenkovits, 2008), a finding that can also be easily integrated within our serial-order learning account of dyslexia.

Fourth, it is important to note that our novel theoretical account of dyslexia is consistent with the observation that the incidence of dyslexia is much lower in logographic orthographic systems such as Chinese or the Japanese Kanji (e.g., Ziegler & Goswami, 2005; Wydell & Butterworth, 1999). In these languages, word forms are unitary symbols that are not composed of successive characters, so that word reading (and orthographic word-form learning) does not rely on serial order of the orthographic constituent elements as much as in alphabetic languages.

Although a serial-order learning account of dyslexia can integrate most of the current theoretical perspectives on dyslexia, one recent theory, which is called the perceptual anchor theory of dyslexia (Ahissar, 2007), is more difficult to reconcile with our theoretical views. The anchor theory is a priming theory that localizes dyslexic impairment at a much earlier stage of stimulus processing, namely perception. It strongly relies on the assumption that long-term representations are not impaired in dyslexia, whereas the current study demonstrates that one prototypical variant of long-term learning, the Hebb effect, appears to be affected in dyslexia. Also the difficulties that dyslexic people experience with rapid naming are difficult to grasp within the perceptual anchor theory (e.g., Di Filippo, Zoccolotti, & Ziegler, 2008), just like the reading difficulties themselves are: *"The direct impact of poorer anchoring on reading is not clear at this point and should be the subject of further research."* (Ahissar, 2007; pp. 463). The current Hebb-learning account of dyslexia however, is able to theoretically frame the rapid naming or reading deficits by proposing that even familiar lexical entries are not optimally accessible in long-term memory due to defective consolidation of verbal-serial representations.

One interesting avenue for future developments that build upon the account presented here, starts from the fact that still little is known about the neurological basis of the Hebb learning paradigm. It has been recognized that the Hebb effect offers a very useful paradigm to investigate serial-order learning in both healthy individuals (e.g., Couture, Lafond, & Tremblay, 2008; Couture & Tremblay, 2006; Hitch, Flude, & Burgess, 2009; Lafond, Tremblay, & Parmentier, 2010; Oberauer & Meyer, 2009; Page, Cumming, Norris, Hitch, & McNeil, 2006; Parmentier, Maybery, Huitson, & Jones, 2008; Tremblay & Saint-Aubin, 2009) and special populations (e.g., Gagnon, Bedard, & Turcotte, 2005; Mosse & Jarrold, 2010), and that particularly its relation to language learning opens promising new lines of research (e.g., Mosse & Jarrold, 2008; Page & Norris, 2009;

Szmalec et al., 2009). Nevertheless, the neural correlates of the Hebb effect are to this day largely unknown. One aging study tentatively proposes that supra-span learning, which is the basis of the Hebb procedure, is associated with medial-temporal cortex (Rieckmann & Bäckman, 2009) but it is clear that more direct neuroanatomical and neurophysiological evidence is necessary to further investigate the structural and functional commonalities underlying Hebb learning and language acquisition, in both healthy individuals and patient populations.

The present study offers various interesting opportunities for future research on dyslexia, starting from the observation of reduced Hebb learning. It is possible that the Hebb learning curve is just flatter in dyslexia and that optimal learning is still obtained after increasing the number of repetition trials. If this is the case, it would be important to know whether the long-term representations that develop throughout Hebb learning are equally well consolidated in people with dyslexia as they are in controls. If so, problems associated with dyslexia may in principle be potentially remedied by intensive, time-sustained word *learning* strategies, focusing on the order of phonemes. This is especially important because previous studies have shown that benefits of initial Hebb learning are still measurable after 3 months in non-dyslexic adults (Page & Norris, 2008), supporting the analogy between Hebb learning and long-term language learning. Moreover, because Hebb learning can be assessed independently of reading abilities (e.g., in young children or people who are illiterate), it may also have potential as a predictive measure for dyslexia. All this is to say that, beside the three Hebb tests conducted here, the present study shows that the Hebb paradigm and its many well-documented and theoretically grounded variations, offer an extensive research agenda for further investigating serial-order learning in dyslexia.

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Footnotes

[1] In the visuospatial condition, people with dyslexia even showed no Hebb learning at all. However, it is unlikely that the absence of visuospatial Hebb learning reflects a particular difficulty with sequence learning of visuospatial materials, since the magnitude of the reduction in the Hebb effect observed in the group with dyslexia, relative to the control group, was comparable across the three conditions

Table 1

Sample characteristics (means with standard deviations between brackets; ns = not significant). Significance tests are based on one-way ANOVA with *df* = (1,30). OMT = One Minute Test. Results for the WAIS-III subscales are the age-corrected scales scores: range 4-18 for Picture Completion, 4-17 for Similarities, 5-19 for Block Design and 6-18 for Comprehension.

	Dyslexia (*n* = 16)	Controls (*n*= 16)	Group difference
Age (years)	21.19 (*2.61*)	19.94 (*.93*)	ns
OMT (# words per minute)	75.25 (*13.94*)	92.50 (*9.34*)	$p < .001$
Klepel (#words per 2 minutes)	65.44 (*12.44*)	95.31 (*11.28*)	$p < .001$
WAIS-III Picture Completion	10.81 (*1.52*)	10.94 (*2.05*)	ns
WAIS-III Similarities	10.94 (*2.18*)	11.00 (*1.83*)	ns
WAIS-III Block Design	10.88 (*2.03*)	10.62 (*1.89*)	ns
WAIS-III Comprehension	10.81 (*2.54*)	11.19 (*2.20*)	ns
Short-form IQ	105.44 (*10.17*)	106.06 (*9.50*)	ns

Table 2

Overview of planned comparisons with *df* = (1,30). Sequence Type = filler vs. Hebb; Group = controls vs. dyslexics.

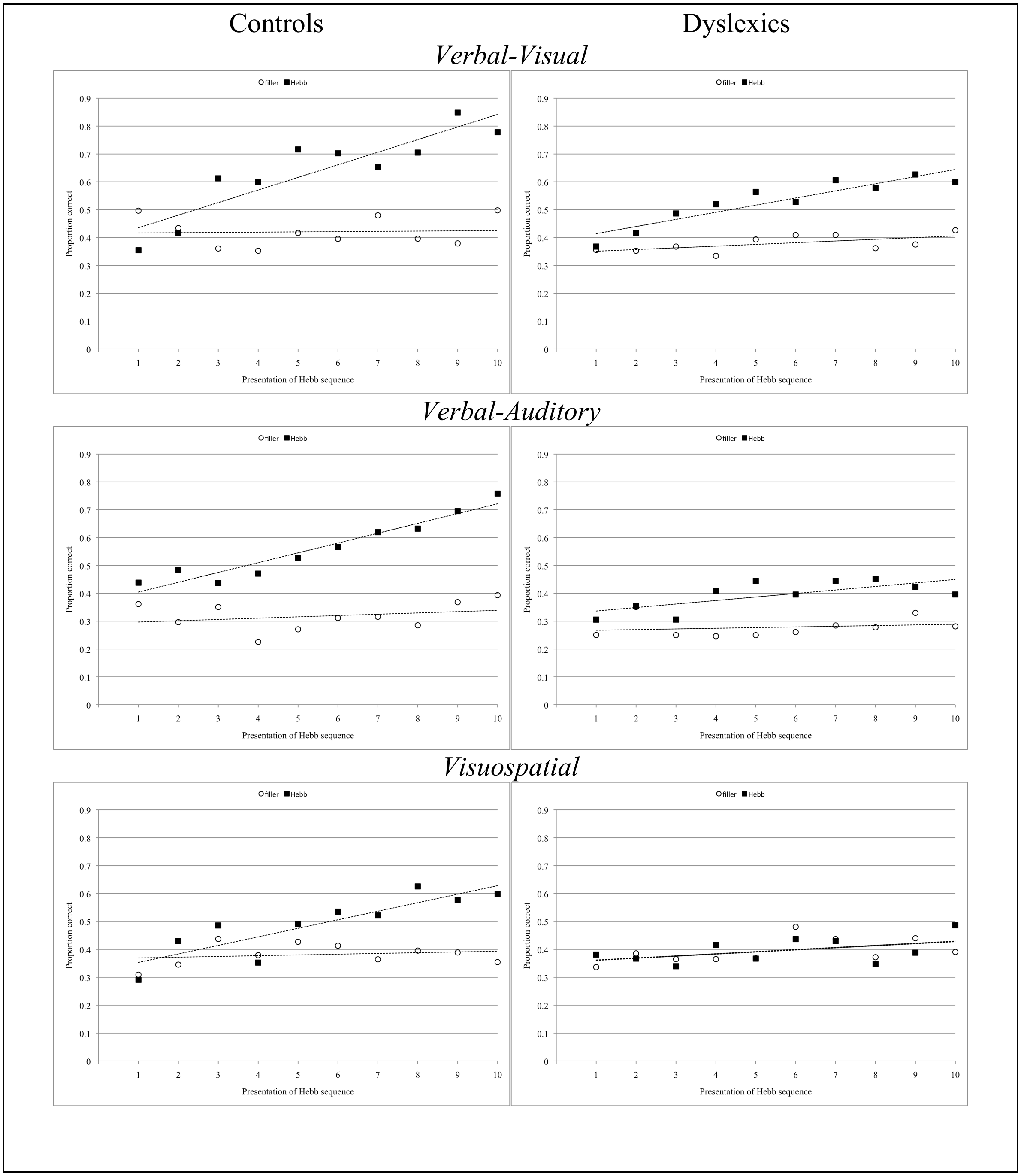
	Verbal-Visual		*Verbal-Auditory*		*Visuospatial*	
	F	n_p^2	F	n_p^2	F	n_p^2
Sequence Type in controls	30.33^{***}	.50	29.59^{***}	.50	16.65^{***}	.36
Sequence Type in dyslexics	3.95^{+}	.12	3.30^{+}	.10	<1	.00
Sequence Type x Group	6.19^{*}	.17	6.56^{*}	.18	8.35^{**}	.22

$^{***}p < .001$, $^{**}p < .01$, $^{*}p < .05$, $^{+}p < .10$

Figure Captions

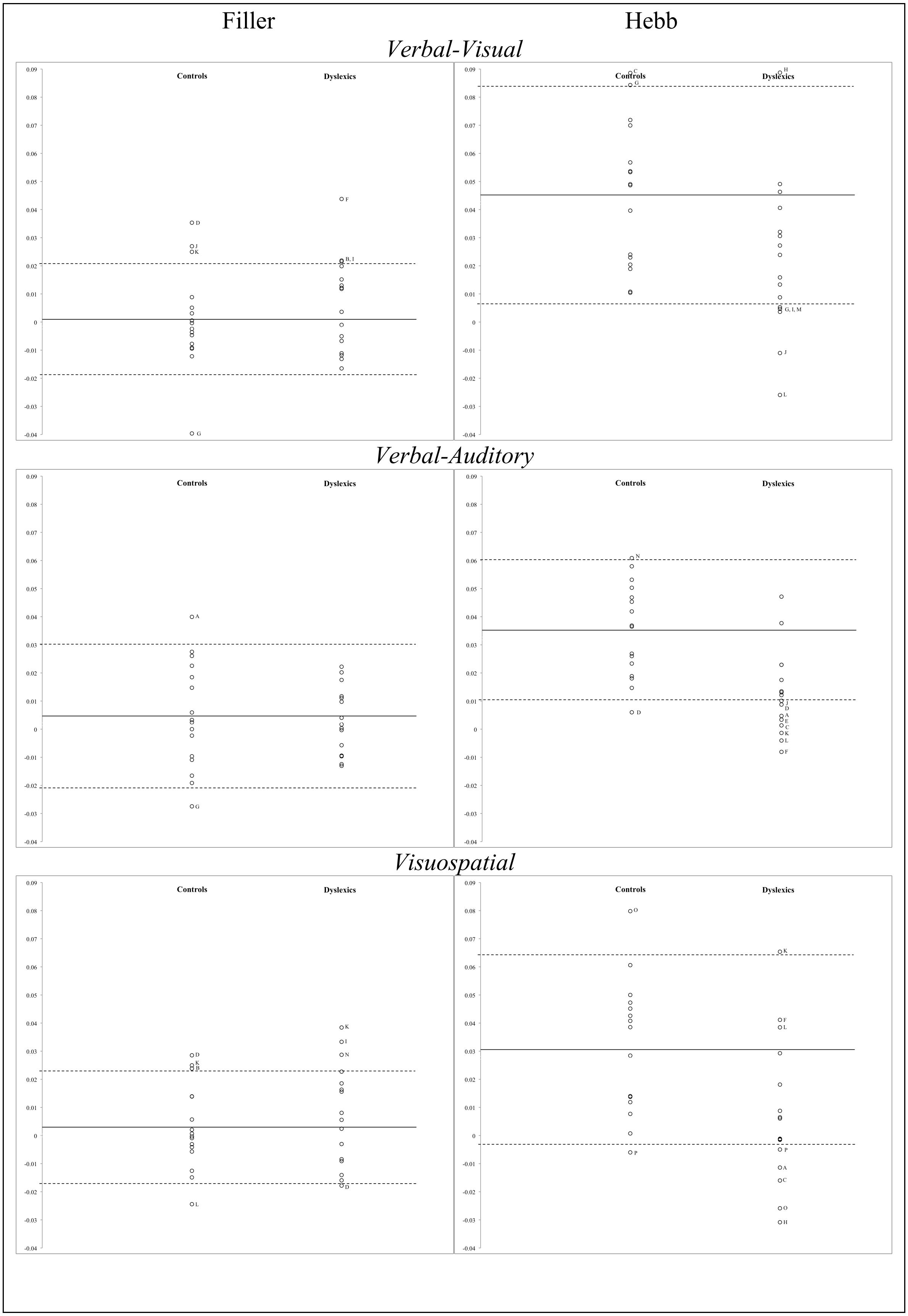
Figure 1. Mean proportion of correctly recalled Hebb and filler items in the different stimulus and presentation modalities used in this experiment, for both people with dyslexia and controls. Regression lines have been added to show the improvement in performance. Accuracy values for filler trials represent the average of the two filler trials that were presented in between each Hebb repetition.

Figure 1


Controls
Dyslexics
Verbal-Visual
Verbal-Auditory
Visuospatial
filler
Hebb
Proportion correct
Presentation of Hebb sequence

Appendix

Data from individual subjects representing the gradients of the regression lines for filler and Hebb sequences in the three different stimulus modalities. Participants with deviating scores are identified by a letter (A to P). The full black line represents the means for each condition; the dotted lines stand 1.65 standard deviations above and below the mean.



Filler
Hebb
Verbal-Visual
Controls
Dyslexics
Verbal-Auditory
Controls
Dyslexics
Visuospatial
Controls
Dyslexics