

Citation for published version:

Louisa Bogaerts, Arnaud Szmalec, Marjolijn de Maeyer, Mike P. A. Page, and Wouter Duyck, 'The involvement of long-term serial-order memory in reading development: A longitudinal Study', *Journal of Experimental Child Psychology*, Vol. 145, pp. 139-156, May 2016.

DOI:

<https://doi.org/10.1016/j.jecp.2015.12.008>

Document Version:

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The involvement of long-term serial-order memory in reading development:

A longitudinal study

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(word count = 8266)

Abstract

Recent findings suggest that Hebb repetition learning – a paradigmatic example of long-term serial-order learning – is impaired in adults with dyslexia. The present study further investigated the link between serial-order learning and reading, using a longitudinal, developmental design. With this aim, verbal and visual Hebb repetition learning performance and reading skills were assessed in 96 Dutch-speaking children whom we followed from first through to second grade of primary school. We observed a positive association between order-learning capacities and reading ability, as well as significantly weaker Hebb learning performance in early readers with poor reading skills, even at the onset of reading instruction. Hebb learning further predicted individual differences in later (nonword) reading skills. Finally, Hebb learning was shown to explain a significant part of the variance in reading performance, above and beyond phonological awareness. These findings highlight the role of serial-order memory in reading ability.

Keywords: reading; memory; language acquisition; Hebb repetition learning; serial-order

Introduction

Whereas most children achieve fluent reading skills with relative ease, for others learning to read involves significant difficulties. About 5-10% of the population develops dyslexia, characterized by unexpected and persistent difficulties with reading in the context of normal intelligence, adequate sensory functions and typical educational opportunities (e.g., Lyon, Shaywitz, & Shaywitz, 2003). What determines this important variability in the acquisition of reading skills? What underlies the difficulties of poor readers? A long tradition of research on literacy acquisition has suggested factors such as phonological skills (e.g., see Melby-Lervag, Lyster, & Hulme, 2012, for a review), letter knowledge (e.g., Bond & Dykstra, 1997; Muter & Diethelm, 2001), and short-term memory capacity (e.g., Gathercole & Baddeley, 1993; Rohl & Pratt, 1995) as important predictors for individual differences in reading ability. In parallel, research on reading disability has focused mostly on phonological problems (e.g., impaired phonological representations, e.g., Snowling, 2000; problematic phonological access and retrieval, e.g., Boets et al., 2013; Ramus & Szenkovits, 2008), as well as other impairments in (cognitive) functions such as vision (e.g., Chase & Stein, 2003; Bosse, Tainturier, & Valdois, 2007), attention (e.g., Hari & Renvall, 2001), perceptual anchoring (Ahissar, 2007), and memory (e.g., Hachmann et al., 2014; Martinez Perez, Majerus, Mahot, & Poncelet, 2012a; Smith-Spark & Fisk, 2007; Szmalec, Loncke, Page, & Duyck, 2011; see Ramus & Ahissar, 2012, for a nuanced overview).

The present study is specifically concerned with the contribution of *serial-order* memory (i.e., memory for the order in which items are presented within a sequence) to early reading. Building on the assumption that learning to read words may be conceived

as the acquisition of ordered sequences of graphemes and their corresponding phonemes (Page & Norris, 2009), and following the study by Szmalec et al. (2011) demonstrating deficient serial-order learning capacities in adults with dyslexia, we hypothesize that serial-order learning may play an important role in normal and pathological reading development.

Linking serial-order memory and language

How does memory for serial order relate to language learning and literacy? From an evolutionary perspective, it has been assumed that short-term memory for verbal information developed primarily to support language learning. Baddeley, Gathercole and Papagno (1998) argued that verbal working memory represents “the processes and mechanisms by which the sound patterns of the words of the (native) language are learned by the child” (p. 159). Indeed, natural language can be regarded as a well-structured environmental input with an inherently sequential nature. A limited number of phonemes and letters form different words, depending on the order of their arrangement, and these words in turn are sequentially arranged to form sentences. It is becoming increasingly clear that both (a) the ability to *temporarily* represent the order of discrete elements occurring in a sequence (i.e., *short-term order memory*), and, (b) the ability to consolidate this sequential information in *long-term memory* (referred to as *serial-order learning* or sequential learning), are implicated in several aspects of human language such as lexical acquisition and reading ability.

Lexical acquisition. Evidence for a tight link between short-term memory for order and lexical development comes, inter alia, from the reports of robust correlations (mostly

in the range of .4 - .5) between performance on verbal immediate serial recall tasks and both nonword repetition (e.g., Gathercole, Service, Hitch, Adams, & Martin, 1999; Gupta, 2003) and vocabulary scores (in either a first or second language; e.g., Gathercole & Baddeley, 1989; Service, 1992). Furthermore, several recent studies by Majerus and colleagues have highlighted the importance of the serial-order component of short-term memory (STM), as opposed to memory for item identity, in relation to early oral language learning (e.g., Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus & Boukebza, 2013) and literacy acquisition (Martinez Perez, Majerus, & Poncelet, 2012b). Finally, recent research has demonstrated that the order component of STM seems to be affected in both children and adults with dyslexia (Hachmann et al., 2014; Martinez Perez et al., 2012a; Martinez Perez, Majerus, & Poncelet, 2013; but see Staels & Van den Broeck, 2014a for a non-replication).

Multiple authors have proposed that these order-STM mechanisms contribute to long-term learning of new phoneme (and by extension orthographic) sequences via Hebbian learning (e.g., Burgess & Hitch, 2006; Gupta, 2003; Page & Norris, 2009). Hebb (1961) showed that when a particular ordered sequence of stimuli was repeated several times in an immediate or short-term serial recall task, recall of that sequence (known as the Hebb sequence) improved, compared with recall of non-repeated sequences (known as the filler sequences). This phenomenon is known as the *Hebb repetition effect* and reflects incidental (repetition-driven) long-term sequence learning. A number of researchers have argued that long-term serial-order learning, operationalized by the Hebb repetition paradigm, provides an analogue for the processes involved in naturalistic vocabulary learning, to the extent that the acquisition of novel word-forms also requires

the retention of letter or phoneme sequences in a specified serial order (e.g., Cumming, Page, & Norris, 2003; Page & Norris, 2009). Consistent with the assumption that Hebb repetition learning mimics naturalistic word-form learning, is the observation of a positive correlation between Hebb repetition learning performance and nonword learning, in a sample of typically developing 5- to 6-year olds (Mosse & Jarrold, 2008). Recent experimental evidence was provided by Szmalec, Duyck, Vandierendonck, Barberá-Mata, and Page (2009), who showed that repeating syllabic sequences in the Hebb-repetition learning paradigm (e.g., the grouped sequence of nine CV items “ri-zo-bu_ni-li-na_sa-ba-du”) resulted in representations in the mental lexicon that are functionally similar to those of newly learned words (e.g., in this case, the novel "words" rizobu, nilina and sabadu). More recent work also showed that these newly acquired Hebb sequences engage in lexical competition with existing words, just like novel word-forms do (Szmalec, Page, & Duyck, 2012).

Reading (dis)ability. The above theoretical framework clarifies the link between memory for serial order and lexical acquisition, and can be extended to the domain of (early) word reading. Models of reading such as the SERIOL model (Whitney, 2001; Whitney & Cornelissen, 2005) stress the importance of the (temporal) alignment of the serial orthographic representations (i.e., letters position and identity) and phonological representations in early reading. Imagine an early reader processing the word ‘CAT’. The child will typically use a decoding strategy through which s/he converts each individual letter (or grapheme) into its corresponding sound (or phoneme), while integrating a representation of the entire sequence of sounds (/k/ - /æ/ - /t/) into a single word-form. Repeatedly processing this visual sequence of letters will then, through Hebbian learning,

gradually develop into an orthographic representation in the mental lexicon, which allows more automatic and proficient processing of the known letter string. This framework, and the observation that many of the experimental tasks (including tasks from outside the linguistic domain) that yield difficulties for people with dyslexia involve sequentiality, have inspired a new account of reading impairment, that we labeled the “SOLID” (Serial Order Learning in Dyslexia) hypothesis (Szmalec et al., 2011). This memory-based account of dyslexia offers an alternative view to the prominent etiological stance that dyslexia results from a phonological deficit, that is, problems with the representation and processing of speech sounds (Snowling, 2000; Stanovich, 1988). It proposes that “dyslexia, and its associated cognitive dysfunctions, may be traced back specifically to the learning of serial order” (Szmalec et al., 2011, p. 1271). Szmalec and colleagues (2011) indeed demonstrated that dyslexic adults showed reduced Hebb repetition learning across both verbal and visuo-spatial modalities. The demonstration of a deficit in a visuo-spatial task implies that Hebb-learning deficits in dyslexia extend beyond the verbal domain, and that a domain-general serial-order component may be the source of impairment. In support of this view, we recently showed that the learning deficit is persistent in the sense that drastically increasing the number of Hebb repetitions, thereby maximizing learning opportunity, does not mitigate the adverse effect of dyslexia on Hebb learning (Bogaerts, Szmalec, Hachmann, Page, & Duyck, 2015). The same study also suggested poorer lexicalization of verbal Hebb sequences in adults with dyslexia, suggesting that problems with serial-order learning may lead to impaired lexical representations, which are in turn assumed to affect reading performance (Perfetti, 2007). The earliest evidence for an association between serial-order learning difficulties and

reading problems comes from Gould and Glencross (1990), who reported a reliable verbal Hebb-learning impairment in reading-disabled children aged 11, but no group difference in a visuo-spatial Hebb task. Recently, Staels and Van den Broeck (2014b) failed to find evidence for weaker Hebb learning in children (sixth graders) and adolescents with dyslexia, which led them to question a Hebb learning impairment as (one of) the underlying problem(s) in dyslexia.

In summary, the research described so far suggests a theoretical link between serial-order learning (of which Hebb learning is a paradigmatic example) and language skills. However, whereas the role of serial-order learning in lexical acquisition (or vocabulary development) has been demonstrated rather convincingly, the exact role it plays in reading acquisition and reading (dis)abilities remains less clear. The evidence linking Hebb learning to dyslexia is not unequivocal, and the generalizability of these findings to early readers requires additional investigation. This is the focus of the present study, which is the first to test Hebb repetition learning in children using a longitudinal approach.

Current Study

The current study investigates the relationship between long-term serial-order learning (here operationalized as Hebb repetition learning) and (poor) reading ability, using a longitudinal design. It is generally accepted that reading difficulty should be considered as a continuum rather than an all-or-none condition (Fletcher, 2009; Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). Yet, the empirical evidence supporting the link between serial-order learning —measured as Hebb repetition learning— and

literacy hinges, to our knowledge, exclusively on group studies comparing dyslexic subjects and matched controls. Here we look, for the first time, both at poor readers versus matched controls and at the relationship between Hebb learning and reading, considering the full reading continuum. The study has thus three major objectives: (1a) First, we aim to investigate whether the observation of Hebb learning deficits in dyslexic adults extends to poor-reading¹ children. Testing children at the very start of reading instruction deals, at least partly, with the alternative explanation that difficulties with serial-order learning are not producing the dyslexic symptoms but are instead the result of impaired reading abilities. (1b) In the same vein, we aim to examine the relationship between long-term Hebb repetition learning and reading skills, using a large sample of readers along the reading continuum. (2) Second, the use of a longitudinal design provides a unique opportunity to estimate the potential of the Hebb repetition paradigm as a predictive tool for (pathological) reading development. (3) A final research question is whether Hebb repetition-learning ability contributes to word and nonword reading skills *independently* of phonological awareness, a well-established and commonly accepted predictor of individual differences in reading ability (Melby-Lervag, Lyster, & Hulme, 2012).

Two types of children were included in the study: children at risk for dyslexia and children without risk. In a first test period (1st grade, 6 – 7 years of age), auditory-verbal

¹ As explained in more detail under the section '*Extreme groups analysis*' we included in the poor-reading group those children who obtained a clinical word and/or nonword reading score in 2nd grade. We opt for the term 'poor-reading children' rather than 'children with dyslexia', because according to the definition of Dyslexie Nederland [Foundation Dyslexia Netherlands] not only has the level of reading and/or writing to be significantly lower than what can be expected based on the educational level and age of the individual, also the resistance to instruction (i.e., defective response to therapeutic remediation) has to be confirmed before one can legitimately speak of dyslexia (Stichting Dyslexie Nederland, 2008).

and visuo-spatial Hebb learning were assessed, in addition to word reading abilities. Importantly, at this time children had received only initial reading instruction and had little reading experience. One year later (2nd grade, ages 7 - 8), we tested the same children with the same Hebb learning tasks and in addition, a nonverbal intelligence measure and word/nonword reading tasks were administered. We further included a spelling task to obtain an estimate of orthographic skills, as well as measures of phonological awareness and naming speed to obtain an estimate of the quality and accessibility of phonological, sublexical and lexical representations. The predictions regarding the major objectives are outlined below:

(1a) We predicted a Hebb repetition effect in the children's group, notwithstanding the fact that Hebb learning has been found to be somewhat weaker in children compared with adults, (e.g., Hitch et al., unpublished; Mosse & Jarrold, 2008). In line with the adult dyslexia data (Bogaerts et al., 2015; Szmalec et al., 2011) we also predicted that poor readers would display weaker Hebb learning compared with good readers, both in the verbal and the visuospatial stimulus modalities. (1b) Considering reading skill as a continuous variable, we predicted a positive relationship between both word and nonword reading scores and Hebb learning performance.

(2) Second, we expected a predictive correlation between the Hebb learning effect and reading performance one year later.

(3) Finally, we anticipated that the Hebb measure would explain a unique portion of the variance in reading, above and beyond phonological awareness.

Method

Participants

Primary school children were tested in the first grade (Timepoint1 = T1) and again one year later, when they attended the second grade (Timepoint2 = T2). At both time points testing took place between March and May. A total of 96 children (47 boys; mean age at T1 = 6.7 year, age range = 6 -7.9 year, SD = .41) participated at both time points. Forty-seven of these children were selected for the study on the basis of their increased risk for reading difficulties. This risk was assessed through parental report of a delay in language development or through family-risk, meaning that the child had a family member (within the third degree of consanguinity) who reported reading difficulties. The children were recruited from 15 primary schools in Flanders, Belgium, and were all monolingual Dutch speakers. They had no history of sensorimotor or neurological disorders according to the parents' reports.

Materials and Procedure

All children were tested individually in a quiet room at their school. At T1 (first grade) all participants underwent the verbal and spatial Hebb task sessions, with the order of presentation of the two sessions counterbalanced across participants. After completing the Hebb tasks, a measure of word reading was administered. At T2 (second grade) the same verbal and spatial Hebb tasks were administered to the participants. In order to avoid the influence of material-specific savings, we made sure that participants were presented with different Hebb sequences from those they had learned one year earlier. The order of the Hebb tasks was again counterbalanced. The remaining tests were

administered in a fixed order: after completing the Hebb tasks, nonverbal intelligence was assessed, followed by word reading, nonword reading and the four subscales of the Dyslexia Screening Test (Kort et al., 2005). Children received a cartoon sticker as a reward.

1. Hebb learning tasks

1.1. Verbal domain. The verbal Hebb learning task was an adaptation of the procedure used by Mosse and Jarrold (2010). The task was presented on a 15-inch laptop computer, and was introduced to the children as an animal-race task. On each trial, a sequence of six Dutch animal words was presented auditorily for immediate serial recall. All animal words (duif, hert, hond, stier, leeuw, paard [pigeon, deer, dog, bull, lion and horse, respectively]) were monosyllabic and had a high frequency (log freq/million: $M = 1.5039$, range = $0.8451 - 2.2253$, calculated using WordGen by Duyck, Desmet, Verbeke, & Brysbaert, 2004). The names were recorded by a female voice and all audio files were edited to have a length of 1000ms. Immediately after the auditory presentation of the six animal names, a visual recall screen appeared, showing six simple black and white animal drawings, arranged randomly in a “noisy” circle around a central question mark. Participants were instructed to recall the order of the animal words by clicking on the corresponding pictures; the question mark could be used for a missing animal word. Note that this procedure allows children to click the same animal more than once. However, it was not possible to recall an animal that was not in the stimulus list. After the participant had clicked six animal pictures, a black screen was presented and the following trial was initiated after a self-paced press on the spacebar. The task consisted of

16 trials in total: 8 repetitions of the repeating Hebb sequence interspersed with 8 random filler sequences. Three different Hebb lists were used (across subjects) to avoid list-specific effects. On the filler trials, which alternated with the Hebb trials, the order of the six animal names was random. The dependent variable was the accuracy of each individual item's recall (i.e., 1 if the animal word was recalled in the correct serial position, 0 otherwise).

1.2. Visuo-spatial domain. The visuo-spatial Hebb learning task was similar to the one used by Mosse & Jarrold (2008, 2010). Seven images of green lily pads and a frog were presented on the screen. Each trial consisted of an animated frog appearing on one lily pad and jumping in sequence onto the remaining six lily pads with an inter-stimulus interval of 1000 ms. After jumping onto the final pad, the frog disappeared from the screen, the pads however remained. Participants responded by clicking the sequence of pads in the correct serial order. Pads changed color (from light green into darker green) when they were clicked. Three different versions of the task were made using different spatial background compositions for the seven lily pads and a different Hebb sequence. All three Hebb lists contained one single path crossing (i.e., the frog crosses the virtual path between two previously visited lily pads). The dependent variable was again the accuracy of each individual item's recall.

2. Intelligence

The Raven Standard Progressive Matrices test (Raven, Court, & Raven, 1992) was used to obtain a measure of nonverbal intelligence, so that intelligence scores would not be confounded with linguistic performance, especially in the poor-reading group.

3. Reading

3.1. *Three minutes test.* The Drie Minuten Test [Three Minutes Test] (Verhoeven, 1995) is a standardized word reading test. The test consists of three reading cards with increasing difficulty. Participants are instructed to correctly read aloud as many words as possible within the time limit of one minute per card. There are three different versions of all reading cards. To avoid effects of re-testing we used version B at T1 (first reading card only) and version C at T2 (all three cards). The total score is calculated for each card as the total number of words read minus the number of reading errors.

3.1. *KLEPEL.* The KLEPEL (van den Bos, Spelberg, Scheepstra, & de Vries, 1994) is a nonword reading test in which participants are instructed to read aloud correctly as many nonwords as possible within two minutes. Because the test is only suitable and normed for children from the second grade on, we only administered the test at T2 and used version B.

4. Other language tests

4.1 Spelling

Spelling was administered with a subtest of the Dyslexia Screening Test (DST, Kort et al., 2005) named *Two minutes spelling*. Children have two minutes to write down as many words as possible. The words are read out loud by the experimenter (a new word is only read after the previous word was spelled) and have an increasing level of difficulty. The number of correctly spelled words is taken as the total score on the subtest.

4.2. *Phonological awareness.* The phonological awareness subtest of the DST consists of two tasks: Phoneme deletion and Spoonerisms. In the phoneme deletion task, children are asked to repeat orally presented words omitting one or multiple phonemes. (e.g., ‘spin’ [spider] without ‘n’). In the Spoonerisms task, the first letters of two orally presented words must be switched (e.g., *Harry Potter* becomes *Parry Hotter*). For each task the number of correct answers determines the raw score. A total phonological awareness score was calculated by summing up the raw scores of both tasks.

4.3. *Rapid automatized naming.* The rapid automatized naming subtest from the DST was used to assess the speed of lexical access. In this task participants are asked to name rapidly a set of objects (boom, eend, fiets, stoel, schaar [tree, duck, bicycle, chair, scissors, respectively]) and a set of letters that are each presented in a 5x10-matrix. The dependent variable is the time in seconds needed to name all items. For wrongly named items, 5 extra seconds are added.

Results

In the Hebb repetition task, an item was scored as correct if it was recalled in its correct serial position in the sequence. To analyze these binary data, we made use of mixed logit models (see Jaeger, 2008). We first focus on the results of the extreme groups (poor/clinical readers vs. controls). A second section considers the full sample and tests the relation between serial-order learning and reading scores across the entire reading continuum.

Extreme groups analysis

For this initial analysis, we selected those children with a clinical (i.e., below the 10th percentile) word and/or nonword reading score at T2 ($n = 23$; 11 boys) and a matched group of 23 children (14 boys) with good reading performance. Eight out of 23 children had a clinical score on both reading tests. An additional 15 children had a clinical score on word reading only. Seventy percent, i.e., 16/23 children with a clinical score at T2 were initially identified (i.e., at T1) as children at risk for dyslexia based on our screening. Good readers were chosen so that the groups differed maximally in reading performance, yet matched (on the group level) as closely as possible on intelligence and age.

Table 1 summarizes the subject characteristics. The poor-reading children and the control children did not differ significantly in their age and nonverbal intelligence. The groups did, however, differ significantly on all language tests, except for the rapid automatized naming of objects.

Table 1. Participant characteristics.

	EXTREME GROUPS			FULL SAMPLE
	Poor readers ($n=23$)	Good readers ($n=23$)	Group difference	All children ($n=94$)
Control variables				
Age (T2, months)	95.1 (4.1)	95.6 (5.6)	$p = .77$	94.8 (4.6)
Raven PM (percentile)	54.9 (18.4)	64.4 (23.0)	$p = .10$	61.6 (22.4)
Reading tests				
T1 TMT (words/1 min., card 1)	18.0 (7.0)	44.2 (18.2)	$p < .001$	32.3 (16.2)
T2 TMT (words/1 min., card 1-3)	28.5 (13.4)	68.0 (10.7)	$p < .001$	49.3 (19.2)
T2 Klepel (nonwords/2 min.)	18.2 (6.4)	44.1 (12.8)	$p < .001$	9.2 (3.1)
Other language tests				
Spelling (words/2 min.)	7.0 (3.0)	12.3 (2.2)	$p < .001$	10.0 (3.7)
Phoneme deletion (max. = 12)	6.6 (2.8)	8.4 (2.4)	$p < .05$	8.1 (2.5)
Spoonerism (max. = 11)	0.8 (1.9)	3.7 (3.5)	$p < .01$	2.0 (3.0)
RAN objects (sec.)	61.2 (16.0)	55.3 (12.2)	$p = .16$	58.3 (14.4)
RAN letters (sec.)	54.6 (15.0)	36.7 (8.5)	$p < .001$	46.3 (15.0)

Note. Means per group with standard deviations between brackets for T1 and T2 variables. Group differences were tested with a one-way ANOVA with $df(1,44)$. Raven PM = Raven's Progressive Matrices, TMT = Three Minute Test

Figure 1 shows the learning curves for the verbal and visual task as a function of group, at T1 and T2. Additionally, Table 2 displays the mean percentage correctly recalled Hebb and filler items.

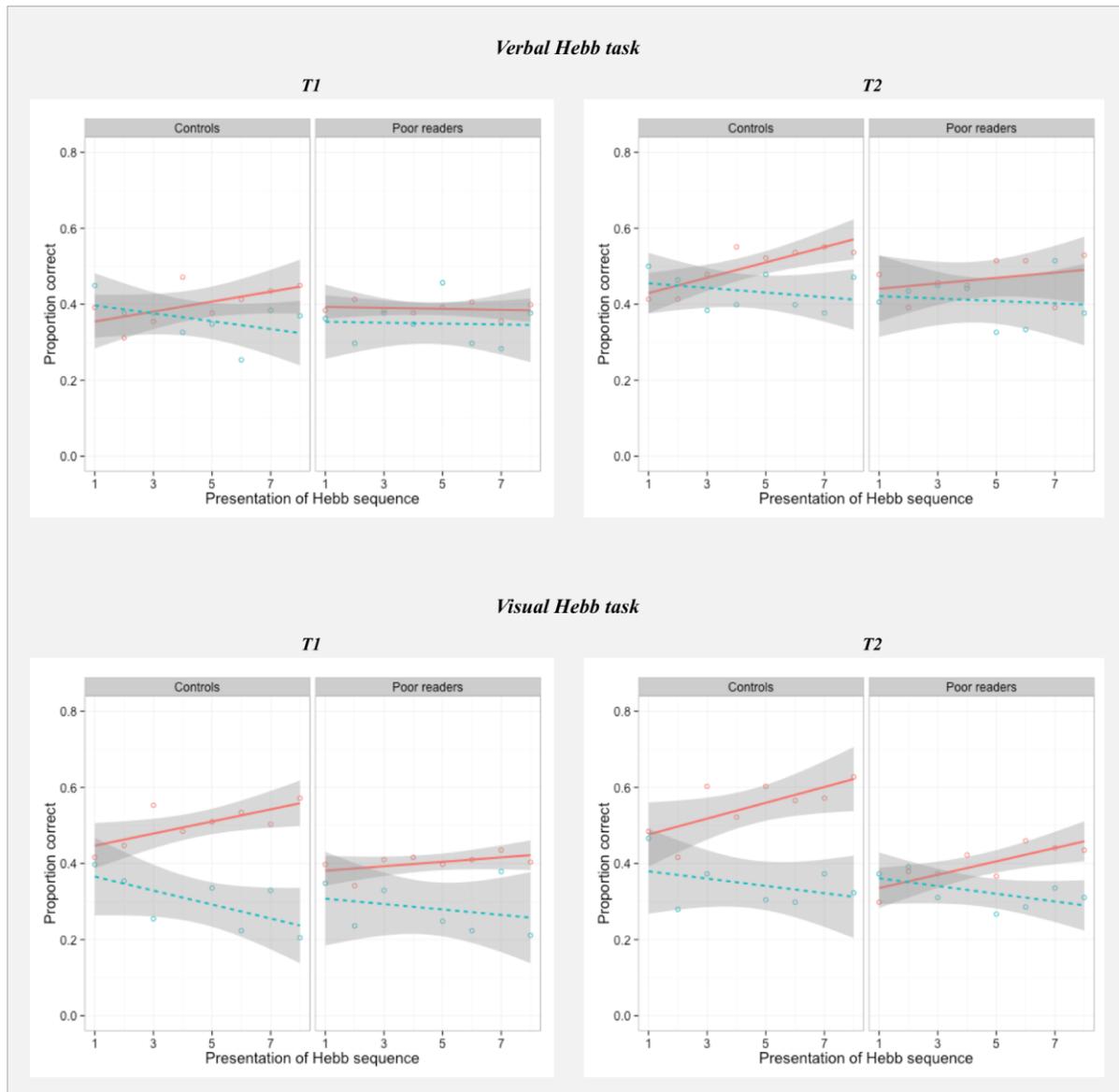


Figure 1. Plots of the average proportion correctly recalled items for Hebb (red) and filler (blue) in function of the presentation position of the Hebb sequence. Regression lines

have been added to show the change in performance, the grey shading denotes their 95% confidence interval.

Table 2. Performance (in percentage) on the two types of trials, averaged across all repetitions. Standard deviations between brackets.

		EXTREME GROUPS		FULL SAMPLE
		<i>Poor readers</i> (n=23)	<i>Good readers</i> (n=23)	<i>All children</i> (n=94)
Verbal Hebb task				
T1	filler	34.96 (12.36)	36.05 (17.33)	35.03 (13.85)
	Hebb	38.86 (16.92)	40.04 (15.87)	42.08 (16.30)
T2	filler	41.03 (17.47)	43.39 (14.73)	41.45 (16.19)
	Hebb	46.56 (19.86)	50.00 (18.74)	45.05 (18.14)
Visuo-spatial Hebb task				
T1	filler	28.22 (10.91)	30.05 (8.52)	29.66 (9.56)
	Hebb	40.14 (20.19)	50.05 (19.55)	45.63 (18.41)
T2	filler	32.48 (14.52)	34.52 (11.90)	36.50 (11.95)
	Hebb	39.67 (14.32)	54.89 (13.37)	50.52 (17.14)

We used the lme4 package in R (CRAN project; The R foundation for Statistical Computing, 2009) to run a mixed logit model with accuracy as the dependent variable. The fixed-effect variables included in the model were Type (filler/Hebb), Presentation (list position in the task block, 1-8), Domain (visual/verbal) and Group (controls/poor readers), as well as their two-way interactions. We included the higher-order interactions of interest Type:Presentation:Domain and Type:Presentation:Group as well as Type:Presentation:Group:Lag (session1/2) and Type:Presentation:Group:Domain. We further included IQ as a control variable². The model included the fullest random effects structure for subjects and for items that still allowed the model to converge (Barr, Levy, Scheepers, & Tily, 2013)³. Concretely, the random effects structure of the model included

² Raven PM scores did not significantly differ on the group level, yet our sample did not allow for a perfect numerical matching on this intelligence measure (see Table 1). By including the Raven PM scores as a control variable we make sure that the results cannot be accounted for by the IQ difference between groups.

³ We always started from the maximal random effect structure justified by the design, with random effects for both subject and item. When the full random model didn't converge, we removed, in a step-wise procedure, non-essential terms such as the random intercept (Barr et al., 2013), if necessary followed by

a random intercept for subject and a random by-subject slope for Type, Presentation, Domain, Type:Presentation and Type:Presentation:Domain. The random effect structure for item, defined as the serial position of an item within a sequence, included a random intercept. All continuous predictors were standardized. Factors were sum coded (a.k.a. contrast or ANOVA-style coding): Type (filler =-1/Hebb=1), Domain (visual=-1/verbal=1), Group (controls=-1/poor readers=1). The results of this mixed logit model are summarized in Table 3. We found a significant main effect of Type, the positive coefficient for this effect reflecting higher performance for Hebb sequences than for fillers⁴. A significant interaction of Type by Presentation confirms the presence of a Hebb repetition effect in the developmental sample. A simple slopes analysis revealed that this interaction was driven by a positive correlation between accuracy and Presentation for Hebb trials ($\beta = .12$; $z = 5.51$; $p < .001$) and a negative correlation for filler trials ($\beta = -.10$; $z = -4.54$; $p < .001$). Marginally significant effects for the interaction terms Type:Domain and Type:Presentation:Domain, both with a negative coefficient, indicate more learning for Hebb lists relative to fillers in the visuo-spatial modality compared with the verbal modality. More importantly, we predicted that Hebb repetition learning would be weaker in the poor reading group. Because the two-way interaction capturing the learning over multiple presentations has a coefficient with a positive sign, a group difference in the disadvantage of the poor readers would surface as a three-way interaction Type:Presentation:Group with a negative coefficient. We observed a

random (interaction) terms that were not of theoretical interest. Once the model converged we always tried to re-include the random intercept in the final model.

⁴ Note, however, that the quantity really modelled in a mixed logit model is the log odds. The coefficient β therefore implies that a one unit change in the level of Type (i.e., from filler (-1) to Hebb (1)) results in difference of β in the logit probability of getting a correct response.

marginally significant interaction of Type:Presentation:Group (as well as Type:Group). This effect did not interact with Domain or Lag. A simple slopes analysis revealed that the Type by Presentation interaction was significant for the control group ($\beta = .14$; $z = 6.74$; $p < .001$) and for the poor reading group ($\beta = .07$; $z = 3.26$; $p < .01$), suggesting that Hebb learning is present in both groups but to a lesser extent for the poor readers ($\chi^2(2) = 56.04$; $p < .001$) (see Figure 1).

Table 3. Summary of the fixed effects in the mixed logit model.

<i>Predictor</i>	β coefficient	χ^2	p
Intercept	-.329	1.69	.19
Raven PM	.185	7.67	<.01 **
Type	.141	26.90	<.001 ***
Presentation	.012	0.23	.63
Domain	.013	0.07	.80
Group	-.102	2.43	.12
Type:Presentation	.116	26.11	<.001 ***
Type:Domain	-.029	3.22	.07 ·
Presentation:Domain	.012	0.28	.60
Presentation:Group	-.018	0.55	.46
Type:Group	-.048	3.00	.08 ·
Type:Presentation:Domain	-.037	3.36	.07 ·
Type:Presentation:Group	-.042	3.29	.07 ·
Type:Pres:Group:Lag		5.29	.26
Type:Pres:Group:Domain		1.32	.52

When running the maximal mixed logit model on T1 data only, a significant three way-interaction Type:Presentation:Group was observed ($\beta = -.07$; $\chi^2(1) = 3.90$; $p < .05$). This shows that worse Hebb learning for the anticipated poor readers was already present at T1.

Finally, we considered whether the group difference in Hebb learning might be associated with differences in baseline serial-recall performance. Filler performance (i.e., performance on nonrepeating lists) did not differ significantly between the groups, $\chi^2(1)$

= .68, $p = .41$, and is controlled for in the mixed logit model by the fact that Hebb learning is evaluated as the improvement over presentations on Hebb trials relatively to improvement over matched filler trials, and by the inclusion of a random by-subject intercept. This makes it an unlikely cause, on its own, of the group differences in Hebb learning. Indeed, as a check, including average filler performance as an additional control variable in the model did not change the result regarding the Type:Presentation:Group interaction.

In summary, by showing the presence of a clear Hebb repetition effect in the children's group and weaker Hebb learning for poor readers compared with good readers (significantly at T1 and marginally across sessions), the analysis presented above largely confirms the first of our experimental predictions.

Full sample analysis

In total, 96 children (47 boys) participated in the study. At T1, 26 children were tested with preliminary versions of the Hebb learning task that contained fewer items (i.e., a shorter Hebb sequence) than the final versions and that could therefore not be used in the analysis. More precisely, 21 children completed versions of the verbal and visual Hebb learning task with fewer items at T1 than in the final versions at T2. Five completed just the visual Hebb learning task with fewer items. This means that at T1 we had complete data for 70 participants and a number of missing values for 26 participants. At T2, the data for all 96 participants were complete.

A model similar to the one described above was run, once with T2 word reading performance (DMT score) as a continuous predictor replacing the factor group, and once

with nonword reading performance (Klepel score). The structure of the model thus included the fixed-predictors Type, Presentation, Domain and Reading_score, their two-way interactions, the interaction-terms Type:Presentation:Domain, Type:Presentation:Reading_score, Type:Presentation:Reading_score:Lag(session1/2), Type:Presentation:Reading_score:Domain and the control variables IQ and age. The random effects structure of the model includes a random intercept for subject and a random by-subject slope for Type, Presentation, Domain, Type:Presentation, Type:Domain and Type:Presentation:Domain, as well as a random intercept for item. All continuous predictors were standardized, and the variables Type, Condition and Domain were again sum coded (see above).

The results of the mixed logit model with word reading score and nonword reading score as predictors are summarized, respectively, in panels A and B of Table 4. Crucially, we observed a significant Type:Presentation:DMT interaction as well as a significant Type:Presentation:Klepel interaction, both with positive coefficients, indicating stronger Hebb repetition learning in children with higher word- and nonword reading scores (see Figure 2). This confirms the subsidiary part of our first prediction (1b, above).

Table 4. Summary of the fixed effects in the mixed logit model.

A. Word reading			
<i>Predictor</i>	<i>β coefficient</i>	<i>χ²</i>	<i>p</i>
Intercept	-.306	1.52	.22
Raven PM	.172	14.91	<.001 ***
Type	.151	56.07	<.001 ***
Presentation	-.005	0.06	.80
Domain	-.014	0.14	.71
DMT	.081	3.03	.08 ·
Type:Presentation	.097	28.44	<.001 ***
Type:Domain	-.025	1.53	.22
Presentation:Domain	.001	0.002	.97
Presentation:DMT	.028	2.00	.16
Type:DMT	.051	6.02	.01 *
Type:Presentation:Domain	-.039	5.29	.02 *
Type:Presentation:DMT	.041	4.86	.03 *
Type:Pres:DMT:Lag		0.30	.86
Type:Pres:DMT:Domain		0.34	.85
B. Nonword reading			
<i>Predictor</i>	<i>β coefficient</i>	<i>χ²</i>	<i>p</i>
Intercept	-.306	1.52	.22
Raven PM	.178	15.36	<.00 ***
Type	.151	54.37	<.00 ***
Presentation	-.005	0.92	.34
Domain	-.014	0.20	.65
Klepel	.121	2.67	.10 ·
Type:Presentation	.096	30.27	<.00 ***
Type:Domain	-.025	0.96	.33
Presentation:Domain	.001	0.02	.88
Presentation:Klepel	.008	0.01	.94
Type:Klepel	.073	12.55	<.00 ***
Type:Presentation:Domain	-.039	5.24	.02 *
Type:Presentation:Klepel	.038	4.44	.04 *
Type:Pres:Klepel:Lag		0.37	.83
Type:Pres:Klepel:Domain		0.05	.97

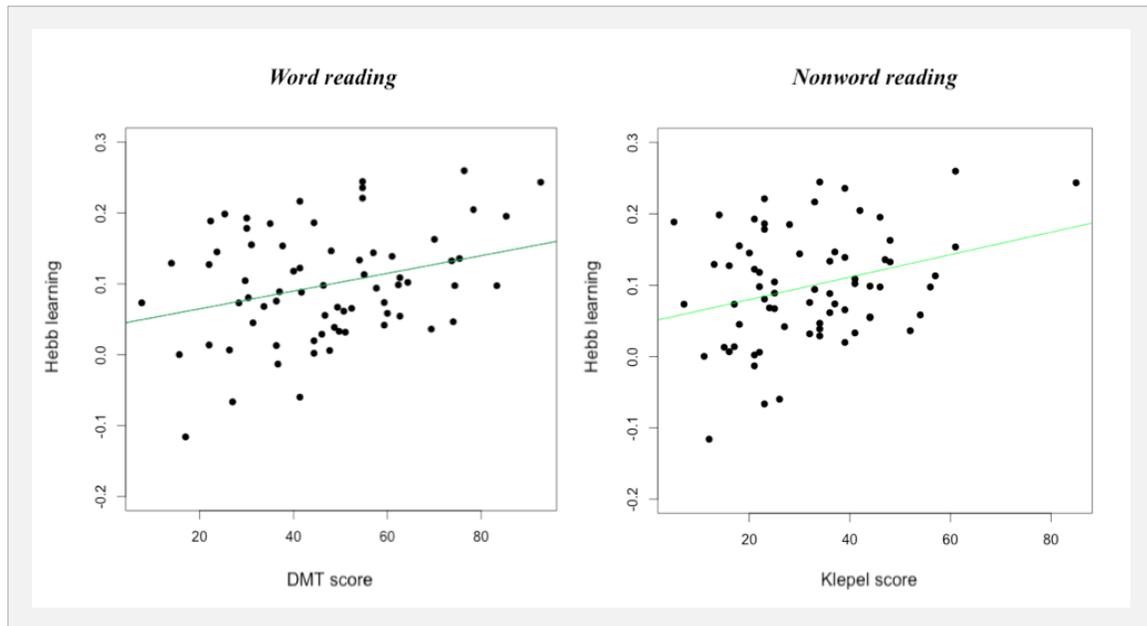


Figure 2. Scatterplots clarifying the relationship between reading scores and Hebb learning, measured by the coefficient for the Type:Presentation interaction (see below). Green lines represent the regression lines. The Pearson's r is respectively .30 for word reading ($p = .01$) and .29 for nonword reading ($p = .01$).

Predicting reading performance

Longitudinal regression. In the following analysis, we tested the predictive value of respectively T1 filler performance and T1 Hebb learning for later (i.e., T2) word- and nonword reading scores. The degree of Hebb learning (i.e., the size of the Hebb repetition effect) for a given subject is measured by the individual's coefficient for the Type:Presentation interaction, as extracted from the mixed logit model with accuracy as the dependent variable⁵, run on the T1 data only. Two linear regression models were run, one with word reading as the dependent (i.e., to-be-predicted) variable and one with nonword reading as the dependent variable. Average filler performance and Hebb

⁵ The structure of the mixed logit model that we ran to extract the individual coefficient included the fixed-predictors Type, Presentation and their interaction. The model further included a random intercept for subject, a random by-subject slope for all fixed terms and a random intercept for item.

learning were included as predictors, as well as the control variable IQ. All predictors were standardized.

Table 5 shows that neither T1 filler performance nor T1 Hebb learning account for significant variance in word reading. However, Hebb learning does reliably predict T2 nonword reading. A model comparison confirms the significant unique contribution of Hebb learning, $F(1) = 4.14, p < .05, \Delta R^2 = .057$, above and beyond all other predictors.

In a second longitudinal regression, we included reading at T1 (DMT score) as an additional predictor. This linear model predicts variance due to the *growth* in reading over time, rather than variance in T2 reading scores per se. Unsurprisingly, word reading at T1 significantly predicts T2 word reading ($\beta = 14.36, t = 8.98, p < .001$) and nonword reading ($\beta = 10.16, t = 7.46, p < .001$). Hebb learning performance, which did not significantly predict later word reading, is also not a significant predictor of growth in reading ($\beta = 1.70, t = 0.99, p = .33$). More interestingly, Hebb learning still does reliably predict T2 nonword reading in this more conservative model ($\beta = 2.87, t = 1.97, p = .05$) and has a unique contribution, $\Delta R^2 = .029$.

In summary, Hebb repetition learning qualifies as a reliable predictor for later nonword reading performance but not word reading performance; our second prediction (2b, above) could therefore be partially confirmed.

Table 5. Summary of the longitudinal linear regression results.

A. Word reading			
<i>Predictor</i>	β	<i>t</i>	<i>p</i>
Intercept	47.05	21.51	<.001 ***
Raven PM	3.37	1.40	.17
T1 Filler	-.37	-.15	.88
T1 Hebb learning	3.53	1.41	.16

A. Nonword reading			
<i>Predictor</i>	β	<i>t</i>	<i>p</i>
Intercept	31.94	18.66	<.001 ***
Raven PM	1.13	.60	.54
T1 Filler	-.07	-.04	.97
T1 Hebb learning	3.99	2.04	.046 *

Explaining variance in reading skills. Finally, we tested our third prediction by evaluating the contributions of filler performance, Hebb learning (across T1 and T2) and phonological awareness in explaining the variance in reading skills. The coefficient for the Type:Presentation interaction, extracted from the mixed logit model, was again taken as a measure of the size of Hebb learning. A linear regression model with reading score as the dependent variable and average filler performance, Hebb learning and phonological awareness (all standardized) as predictors was run. As can be seen in Table 6, filler performance did not account for a significant proportion of any of the reading variables variance at T2. However, both Hebb learning and phonological awareness explained a significant amount of variance in word reading and nonword reading. Model comparisons confirm the significant unique contributions of phonological awareness and Hebb learning in explaining the variance in word reading (ΔR^2 phon = .202, ΔR^2 Hebb = .042) and in and nonword reading (ΔR^2 phon = .155, ΔR^2 Hebb = .048), above and beyond all other predictors.

Table 6. Summary of the linear regression results.

A. Word reading				
<i>Predictor</i>	β	<i>t</i>	<i>p</i>	
Intercept	47.05	24.64	<.001	***
Raven PM	.97	0.46	.65	
Filler	-3.14	-1.44	.15	
Phon awareness	9.32	4.38	<.001	***
Hebb learning	4.30	2.00	.049	*

A. Nonword reading				
<i>Predictor</i>	β	<i>t</i>	<i>p</i>	
Intercept	31.94	20.35	<.001	***
Raven PM	-.23	-.13	.90	
Filler	-1.69	-.94	.35	
Phon awareness	6.41	3.67	<.001	***
Hebb learning	3.59	2.03	.046	*

4. General discussion

The question of how memory supports language development has been a topic of wide scientific interest in the last decades (see Baddeley et al., 1998). An increasing number of studies suggest that both short- and long-term memory processes underlie various aspects of language development, such as vocabulary acquisition (e.g., Gathercole et al., 1999; Leclercq & Majerus, 2010; Page & Norris, 2009) and reading (e.g., Bogaerts et al., 2015, Martinez Perez et al., 2012b, Szmalec et al., 2011). In previous work, Szmalec and colleagues clarified the role of long-term serial-order learning in novel word-form acquisition (Szmalec et al., 2009, 2012). In contrast, the role of this type of learning in reading remains less well understood. The goal of the current study was to clarify the involvement of serial-order memory in the development of reading skills.

First, we investigated whether the association between serial-order learning problems and dyslexia that has been demonstrated in adults (Bogaerts et al., 2015; Szmalec et al., 2011) may be generalized to early reading development. This is crucial because dyslexia is of course primarily a developmental disorder. The results of our extreme groups analysis suggest weaker Hebb repetition learning in poor readers, even at the beginning of reading instruction. As such, the results provide evidence of an association between long-term serial-order learning and reading difficulties. Importantly, weaker Hebb repetition learning for poor readers could not be attributed to worse baseline (short-term) memory capacity. Poor-reading children did not differ significantly from controls in baseline serial recall (or filler) performance and filler performance was controlled for in the statistical analysis. We further explored the relationship between short-term serial recall (i.e., filler performance) and long-term serial-order learning (i.e., Hebb repetition performance) on the one hand, and reading skill as a continuous variable, on the other. As predicted, we observed a significant positive relationship between the degree of Hebb learning and reading performance measured at T2. Also, note that the association between reading and Hebb learning did not interact with domain, suggesting that the serial-order deficiency is independent of the modality of memory content and thus probably reflects a core deficit in serial-order learning.

Second, concerning the predictive value of the Hebb task, we observed that the magnitude of Hebb learning measured at T1 predicts individual differences in nonword reading abilities one year later (with a similar although nonsignificant result for word reading), thus hinting at a possible underlying role of serial-order learning in reading acquisition.

Third, as we administered both measures of phonological awareness and Hebb learning, we were able to show that both variables explained a significant and unique part of the variance in T2 reading performance. This suggests that in addition to the well-established phoneme awareness deficit, other factors such as impairments in serial-order memory, contribute to reading difficulties.

Our joint findings of 1) weaker Hebb learning in poor-reading children, 2) the positive association between Hebb learning and reading performance, and 3) a predictive correlation between the magnitude of Hebb learning and future (nonword) reading abilities, supports the view that difficulties with the long-term learning of serial-order information may, at least to some extent, underlie reading disability (cf. the SOLID hypothesis, Szmalec et al., 2011). From the SOLID-hypothesis perspective, serial-order learning is crucial for registering sequence regularities in the phonological and orthographic input. Especially for early readers, who assemble phonology for reading, the correct alignment of letters in written words (i.e., serial orthographic representations) and their conversion to spoken forms (i.e., serial phonological representations) is seen as a key aspect of the reading mechanism (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; see also Whitney & Cornelissen, 2001, 2005). Proficient reading is further dependent on the development of long-term, stable phonological and orthographic lexical representations. These representations presumably develop through repeated exposure to phoneme or letter sequences, a process that is an instantiation of Hebb learning. If, due to poor long-term serial-order learning, the order of the individual sublexical items in a sequence is not optimally consolidated as a single lexical entry in lexical memory, the quality of the phonological and orthographical word-form representation will be poor

(see Bogaerts et al., 2015). Impoverished representations complicate lexical access during reading in the sense of disrupting the - usually highly automatized - procedures for mapping grapheme and phoneme sequences in word identification (e.g., Whitney & Cornelissen, 2005). This way, poor serial-order learning skills may affect novel word-form acquisition (see also Di Betta & Romani, 2006) and reading performance (e.g., Perfetti, 2007; Kuperman & Van Dyke, 2011).

Considering the interrelationship between serial-order learning, novel word-form acquisition and reading, we acknowledge the possibility that not only the quality of orthographic lexical representations but also vocabulary size could (partially) mediate the link between Hebb repetition learning and reading skill. In this context it's noteworthy that poor serial-order learning abilities have recently also been observed in children with Specific Language Impairment (SLI), diagnosed when oral language lags behind normal expectations (Hsu & Bishop, 2014). SLI and reading disability are closely related language disorders (see Bishop & Snowling, 2004, for a discussion). On the one hand, the oral language deficits that are typically observed in SLI have also been reported in children with dyslexia (e.g., McArthur et al., 2000; Starck & Tallal, 1988). On the other hand, high rates of literacy problems that are characteristic of dyslexia have also been demonstrated in children with SLI (e.g., Conti-Ramsden, Botting, Simkin, & Knox, 2001; Haynes & Naidoo, 1991; Tallal, Allard, Miller, & Curtiss, 1997). In this sense, our Hebb learning account of language development may be potentially useful to investigate the still poorly understood sources of comorbidity between language disorders.

Interestingly, the positive association between reading and Hebb learning appears to be domain general in nature. These results are consistent with the results of Mosse and

Jarrold (2008), who reported an association between Hebb learning across modalities and nonword learning, and with the finding of a general Hebb learning impairment in dyslexic adults (Szmalec et al., 2011). Taken together, this suggests that both vocabulary acquisition and reading are not depending on a uniquely verbal (e.g., phonological, orthographical) sequential learning mechanism but that they rather seem to rely on the core ability to represent serial-order information (see Depoorter & Vandierendonck, 2009; Parmentier, 2014, for a discussion on the domain-specificity of order representation).

Caveats, limitations and future research

We should emphasize that although our results (especially the weaker Hebb learning performance in children who just began reading instruction and who turned out to experience reading difficulties one year later) are consistent with the SOLID account, they do not preclude other existing etiological hypotheses of reading disability. Our findings should not be taken to demonstrate that deficient serial-order learning ability is the single core deficit underlying reading difficulty. Rather, we suggest that serial-order learning provides a novel perspective for understanding both normal and pathological language development, one which merits further investigation. More precisely, problems with serial-order information can explain why people with dyslexia also show impairments outside the linguistic domain such as impaired procedural learning (e.g., Lum, Ullman, & Conti-Ramsden, 2013; Pavlidou, Kelly, & Williams, 2010; see also Howard, Howard, Japikse, & Eden, 2006) motor sequencing (e.g., De Kleine & Verwey, 2009) and working memory functions (e.g., Smith-Spark & Fisk, 2007; see Szmalec et

al., 2011, for discussion). Our demonstration that both phonological awareness and Hebb learning explain unique variance in reading ability is compatible with a multi-deficit view of reading disability (Menghini et al., 2010; Pennington, 2006): it suggests that a serial-order learning deficit can be seen as one of the sources of reading difficulty, next to phonological awareness and possibly other factors. Future research requires further examination of the relative importance of the different factors (in normal as well as abnormal reading development) and of the extent to which they are interrelated.

Turning to the limitations of the current study, it should be noted that we have tested children within relatively small age range and that, despite the big sample, our group of clinical readers (at T2) was limited to 23 subjects. A second limitation arises from our choice of tasks. We opted to administer nonverbal IQ as a control task and a maximal amount of language tests, and did not administer (/control for) attentional functioning (see Staels and Van den Broeck, 2014b, for a discussion). We acknowledge that given the comorbidity between reading disability and attention problems (Boada, Willcutt, & Pennington, 2012) future studies may want to control explicitly this factor. This being said, we believe it is unlikely that Hebb learning impairment observed in our poor reading group arises from attentional functioning problems. First, assuming attentional problems in the poor reading group, we would expect a larger drop in filler performance for poor-readers compared to the controls, which is not what we observe. Second, Staels and Van den Broeck (2014b) carefully controlled for attentional functioning in a Hebb paradigm and none of their results were significantly altered by the inclusion of attentional measures as covariates. A final limitation we want to outline is related to our experimental task, the Hebb repetition paradigm. The current investigation provides

preliminary evidence for differences between individuals in their (repetition-driven) long-term sequence learning abilities and relates these to reading skills. However, it is currently not clear to what extent sequence learning capacity – as measured through the Hebb task – is a stable individual capacity and to what extent it correlates with other measures of (incidental) sequence learning. This latter limitation indicates an important avenue for future research.

Conclusion

The present study aimed to investigate the link between serial-order learning and the development of reading skills in young children. Our results suggest that children who have just begun reading instruction and turned out to experience reading difficulties one year later, demonstrated weaker Hebb learning performance, when compared with normal reading controls. In the same vein, we observed a positive association between serial-order learning capacities and both reading and nonword reading skill across the full reading continuum. Moreover, Hebb learning was shown reliably to predict later nonword decoding abilities, providing the very first evidence for a possible causal role of serial-order learning in reading acquisition. These results highlight the contribution of serial-order learning to reading, and suggest that Hebb repetition learning performance explains a significant and unique amount of variance in reading performance. Overall, these findings contribute to a growing body of evidence for the involvement of serial-order memory in normal and pathological language development.

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