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# The involvement of serial-order memory in reading disability

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Dedicated to

Sylva

my parents

and all significant others who have read to me

# CONTENTS

# CHAPTER 1
## INTRODUCTION

Reading, an ability unique to humans, is highly valued by our society in which written language is omnipresent. Fluent reading is no less than a prerequisite for educational and economic success.

Contrary to most aspects of oral language development, literacy is acquired mostly via formal instruction and education (Pinker, 1997). Learning to read in an alphabetic language requires learning the correspondences between arbitrary visual symbols (i.e., letters) and the linguistically meaningful sounds of a language (i.e., phonemes). The common view of literacy acquisition focuses then on the learning of such correspondence rules (e.g., Share, 1999). Yet, natural language (whether spoken or written) can also be regarded as a well-structured environment with an inherent sequential nature. As such, the order of basic linguistic units is critical: a limited number of phonemes and letters form different words, depending on their order, and these words in turn are sequentially aligned to form sentences. Therefore, by definition, reading involves serial-order memory. But how exactly is our ability to process, and learn, lists of ordered stimuli implicated in language learning and literacy acquisition? Can reading difficulties be understood in terms of a problem in the processing and/or the long-term retention of serial-order information? Can individual differences in the ability to learn lists predict relative success in literacy acquisition? These questions are the focus of this doctoral dissertation. They lie at the intersection of (a) fundamental theoretical questions about the interplay between memory and language, and (b) important debates regarding the underlying cause of reading difficulties.

We start our introduction with a description of the reading process. How do we construct meaning from a sequence of printed letters? The second part of the introduction focuses on reading disability and the different views regarding its origin. Then we turn to the role of serial-order memory in relation to language learning and literacy. We will provide a general theoretical framework for the studies that were carried out for this dissertation, and introduce the Hebb repetition paradigm (Hebb, 1961) as an operationalization of serial-order learning. Finally, we will conclude the introduction by giving an overview of the studies presented in the different empirical chapters.

## READING

Imagine the struggles of a beginning reader —maybe simply your much younger self— faced with the task of making sense of the printed text in a children's book. When picturing this scene we realize what an immense feat of cognitive effort reading is. Reading is a complex act in that it recruits, in parallel, multiple mental processes related to very different cognitive faculties: visual processing related to the identification of letters, linguistic processing related to the recovery of syntactic structure and semantic meaning, attention, and memory. While this complexity is widely acknowledged, most theoretical models of reading—in order to make the problem more tractable—focus on only a portion of the reading process, namely visual word recognition and lexical processing.

## MODELS OF WORD READING

The recognition of visually presented words requires recognizing graphic symbols as specific letters, encoding the letter-order within the word, and combining the recognized letters into meaningful units. A printed word must activate an orthographic word-form stored in the mental lexicon, allowing access to the prior knowledge that the reader has about this word. But how is this done?

### *The Interactive Activation model*

Following the early models of word recognition (e.g., the logogen model Morton, 1969; the serial search model, Forster, 1976), the Interactive Activation Model (IAM) proposed by McClelland and Rumelhart in the 1980s is arguably the most well-known and influential computational model of word recognition (Mcclelland & Rumelhart, 1981). The IAM consists of three layers (or "pools") of neuron-like processing units (see Figure 1), with both excitatory and inhibitory connections between the different layers. Importantly, within-layer connections at the letter and word level are inhibitory, introducing competition.

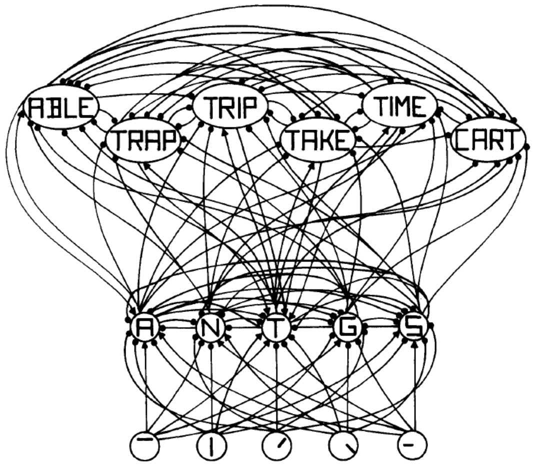


***Figure 1*. Recognition of the letter 'T' according to the Interactive Activation Model (McClelland & Rumelhart, 1981).** Arrows indicate excitatory connections; circle-terminated lines represent inhibitory connections.

The dynamics of the IAM are straightforward: based on sensory input, units that represent visual features are activated. When a particular feature unit is activated, it sends activation to all of the letter units it is connected to (e.g., a vertical line sends activation to all letters with a vertical line). Note that the IAM uses a channel-specific coding scheme: each letter is assigned a position-specific channel and is then processed within this channel. The activated letter units feed forward activation to word units compatible with them, which in turn send top-down feedback to the letter units. The word unit, or lexical representation, that is the first to pass a certain threshold of activation is selected. The IAM assumes that once a lexical representation is selected, all the information stored together with that representation (e.g., the word's pronunciation and sound, syntactic and morphological specifications, semantics) becomes available, though these high-level linguistic processes are not formally a part of the model.

*The Dual Route Cascaded model*

The Dual Route Cascaded (DRC) model also includes representations of phonology and semantics in its architecture (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001, see Figure 2). It comprises a direct pathway from print to the orthographic lexicon as well as an indirect or non-lexical pathway that goes via the grapheme-to-phoneme rule system, and is a direct implementation of the dual-route to reading (aloud) as originally proposed by Colthaert (1978). Regular words can be read via either pathway. However, exception words can only be read out loud correctly via the direct lexical procedure, and the correct pronunciation of nonwords requires the indirect rule-governed procedure. DRC has strong explanatory power: it can account for frequency effects, the advantage of words over non-words, regularity effects, developmental changes in reading, etc. Moreover, the DRC model has proven also useful for understanding reading disability. Impaired reading within the dual-route framework can stem from a deficit in the lexical route (which leads to errors mainly in reading aloud irregular words: pronouncing *PINT* as if it rhymes with “MINT”), a deficit in the non-lexical route (which leads to problems in decoding unknown orthographical word-forms and to lexical captures: pronouncing *STARN* as “STAR” or “START”), or a combination of the two. Ziegler et al. (2008) demonstrated how different profiles of reading difficulties can be accurately simulated within the DRC model by adding noise to the letter encoding level, the phoneme system and/or the phonological lexicon.

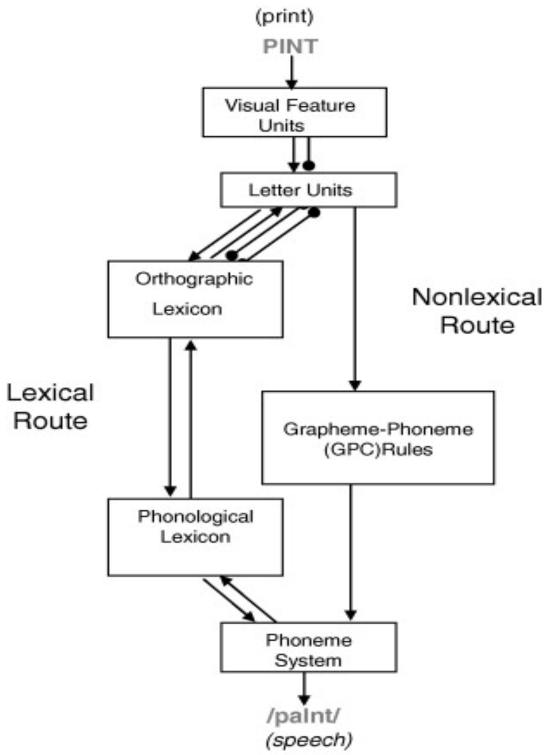


***Figure 2*. Architecture of the Dual Route Cascade Model (Coltheart et al., 2001).**

*The SERIOL model*

An important process in the early stage of visual word recognition is the registration of letter positions (i.e., their *serial order*, which will prove to be a key concept in this dissertation). Whereas older computational models, such as IAM and the DRC model described above, treated letter positions in absolute terms, newer models of visual word recognition have implemented relative-position encoding. We here discuss the Sequential Encoding Regulated by Inputs to Oscillations within Letter units model (in short, the SERIOL model; Whitney, 2001), but also many others have been developed (e.g., the SOLAR model, Davis, 2010; the Overlap model, Gomez, Ratcliff, & Perea, 2008; The Bayesian Reader model, Norris, Kinoshita, & van Casteren, 2010).

Order position encoding in the SERIOL model is based on a serial (left-to-right) activation of letter detectors. This firing sequence serves as input to a higher layer of so-called open bigram units. These bigrams contain two letters in the same relative order as in the target word, but the letters are not necessarily next to each other. Bigrams of contiguous letters receive more activation than bigrams of letters further away from each other (e.g. *PI* will be highly activated in the target *PINT*; *PT* also receives activation though to a lesser extent). The bigram units in turn activate word units, and there is within-layer inhibition at the word layer, so that words compete to be activated and recognized. In relation to reading difficulties, Whitney and Cornelissen (2005) proposed that impaired reading can be understood in terms of a problem with the left-to-right processing of words (but see also Callens, Whitney, Tops, & Brysbaert, 2013).

Although we have by no means covered the large number of computational reading models that have been offered (see Seidenberg, 2005, for a review), the models described above reflect important insights of the past decades regarding the mechanisms of reading.

## READING DISABILITY AND THE PROBLEM OF ITS DEFINITION

About 5-10% of the population exhibits a learning disorder labeled *developmental dyslexia* or *specific reading disability* (Snowling, 2000). It is commonly defined as a disability characterized by significant difficulties with reading, despite appropriate educational opportunities and in the absence of intellectual impairments or an identifiable disease or disorder that might otherwise account for the reading problem (American Psychiatric Association, 2000; World Health Organization, 2008). The low reading achievements (and the often-associated problems with spelling) typically persist through development, although adults with developmental dyslexia may compensate to some extent and the patterns of symptoms sometimes change over time (Bishop & Snowling, 2004). Unfortunately, poor reading skills often interfere with academic progress (e.g., Perie, Grigg, & Donahue, 2005) and may give rise to feelings of low self-esteem and anxiety (e.g., Raskind, Goldberg, Higgins, & Herman, 1999).

There are multiple definitions and descriptions of dyslexia available (see Bishop & Snowling, 2004 and Lyon, Shaywitz, & Shaywitz, 2003, for a discussion) and important questions surround the fact that dyslexia is diagnosed differently across studies (i.e., use of more or less stringent criteria for a person to be labeled as "dyslexic"; see Bishop & Snowling, 2004; Ziegler & Goswami, 2005). In what follows, we therefore describe the view of dyslexia that we applied throughout the studies presented in this thesis. As the precise underlying causes of developmental dyslexia remain a source of debate, we avoided any etiological reference in the definition and adapted the pure descriptive definition of dyslexia as formulated by the Foundation Dyslexia Netherlands (Stichting Dyslexie Nederland, 2008). Their definition is as follows: "Dyslexia is an impairment characterized by a pervasive problem in the automatization of reading and/or writing on a word level". According to this definition, three criteria have to be fulfilled for a dyslexia diagnosis: First, compared to a relevant reference group, the individual should score in the bottom 10 percent on validated and reliable tests of reading and/or spelling. Second, a non-response to instruction should be demonstrated, meaning that the low literacy scores remain present despite adequate remedial teaching and instruction. [1] Third, the impairment cannot be attributed to external factors (such as educational deprivation) or individual factors (such as a lower intelligence, sensory dysfunctions or any other developmental or behavioral disorders).

The ability to read shows large variability across children and adults, ranging from highly proficient and fluent reading in the upper tail of the reading distribution to inaccurate and slow reading in the lower tail (Fletcher & Prior, 1990; Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992).

Although we strictly apply the cut-off score of the $10^{th}$ percentile for a diagnosis of dyslexia, we acknowledge that this cut-off is arbitrary and that reading difficulties should be considered as a continuum rather than an all-or-none condition.

## THE UNDERLYING DEFICIT OF DYSLEXIA: PAST AND CURRENT PERSPECTIVES

A growing body of evidence supports a characterization of dyslexia as a neurobiological disorder (Lyon et al., 2003) and the disorder is assumed to

[1] The "response to instruction model" by Vaughn and Fuchs (2003) defines adequate instruction at three levels. First, the quality of the classroom instruction should be such that adequate learning is expected. Second, when this first level instruction proves insufficient for a particular individual, adjusted didactics should be applied. Finally, when corrective intervention fails to yield improved learning, individual therapeutic remediation should be provided.

have a strong genetic component. However, what exactly underlies dyslexia has been the focus of extensive controversy.

The first descriptions of developmental dyslexia date from the late 19th century and defined dyslexia as a “congenital word blindness” (Hinshelwood, 1900; Morgan, 1896). The idea of an underlying visual deficit (e.g., Orton, 1937) continued to dominate the literature until in the 1970s when, with the development of research on speech perception (in particular the work of Liberman and colleagues at Haskins Laboratories), the visual deficits were reinterpreted as phonological ones (e.g., Liberman, 1973; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). The theory of a phonological deficit gradually became dominant and is discussed in more detail below.

## THE PHONOLOGICAL DEFICIT HYPOTHESIS

The influential phonological deficit hypothesis (Snowling, 2000; Stanovich, 1988) postulates that dyslexia results from a core deficit in phonological representations. Individuals with dyslexia are assumed to have specific problems with the representation or recall[2] of phonemes, impeding the letter-to-sound mapping required for reading and spelling. Impairments in phonological processing can be identified at different levels (see Snowling, 2000, for a review). To tap phonological processing at the level of auditory analysis, researchers have employed discrimination tasks that require participants to

[2] Recent variations of this account suggest that the deficit is situated in phonological access and retrieval rather than the representations themselves (e.g., Boets et al., 2013; Ramus & Szenkovits, 2008).

make a same-different judgment about two auditory sequences (typically nonwords), which are either identical or differ by one (or more) phonetic feature(s). The ability to manipulate phonological information is typically monitored by phonological awareness tests such as phoneme deletion or Spoonerisms. In the phoneme deletion task children are asked to repeat orally presented words with one or more phonemes omitted (e.g., *spider* without *r*). In the Spoonerisms task, the first letters of two orally presented words must be switched (e.g., *H*arry *P*otter becomes *P*arry *H*otter). To assess the ability to temporarily store phonological information researchers have used verbal short-term memory tasks such as verbal serial recall. Finally, rapid automatized naming tasks (that measure how quickly individuals can name aloud objects, pictures, colors, letters or digits) have been used to assess the quality of / access to lexical phonological representations.

Overall, there are consistent reports of problems with phonological processing (on all of these levels) in individuals with dyslexia, across ages and languages (e.g., Ramus & Szenkovits, 2008; Ziegler & Goswami, 2005; and see Melby-Lervag, Lyster, & Hulme, 2012, for a recent meta-analytic review). However, the etiological and causal role of these phonological problems in relation to reading is controversial (e.g., Castles & Coltheart, 2004; Melby-Lervag et al., 2012; Morais & Kolinsky, 1994). Some authors consider the phonological deficit not as the primary cause of dyslexia but as secondary to other low-level cognitive, sensory or motor deficits (see Bishop, 2006). Moreover, as phonological awareness has been shown to develop in interaction with reading (Morais, Cary, Alegria, & Bertelson, 1979; Morais & Kolinsky, 1994), it has been postulated that problems in phonological awareness might be a symptom rather than a cause of reading difficulties (e.g., Blomert & Willems, 2010; Dehaene et al., 2010).

Whereas a phonological deficit can account for the language problems that are typically seen in dyslexia, it does not suffice as the sole determinant of dyslexia. First, there is a double dissociation between dyslexia and phonological deficits: some individuals with severe reading disability do not show a phonological impairment, while some children with an apparent phonological deficit nevertheless achieve fluency in (word) reading (e.g., Paulesu et al., 2001; Wimmer, Mayringer, & Landerl, 2000). Second, even though the hallmark of dyslexia is a persistent difficulty with reading and/or spelling, people with dyslexia also show deficits on various nonlinguistic cognitive processes, among which are working memory (e.g., Smith-Spark & Fisk, 2007), implicit learning (e.g., Jimenez-Fernandez, Vaquero, Jimenez, & Defior, 2011; Pavlidou, Kelly, & Williams, 2010; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003), motor sequencing (e.g., De Kleine & Verwey, 2009), and sensorimotor functioning (e.g., Stein, 2001, but see also Ramus, 2003). In fact, the co-occurrence of dyslexia with such deficits is often the rule rather than the exception. It is unclear how these impairments outside the linguistic domain may be accounted for by a phonological deficit.

Based on (1) the observation that poor phonological decoding skills do not necessarily result in dyslexia and (2) the observation that a wide range of cognitive abilities are impaired over and above the observed reading difficulties, some researchers have argued that the underlying cause of dyslexia should be situated in more general sensory or cognitive processes.

## EARLY ALTERNATIVE ACCOUNTS

*The General Magnocellular theory*

The general[3] magnocellular theory (Stein, 2001; Stein & Walsh, 1997) is a biologically inspired framework. It states that the symptoms of dyslexia can be traced back to the secondary phonological decoding problems that arise as a developmental result of sensory deficiencies in both the visual and auditory modality. These deficiencies are attributed to the abnormal functioning of magnocells in the brain, implicated in the processing of fast-incoming sensory information. Research inspired by the magnocellular hypothesis focused on contrast sensitivity to moving or flickering stimuli and on a variety of motion discrimination tasks. Dyslexic impairments on these tasks were observed (see Skottun, 2000, for a review) and initially interpreted to support the idea of a magnocellular deficit. However, later studies that employed better control conditions or compared the deficit across different magnocellular tasks (see Amitay, Ben-Yehudah, Banai, & Ahissar, 2002) concluded that "neither consistent nor specific magnocellular deficits were found" [Ramus & Ahissar, 2012, p. 111]. At best, the magnocellular theory describes a rather narrow subgroup of dyslexic individuals (e.g., Cohen et al., 2006).

*The Cerebellar Theory*

Another influential theoretical view posits that the underlying deficit in dys-

[3] The "general" version of the magnocellular theory covers both visual and auditoy impairments, aiming to integrate the seminal visual magnocellular account proposed by Stein and Walsh (1997) and the rapid auditory processing theory put forward by Tallal and collegues (Tallal, 1980; Tallal, Miller, & Fitch, 1993).

lexia is a procedural learning problem, caused by a dysfunction in the cortico-cerebellar and/or cortico-striatal circuits in the brain (Nicolson & Fawcett, 1990; Nicolson, Fawcett, & Dean, 2001). This neurocircuitry is involved with perceptual learning, and underlies the non-declarative or implicit acquisition of a wide range of skills and their automatization. These include motor functions, learning of sequences, statistical learning, and linguistic skills related to the learning and use of rule-governed aspects of phonology, morphology and syntax (see Hedenius et al., 2013, for a discussion). Studies investigating implicit learning have employed paradigms such as the serial reaction time (SRT) task and artificial grammar learning (AGL). In the SRT paradigm (Nissen & Bullemer, 1987), participants are presented with sequences of visual stimuli appearing in four locations on the screen, and they are required to press a key corresponding to that location. The serial order of locations, which is probabilistically determined, is learned implicitly by the participants, as indicated by faster reaction times. In a typical AGL task (Dienes, Broadbent, & Berry, 1991) participants view and memorize symbol sequences that are generated from a pre-defined grammar, and learn to recognize novel items generated on the basis of that grammar. Note that both paradigms are in principle non-verbal in nature. Overall, a large number of studies have reported impaired implicit learning performance for both children and adults with dyslexia (e.g., Du & Kelly, 2013; Hedenius et al., 2013; Jimenez-Fernandez et al., 2011; Lum, Ullman, & Conti-Ramsden, 2013; Pavlidou et al., 2010; Stoodley, Harrison, & Stein, 2006; Vicari et al., 2003; but see Russeler, Gerth, & Munte, 2006, for different results).

## ADDITIONAL RECENT ALTERNATIVES ACCOUNTS

In addition to the above historically prominent theories, accounts of dyslexia have focused on specific deficits in cognitive faculties. For example, Hari and Renvall (2001) have suggested that dyslexia is tied to impaired attentional functions, and demonstrated sluggish attentional shifting in reading-impaired participants. In contrast, Ahissar and her colleagues reported that dyslexics show substantial difficulty in using cross-trial statistics of pure tones for pitch discrimination. These findings formed the basis of their perceptual anchoring hypothesis (Ahissar, 2007; Ahissar, Lubin, Putter-Katz, & Banai, 2006). This hypothesis states that dyslexia is characterized by a general difficulty in the automatic extraction of regularities from auditory inputs. Another recently formulated proposal, the so-called "visual attention span hypothesis" proposes that a difficulty in simultaneously processing visual elements is at least one cause of dyslexia (Bosse, Tainturier, & Valdois, 2007). According to the visual crowding hypothesis, dyslexics are impaired in recognizing a visual target due to the presence of neighboring objects in the peripheral visual field, which impairs their perception of printed text (Spinelli, De Luca, Judica, & Zoccolotti, 2002). Yet another hypothesis attributes the problems of dyslexics to abnormal temporal sampling or, put differently, a deficit in the perceptual experience of rhythmic timing (Goswami et al., 2002; Goswami, 2011).

Note that whereas most of these theories reflect the (sometimes implicit) stand that *one* core deficit underlies dyslexia, it is possible that various combinations of a range of perceptual and cognitive impairments can interact and result in the same surface symptom of reading impairment, as put forward by the multifactorial view of dyslexia (e.g., Bishop, 2006; Menghini et al., 2010; Pennington, 2006).

Given the wide variety of competing theories a critical theoretical question is whether there are unifying common features underlying most tasks that show impaired performance by dyslexics. Asking exactly this question, our research group has recently suggested that the paradigms used to investigate the wide range of hypothesized dyslexic impairments typically implicate the processing or learning of serial-order information, whereas tasks that do not rely on sequentiality often appear unaffected (Szmalec, Loncke, Page, & Duyck, 2011). Serial-order memory could therefore offer an elegant path to integrating some of the conflicting theories under one theoretical construct (see also Bryden, 1972; Corkin, 1974). The next part of this introduction discusses in depth this theoretical framework and its empirical evidence.

## LINKING SERIAL-ORDER MEMORY, LANGUAGE LEARNING AND LITERACY ACQUISITION

Memory for serial-order information plays an important role in human cognition: much of what we need to remember consists of sequences of stimuli, events or actions (e.g., Acheson & MacDonald, 2009; Conway & Christiansen, 2001). In serial-order learning, it is not only important to remember the elements within a sequence, but also the specific order in which they appeared. The importance of memory for order is probably most evident in the domain of language. 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 processing (e.g., Conway & Pisoni, 2008; Conway & Christiansen, 2001). In what follows, we discuss in more detail how serial-order memory is implicated in the process of lexical acquisition and in reading.

## LEXICAL ACQUISITION

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). 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 to .5) between performance on verbal immediate serial recall tasks and both nonword repetition and vocabulary scores (in either the first or second language; e.g., Gathercole & Baddeley, 1989; Service, 1992). Multiple authors have proposed that these short-term memory mechanisms contribute to long-term learning of new phoneme (and by extension orthographic) sequences via Hebb repetition learning (Burgess & Hitch, 2006; Gupta, 2003; Page & Norris, 2009).

### *The Hebb repetition effect*

In the early sixties, Hebb (1961) asked his participants to perform an immediate serial recall task in which one specific sequence of digits was repeated every third trial. Hebb reported that participants performed significantly better in the recall of repeating sequences compared with nonrepeating sequences (see Figure 3). This effect was later labeled the *Hebb repetition effect*. In essence, the Hebb repetition effect reflects how, through repeated exposure, a sequence of information in short-term memory is gradually learned and develops into a more stable, long-term memory trace. In the past two decades, the Hebb repetition effect has been the subject of renewed interest. As an operational construct, it was taken to provide a laboratory analogue for the learning process involved in naturalistic vocabulary acquisition.

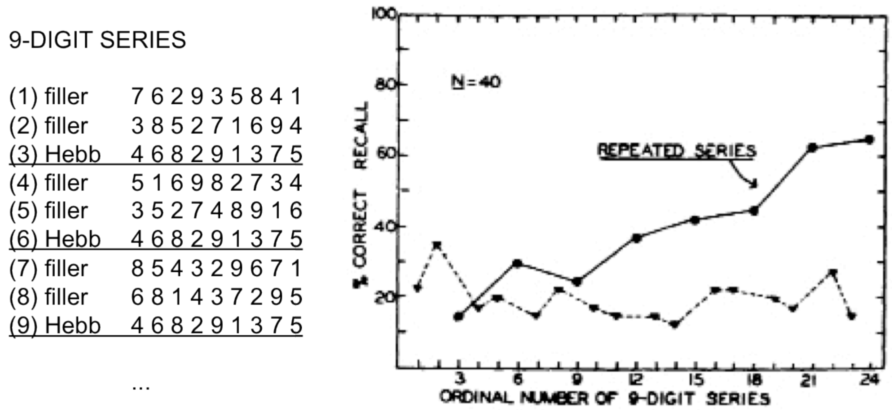


***Figure 3*. Visual depiction of the Hebb repetition paradigm and the results of the study by Hebb (1961).**

*Hebb learning as analogue of word learning*

*A modeling framework.* Page and Norris (e.g., Page & Norris, 2008, 2009; see also Cumming et al., 2003) explicitly related word learning to serial-order learning. In their view, new phonological word-forms can be conceived as memorized sequences of sublexical units (phonemes, syllables). Suppose that a participant is repeatedly presented with the letter sequence 'B J F M L' in a Hebb paradigm, and he/she therefore recalls the list several times over the course of the experiment. The authors argue that performance in this task is functionally equivalent to the repeated presentation of the stimulus 'bejayeffemmelle', which is recalled as a novel object name. This account suggests that the Hebb repetition effect represents generic long-term learning of sequences, such as phonological word-forms. Figure 4 depicts the computational model proposed by Page and Norris (2008, 2009). The localist model has four layers: an occurrence layer, a recognition layer, an order layer and a response layer. Importantly, there is no hierarchical structure so that a single node or connectionist unit can represent either sublexical or lexical information (or even familiar sequences of words).

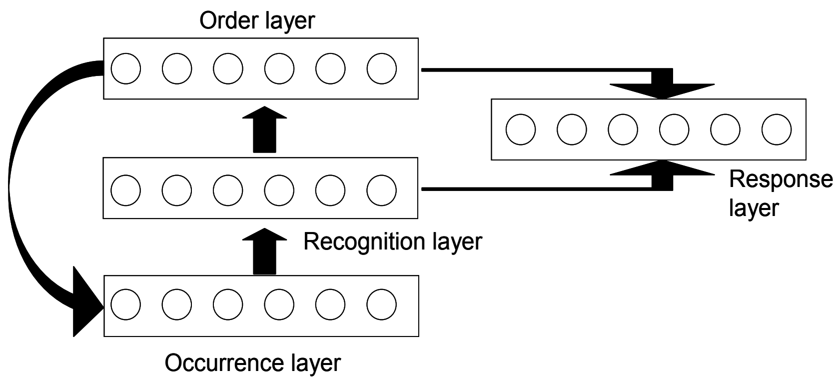


***Figure 4*. Architecture of the connectionist model by Page and Norris (2008, 2009).** Black arrows indicate one-to-one between layer connections. Within-layer connections are inhibitory in the recognition layer.

How does the model implement list recall and list learning? Units in the occurrence layer get activated by the presence (in the environmental stimulus) of their corresponding item (under the assumption that the model already contains a unit for each list-item). The occurrence layer also has so-far uncommitted units that can be assigned to represent a particular (new) item. Within the recognition layer above, units compete with each other to signal recognition, so that lower-level representations (i.e., individual items of a list) are suppressed by higher level ones (i.e., chunks). The order layer on top stores items and serial-order information relating to them. A new stimulus list[4] (e.g., C-A-T) causes the units of the order layer to respond with the highest activation for the first item (i.e., C), a little less for the second (i.e., A) and the lowest activation for the last (i.e., T), forming a primacy gradient of activation. This order layer activation is copied into the connection weights of the occurrence layer, and this information is used to establish a new occurrence unit that comes to represent a chunk of lower-level items (i.e., "CAT", see Figure 5). The primacy gradient, which is also copied into the response layer, becomes steeper through repeated presentation, leading to fewer omissions and fewer order errors in list recall. Importantly, repetition learning within the model depends on two parameters: the short-term (order) representation of a list (or, the presence and strength of the primary gradient) and a weight-change process governed by a variable learning rate.

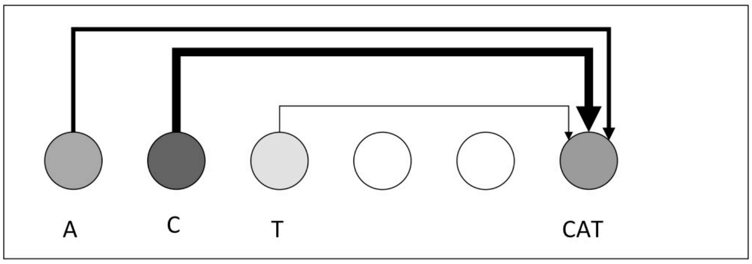


***Figure 5*. Depiction of the primacy gradient in the connection weights and the committing of an occurrence unit.**

[4] This can be a sequence of phonemes/syllables forming an unfamiliar word (cf. nonword repetition) but also a list of words (cf. a typical immediate serial recall task).

*Empirical evidence.* In support of the claim that the Hebb repetition effect is a laboratory analogue for natural word learning, Mosse and Jarrold (2008) indeed showed 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). This claim has further been elaborated by Szmalec, Duyck, Vandierendonck, Barberá-Mata, & Page (2009). In this study, syllabic sequences (nine syllables, grouped into three sets of three syllables, e.g., ri-zo-bu_ni-li-na_sa-ba-du) were used in a Hebb learning procedure. Following this learning phase, participants were tested on an auditory lexical decision task. The nonwords in this task were constructed from the syllables used in the repeating Hebb sequences (rizobu, nilina and sabadu). Responses for the Hebb-based nonwords were significantly slower than for the control nonwords (i.e., they were more slowly identified as nonwords). In a second study (Szmalec, Page, & Duyck, 2012), the same participants demonstrated a lexical engagement of the newly acquired Hebb sequences. Lexical engagement refers to the interaction of novel word-forms with existing entries in the mental lexicon (Gaskell & Dumay, 2003). Specifically, in the Hebb learning phase, participants were presented with syllabic sequences of which the constituent three-syllable units overlapped with existing Dutch words (e.g., la-va-bu_sa-fa-ro_no-ma-du, overlap to a large extent with the words "lavabo", "safari" and "nomade"). In a subsequent pause-detection task, participants were asked to detect the presence of an artificially embedded pause in connected speech. Mattys and Clark (2002) had previously demonstrated that the speed, at which such an artificial pause can be detected, depends on the overall amount of lexical activity caused by the speech preceding this pause. Therefore, the pause-detection time is a function of the number of phonological neighbors of the target word, and can be used as a test of the lexical status of newly acquired word forms. The result of the study by Szmalec et al. (2012) showed significantly slower pause-detection times on Dutch base words that overlapped with the repeated three-syllable units in the Hebb paradigm, in comparison to control words. This result strongly suggests that the repeated presentation and recall of syllable sequences led to the integration of these verbal materials in the mental lexicon.

## READING

The above theoretical framework clarifies the link between memory for serial order and lexical acquisition. This framework can easily be extended to the domain of word reading.

Several recent models of reading stress the importance of the (temporal) alignment of the serial orthographic representations (i.e., letters position and identity) and phonological representations in reading acquisition (e.g., the SERIOL model, Whitney, 2001; The Overlap Model, Gomez et al., 2008). When encountering an as-yet-unknown orthographical word-form, a (beginning) reader will typically use a decoding strategy through which s/he converts letters into the corresponding sounds, integrating a representation of the entire sequence of sounds into a single word-form (e.g., the DRC Model, Coltheart et al., 2001). By hypothesis, repeatedly processing the same visual sequence of letters will then (through Hebbian learning) gradually develop into an orthographic representation in the mental lexicon. The presence of such representations allows more automatic and proficient processing of the (now known) letter string. In this view, the acquisition of orthographical word-forms is taken to involve memory for serial information, and conversely, reading impairments are hypothesized to be associated with a deficit in serial-order learning (Szmalec et al., 2011).

*Dyslexia as a dis-order?*

Szmalec and colleagues (2011) tested adults diagnosed with dyslexia and a matched control group in three Hebb learning conditions: a visual-verbal condition with sequences of syllables presented visually; a verbal-auditory condition with auditory syllable sequences; and a visuo-spatial condition with sequences of dot locations. The results of both groups, for the different stimuli and presentation modalities, are presented in Figure 6. They show that dyslexic adults display reduced Hebb repetition learning across both verbal and visuo-spatial modalities. The demonstration of a deficit in the visuo-spatial Hebb task—an unambiguously non-linguistic task—implies that a domain-general serial-order component may be the locus of impairment in dyslexia. It must be noted, however, that whereas the study by Szmalec et al. convincingly shows an impairment in both verbal and nonverbal Hebb learning conditions, the results reported in the literature are not always consistent (Gould and Glencross, 1990; Staels and Van den Broeck, 2014; see our discussion of this issue, p. 226).

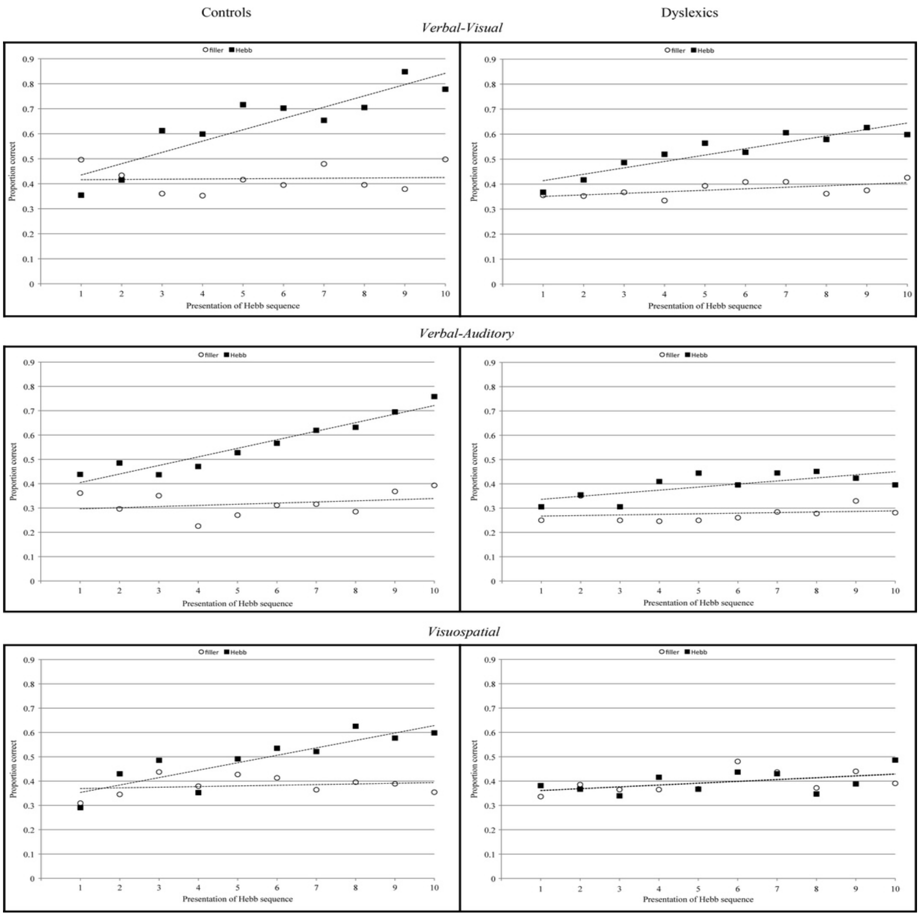


***Figure 6*. Results of Szmalec et al. (2011), demonstrating reduced Hebb repetition learning for adults with dyslexia.**

*Short-term memory for order*

The serial-order account proposed by Szmalec et al. (2011), and the studies discussed above, focus on the *long-term learning* of serial-order information. In other words, they are concerned with the transfer of serial-order information, initially stored in short-term memory, into a stable long-term memory trace or representation. However, it is almost self-evident that the learning of a sequence (by repeated presentation and recall) is dependent on the successful encoding and temporary retention of the sequence in short-term memory. This raises the question whether the problem with order-information can possibly (also) be attributed to the temporary processing of serial-order information in short-term memory, rather than exclusively to the learning and retention in long-term memory of lists presented over multiple trials.

Indeed, a consistent finding in the dyslexia literature is the low short-term memory span of dyslexic readers (e.g., Kibby, Marks, Morgan, & Long, 2004; Ramus & Szenkovits, 2008; Smith-Spark & Fisk, 2007). How can the 'order' component of short-term memory be isolated? Measures of short-term memory such as digit span and nonword repetition do not distinguish between correct recall of item identity and correct recall of item order. For example, when asked to repeat the digit list '2 4 6 9 1 0 7', a participant has to remember not only the identity of the items (i.e., that '4' is present) but also the correct serial order in which they appeared in the list. Recent computational models, however, suggest that processing of item identity in short-term memory (henceforth 'item STM'), and processing of serial order (henceforth 'order STM'), are distinct and dissociable (Brown, Preece, & Hulme, 2000; Burgess & Hitch, 2006; Page & Norris, 2009). These models contend that the storage of items in memory is modality-specific, depending primarily on the *quality* of long-term traces. In contrast, the processing of order occurs via a system that operates on items independently of their exact nature.

In their recent behavioral work[5], Majerus and colleagues aimed to disentangle item and order storage in short-term memory. These studies highlighted the importance of the order STM, relative to item STM in relation to novel word learning. Order STM was found to be the most important predictor for vocabulary knowledge as well as for speed and quality of new word learning (Leclercq & Majerus, 2010; Majerus et al., 2006; Majerus & Boukebza, 2013; Majerus, Poncelet, Van der Linden, & Weekes, 2008). In the domain of reading, order STM but not item STM capacity was found to reliably predict later print-to-sound decoding abilities in kindergarten children (Martinez Perez, Majerus, & Poncelet, 2012).

Drawing on the item vs. order distinction, Martinez Perez and colleagues investigated whether the verbal short-term memory deficits in dyslexia can be explained exclusively by poor phonological processing abilities, or whether children with dyslexia in fact suffer from an (additional) order deficit (Martinez Perez, Majerus, Mahot, & Poncelet, 2012).

They employed a nonword delayed repetition task to measure item STM, and a serial order reconstruction task to measure order STM. In the latter task, pictures had to be arranged so that they conformed with their order in an auditorily presented sequence of picture names. Children with dyslexia were shown to be impaired on both STM for item and STM for order, but

[5] Also neurologically these two functions of short-term memory have been dissociated. Majerus et al. (2009) showed that order tasks engage a network of domain-general executive and attentional functions (including the dorsolateral prefrontal cortex, inferior parietal lobe, intraparietal sulcus and cerebellar regions) whereas regions specific to long-term content are activated for item task requirements (all three temporal gyri, the fusiform gyrus, hippocampus and precuneus).

with the order impairment being the most severe. The authors further suggested that the impairment in STM for order could be a factor contributing to reading-acquisition difficulties. Note that if the order STM impairment is indeed domain general (this has never been explicitly investigated), it could easily explain why dyslexia is often associated with memory and learning deficiencies outside the domain of language. The reports of reduced memory span in dyslexia – even with nonverbal material (e.g., Kibby et al., 2004; Smith-Spark & Fisk, 2007) could possibly be framed in terms of a problem with the sequential, or order, component in the task. This standpoint further predicts difficulties for persons with dyslexia specifically in memory tasks that require the processing and storage of serial-order information. This is the focus of the present dissertation.

## THE PRESENT DISSERTATION

The overarching aim of this doctoral project is to investigate in depth the role of both (a) the processing and short-term storage of order information and (b) the long-term learning of ordered lists, in reading and dyslexia. We conducted four independent comprehensive studies, which are presented in four empirical chapters.

CHAPTER 2 deals with the question of whether developmental dyslexia is associated with a selective difficulty with the *order* component of short-term memory, and whether this difficulty is specific to linguistic material or is domain-general. A sample of adults with dyslexia and a matched control group participated in a behavioural experiment that assessed short-term recognition performance for both item and order information, using both verbal and nonverbal material. We expected that, irrespective of stimulus domain, participants with dyslexia would not differ from controls on item recall performance, but would show impaired recognition of the serial order in which those items were presented.

CHAPTER 3 explores whether impaired serial-order processing in people with dyslexia involves additional problems in memory functions. We focus on one important phenomenon that emerges when the representation of serial-order information is affected, namely increased susceptibility to proactive interference (i.e., difficulties in retrieving information due to interference from memory traces that were stored prior to the to-be-remembered materials, Jonides & Nee, 2006). This form of interference contaminates the retrieval of information from working memory (e.g., Suprenant & Neath, 2009). In our study, adults with dyslexia and matched controls were subjected to a working-memory recognition task, in which interference was elicited. Given that overcoming proactive interference in this type of task relies on a representation of the items in their correct serial order, we predicted impaired performance in dyslexia.

CHAPTER 4 considers the long-term serial-order learning impairments, operationalized as reduced Hebb repetition learning, in people with dyslexia. In a first multi-session experiment, we investigated the precise nature of the serial-order learning impairment (i.e., asking whether learning is fundamentally limited in its extent, or whether it is simply delayed, and examined the retention of the learned serial-order representations (i.e., asking whether the learned material is forgotten at a different rate) in adults with dyslexia. Relying on the assumption that Hebb repetition learning mimics naturalistic word-form acquisition, we tested, in a second experiment, the lexicalization of novel word-forms acquired through Hebb repetition learning. We not only predicted slower Hebb learning for the dyslexic group, but also a fundamental impairment in Hebb learning, despite an experimentally induced opportunity (in terms of number of repetitions) for substantial overlearning. We further anticipated that people with dyslexia would be likely to benefit less from prior learning when asked to relearn the same Hebb sequences across sessions. Finally, we expected that the lexicalization of word-forms acquired through Hebb repetition learning would be worse for people with dyslexia than for normal reading controls.

In the final empirical chapter, CHAPTER 5, we asked whether the association between serial-order learning and reading skills can also be demonstrated in beginning readers and whether relative order learning difficulties can reliably predict poor reading development. These questions were addressed in a large-sample longitudinal study. Verbal and visual Hebb repetition learning and reading skills were assessed in a large sample of children, including both children at risk for dyslexia and children without this increased risk. The study had three major objectives: First, to investigate whether the observation of Hebb-learning deficits in dyslexic adults can be replicated in poor-reading children. Second, to explore the intercorrelations between long-term Hebb repetition learning and reading skills, using a full sample of readers along the reading continuum. Tracking the children from first through second grade allowed us to also estimate the potential of the Hebb repetition paradigm as a predictive tool for (pathological) reading development. Third, we aimed to test whether Hebb repetition learning explains a unique portion of variance in reading (that cannot be accounted for by phonological skills). We predicted a reliable Hebb repetition effect in the child group and weaker verbal and visual Hebb learning for poor readers. Considering reading skill as a continuous variable, we predicted positive (predictive) correlations between reading skill and Hebb learning performance. Finally, we anticipated the Hebb measure to explain unique variance in reading, above and beyond phonological awareness.

To conclude this dissertation, CHAPTER 6 summarizes the results of the different studies and discusses their theoretical implications. We further discuss a number of methodological caveats in this line of research, and outline potential avenues for future investigations.

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# CHAPTER 2
## SHORT-TERM MEMORY FOR ORDER BUT NOT FOR ITEM INFORMATION IS IMPAIRED IN DYSLEXIA[6]

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, Loncke, Page, & Duyck, 2011). At the same time, models of short-term memory increasingly incorporate a distinction of order and item processing (Majerus, Poncelet, Van der Linden, & Weekes, 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 x 2 x 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

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[6] Hachmann, W. M., Bogaerts, L., Szmalec, A., Woumans, E., Duyck, W., & Job, R. (2014). Short-term memory for order but not for item information is impaired in developmental dyslexia. *Annals of dyslexia*. DOI:10.1007/s11881-013-0089-5.

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.

## 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, Shankweiler, & Liberman, 1981; Ramus & Szenkovits, 2008; Swan & Goswami, 1997; Ziegler & Goswami, 2005, but see also Castles & Coltheart, 2004 and Morais & Kolinsky, 1994)— or instead related to a more general dysfunction, such as perceptual problems (Bosse, Tainturier, & Valdois, 2007; Romani, Tsouknika, di Betta, & Olson, 2011), working memory and executive impairments (Brosnan, Demetre, Hamill, Robson, Shepherd, & Cody, 2002; Kibby, Marks, Morgan, & Long, 2004; Smith-Spark & Fisk, 2007) or implicit learning difficulties (Pavlidou, Kelly, & Williams, 2010; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003).

Recently, Szmalec, Loncke, Page and Duyck (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 forty years ago, the question of domain-specificity[7] remained open, and consecutively, the

[7] 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

debate centered around the more predominant verbal impairments in support of the phonological deficit hypothesis (for a summary see Beaton, 2004, p. 115ff; Katz, Shankweiler, & Liberman, 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, Dannadieu, Berger, & Valdois, 2010; Lobier, Zoubrinetzky, & Valdois, 2012; Romani, Tsouknika, di Betta, & Olson, 2011; Vidyasagar & Pammer, 2009). Convincing evidence in support of a serial order impairment was reported by Howard, Howard, Japikse and Eden (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 & 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

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that of nonverbal material. Most of our stimulus material was presented visually, in which one experimental factor, labeled *domain*, varied verbal versus nonverbal content.

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 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 visuo-spatial sequences of dots presented on a computer screen.

Within the computational models of Hitch, Flude and Burgess (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 (STM) 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, Marks, Morgan, & Long, 2004; Nithart et al., 2009; Pennington, Van Orden, Kirson, & Haith, 1991; Ramus & Szenkovits, 2008; but see also Smith-

Spark & 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, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Farrell & Lewandowsky, 2002; Majerus et al., 2009; Page & 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 & Kelly, 2004; Saint-Aubin & 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, Poncelet, Elsen, & van der Linden, 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 & 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 visuo-spatial and in verbal serial-order learning performance (i.e., verbal and visuo-spatial 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.

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, Szmalec et al.´s (2011) earlier claim 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, Majerus, Mahot, & Poncelet (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 3-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 & Norris, 2009; Szmalec, Page, & Duyck, 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 et al. (2012) and Majerus et al. (2006; 2008). Nithart et al. (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, Bennetto, McAleer, & Roberts, 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 non-linear fashion in span tasks (May, Hasher, & Kane, 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 2x2x2 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 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 two 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 six 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 one minute word reading task in Dutch ("Éen Minuut Test" (EMT), Brus & Voeten, 1979) and a Dutch nonword reading task ("Klepel", Van den Bos, lutje Spelberg, Scheepsma, & de Vries, 1994), and IQ testing (short version of the Kaufman Adolescent and Adult Intelligence Test (KAIT) in Flemish, see Dekker, Dekker, & Mulder, 2004), either less than two years before or during participation. The cutoff criteria of the reading tests had been recently evaluated for adults with dyslexia by Callens, Tops & Brysbaert (2012) and Tops, Callens, Lammertyn, Van Hees, & Brysbaert (2012). In each reading test, the participant was asked to correctly read aloud as many words and respectively nonwords as possible in one minute.

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 & 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 2.4SD 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: $\chi2=960$, simulated $p < .001$; and in group D: $\chi2=924$, simulated $p < .001$). 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.

***Table 1*. Sample characteristics.**

| | *Dyslexia* (n=21) | *Control* (n=24) | t-test (paired, 2-sided) |
|---|---|---|---|
| Gender f/m | 10/11 | 10/14 | |
| Handedness r/l | 19/2 | 19/5 | |
| Age (years) | 20.8 (1.4) | 21.4 (1.6) | *p =.207* |
| KAIT total IQ | 107.5 (9.4) | 111.4 (8.7) | *p* =.152 |
| Fluid measure (IQ) | 107.2 (11.3) | 108.5 (12.0) | *p* =.701 |
| Symbol learning [a] | 81.8 (9.3) | 84.6 (14.8) | *p* =.449 |
| Logic thinking [a] | 12.2 (3.4) | 11.3 (3.6) | *p* =.392 |
| Hidden code [a] | 27.6 (4.6) | 28.7 (4.6) | *p* =.432 |
| Crystallized measure (IQ) | 106.4 (8.2) | 112.3 (7.3) | *p* =.014 |
| Word definitions [a] | 21.0 (1.9) | 23.2 (2.5) | *p* =.002 |
| Auditory comprehension [a] | 12.5 (3.1) | 13.9 (2.9) | *p* =.126 |
| Double meaning [a] | 15.8 (3.3) | 16.6 (3.3) | *p* =.435 |
| Word reading (EMT) | 84.9 (18.3) | 101.6 (10.1) | *p* <.001 |
| Nonword reading (Klepel) | 46.4 (13.1) | 64.6 (11.0) | *p* <.001 |

*Note.* Means per group with standard deviations between brackets
[a] test scores

## 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 were 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 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 (2009) formed 18 lists of 13 pictures each. As targets we chose those word-picture combinations that were represented by disyllabic Dutch words within a restricted frequency range (2 to 52 times less frequent than the most frequent word of the underlying corpus (Celex), log frequency range=.6-1.7, mean (M)=.982, SD=.408). Mean age of acquisition for target words was 4;8 years (SD=2;4; see Severens, van Lommel, Ratinckx, & Hartsuiker, 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 like follows: List selection per trial was randomized and each trial started with a fixation cross that was displayed for 1000 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 1000msec 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 1000msec. 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 seconds, 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 Figure A1 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 1000msec. Also here, none of the drawings was 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.

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 1000msec 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.

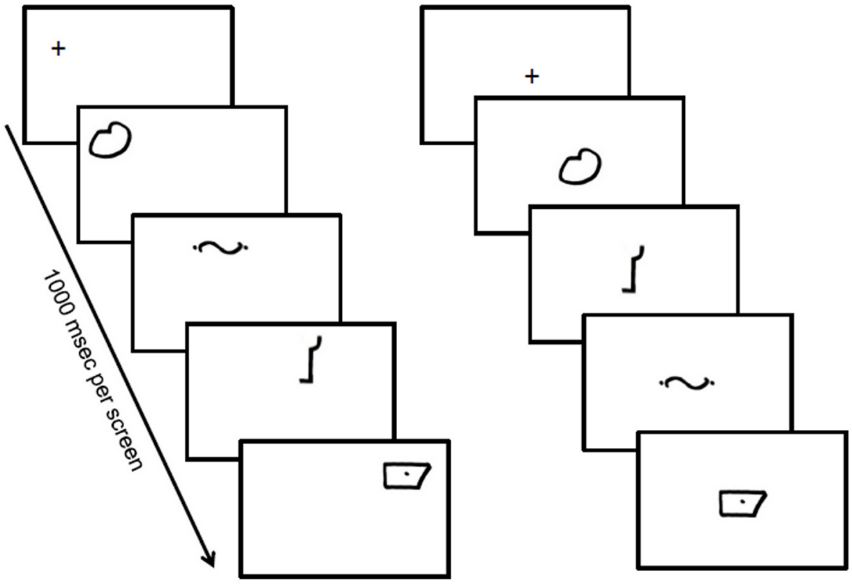


***Figure 1.*** **Procedure of the nonverbal order task, example of a mismatch trial.** Participants could press a response key during presentation of the second list, in this case a fast and correct response would be *no* during the second screen of the second list.

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 one day apart. In session one the participants performed the four memory tasks, and one 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.

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

| | **Item tasks** | | **Order tasks** | |
|---|---|---|---|---|
| | ***verbal*** | ***nonverbal*** | ***verbal*** | ***nonverbal*** |
| *Control* | 14.92 (1.59) | 13.83 (1.79) | 12.08 (2.06) | 13.625 (2.70) |
| *Dyslexia* | 15.57 (1.40) | 13.62 (1.40) | 10.76 (2.49) | 12.286 (2.45) |

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, $F(1,43)=61.351$, $MSE=3.69$, $f=1.193$, $\eta^2=.5879$, $p<.001$, and an interaction of task and domain, $F(1,43)=25.435$, $MSE=4.04$, $f=.848$ $\eta^2=.3717$, $p<.001$, 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, $F(1,43)=7.288$, $MSE=3.69$, $f=.497$, $\eta^2=.1449$, $p<.01$, 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, $F(1,43)=24.264$, $MSE=2.06$, $f=.998$, $\eta^2=.3607$, $p<.001$, 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, $F(1,43)=9.376$, $MSE=5.64$, $f=.649$, $\eta^2=.1790$, $p<.01$, and a main effect of group, $F(1,43)=6.386$, $MSE=6.21$, $f=.540$, $\eta^2=.1293$, $p<.05$, 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 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 are 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 and colleagues, 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 and colleagues 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 and colleagues used might have elicited more executive function requirements that are usually related to working memory processing, than our recognition task (Pennington, Bennetto, McAleer, & Roberts, 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, Lipinski, & Actunc, 2005; Hitch et al., 2009; Page & 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, Duyck, Vandierendonck, Barberá-Mata, & Page, 2009; Szmalec et al., 2009; 2012). The unity of this long-term representation, according to Page and Norris (2009), 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, Burani, Di Filippo and Zoccolotti (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, Cohen, & Dehaene, 2003). Also phonological awareness and the skill to segment speech into phonological elements develop in interaction with reading (Morais, Gary, Alegria, & Bertelson, 1979; Morais & 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 consecutively 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 & Friedmann, 2010).

Neurologically, order memory is essentially related to a network based on inferior parietal lobe (IPL) and additionally on dorsolateral prefrontal cortex (DLPFC) in conjunction with intraparietal sulcus and cerebellar regions (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 (TMS) during nonword reading (Costanzo, Menghini, Caltagirone, Oliveri, & Vicari, 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 temporo-parietal 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, Cohen, & Dehaene, 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

A.1. Example stimuli for the nonverbal item task

***Figure A1*. Nineteen example stimuli of a total of 171 drawings from the nonverbal item task**

# CHAPTER 3

## INCREASED SUSCEPTIBILITY TO PROACTIVE INTERFERENCE IN ADULTS WITH DYSLEXIA?[8]

Recent findings show that people with dyslexia have an impairment in serial-order memory. Based on these findings, the present study aimed to test the hypothesis that people with dyslexia have difficulties dealing with proactive interference in recognition memory. A group of 25 adults with dyslexia and a group of matched controls were subjected to a 2-back recognition task, which required participants to indicate whether an item (mis)matched the item that had been presented 2 trials before. Proactive interference was elicited using lure trials in which the item matched the item in the 3-back position instead of the targeted 2-back position. Our results demonstrate that the introduction of lure trials affected 2-back recognition performance more severely in the dyslexic group than in the control group, suggesting greater difficulty in resisting proactive interference in dyslexia.

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[8] Bogaerts, L., Szmalec, A., Hachmann, W.M., Page, M. P .A., Woumans, E., & Duyck, W. (2014). Increased susceptibility to proactive interference in adults with dyslexia? *Memory.* DOI: 10.1080/09658211.2014.882957.

## INTRODUCTION

### DYSLEXIA

Developmental dyslexia is a learning disorder characterized by persistent difficulties with reading and/or spelling (e.g., Lyon, Shaywitz, & Shaywitz, 2003; Vellutino, Fletcher, Snowling, & Scanlon, 2004). The influential phonological deficit hypothesis (e.g., Snowling, 2000) postulates that an impairment in the processing and representation of phonological information is the core deficit underlying dyslexia, responsible for the wide variety of language problems that are seen in the disorder. However, a consensus on the underlying cause of developmental dyslexia has not been reached (e.g., Pennington, 2006). First, there are instances where people with developmental dyslexia do not show a phonological impairment and nevertheless fail to achieve fluency in (word) reading (Paulesu et al., 2001; Wimmer, Mayringer, & Landerl, 2000). Second, even though the hallmark of dyslexia is the persistent difficulty with reading and/or spelling, people with dyslexia also show deficits on various nonlinguistic cognitive processes, among which are working memory (WM; e.g., Smith-Spark & Fisk, 2007), implicit learning (e.g., Jiménez-Fernández, Vaquero, Jiménez, & Defior, 2011; Pavlidou, Kelly, & Williams, 2010; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003), motor sequencing (e.g., De Kleine & Verwey, 2009), and sensorimotor functioning (e.g., Stein, 2001, but see also Ramus, 2003).

Recently, Szmalec, Loncke, Page, and Duyck (2011) introduced a novel, integrative hypothesis, which proposes that both the linguistic and nonlinguistic (memory or learning) dysfunctions in dyslexia arise from a deficit in memory for serial-order information (i.e., the order in which items are presented within a sequence).

This hypothesis was grounded on the observation that Hebb repetition learning, that is, improved recall for a repeated sequence of (verbal, visual or spatial) items over the course of an immediate serial recall task (Hebb, 1961), is impaired in adults with dyslexia. It has been shown experimentally that Hebb repetition learning can be considered a laboratory analogue of lexical acquisition, in the sense that acquiring a novel lexical form (e.g., the novel word "beejayeffemmelle") is closely related to learning a sequence of verbal items (e.g., B J F M L) over the course of repeated exposures (Page & Norris, 2008, 2009). Following this rationale, Bogaerts, Szmalec, Hachmann, Page, and Duyck (submitted) went further to directly demonstrate that impaired Hebb learning of verbal serial information in dyslexia is associated with difficulties in acquiring novel lexical representations. These findings were very recently extended by Perham, Whelpley, and Hodgetts (2013), who observed impaired memory for syntactical information (potentially another instance of serial-order learning) in poor readers. Furthermore, three recent studies demonstrated that both children and adults with dyslexia have difficulties with short-term memory for order (i.e., retaining the serial position of an item within a list) but not, or not to the same extent, for item information (Hachmann et al., in press; Martinez Perez, Majerus, Mahot, & Poncelet, 2012 ; Martinez Perez, Majerus, & Poncelet, 2013). Importantly, these serial order impairments again show affected processing beyond the verbal domain, affecting memory for non-verbal materials too. These data are consistent with older studies from the seventies showing impairments for people with dyslexia in both visuo-spatial and verbal serial recall tasks (Bryden, 1972; Corkin, 1974).

The hypothesis that dyslexia originates from an underlying deficit in serial-order memory advances our understanding of the relation between the linguistic problems and the associated learning dysfunctions that are often observed in dyslexia. It is widely recognized that memory for serial-order information (or sequential memory) is involved in a variety of cognitive functions and therefore plays a crucial role in human cognition (e.g., Acheson & MacDonald, 2009; Conway & Christiansen, 2001; Conway & Pisoni, 2008). This raises the question of whether impaired serial-order memory in dyslexia possibly leads to other, perhaps more subtle impairments that until now have remained unidentified. The current study focuses on one important phenomenon that emerges when the representation of serial-order information is affected, namely increased susceptibility to proactive interference.

## PROACTIVE INTERFERENCE

The term proactive interference (PI) refers to difficulties in retrieving information due to interference from memory traces that were stored prior to the to-be-remembered materials (Jonides & Nee, 2006). PI is seen as an important source of forgetting in long-term-memory (Underwood, 1957; Wixted & Rohrer, 1993), but more recent studies show that PI also affects retrieval from working memory (e.g., Dempster & Corkill, 1999; Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999; Suprenant & Neath, 2009; Whitney et al., 2001). Retrieving information that has (temporarily) been stored in memory can occur in two ways: by active *recall* or by simple *recognition* (if a cue or trigger is presented). The influence of PI on active recall memory is nicely demonstrated by the fact that WM span is higher when the length of the span sequence is manipulated in a decreasing procedure (i.e., starting with sequences of 9 down to 3 items), compared with an increasing procedure (i.e., starting with sequences of 3 up to 9 items). In the latter, the standard span procedure, the largest set sizes are presented last, that is, after numerous other trials, and therefore suffer more from PI. Participants show increased span scores when PI on the most vulnerable, long sequences is reduced by reversing the sequence of trials so that the larger set sizes are presented first or, alternatively, by adding breaks between span trials (May et al., 1999). Although most studies investigating PI have made use of recall tasks, there is also much evidence that PI affects recognition memory negatively (e.g., Oztekin & McElree, 2007; Petrusic & Dillon, 1972; Szmalec, Verbruggen, Vandierendonck, & Kemps, 2010). In the current study we used the *n*-back recognition task (Smith & Jonides, 1997). In this task participants are instructed to indicate for each item (e.g., letters, pictures) in a list whether it matches the item that was presented *n* positions earlier. To perform this task, participants are required to remember the *n* most recently presented items in serial order. When new items are presented, participants need to update their WM, which means that they unbind the oldest item and bind the new item to a position in WM. We chose this task because it has been shown that the constant updating of items in WM prevents strong binding of those items to their contexts (i.e., their serial position in a list), which makes this recognition task a sensitive measure of PI (Szmalec et al., 2010).

Dual-process theories of recognition memory (see Yonelinas, 2002) assume that recognition memory can be subdivided into two distinct memory processes: *familiarity matching* and *recollection*. Familiarity matching refers to the fast and automatic assessment of whether an item has been encountered before (or feels familiar); recollection is the controlled retrieval of contextual details associated with an event. A common illustration of the distinction between these two memory processes is the experience of recognizing a person as being familiar but being unable to recollect the details about when or where the person was seen before. Familiarity matching and recollection were initially thought to underlie the recognition of items in long-term memory, but several studies suggest that the same processes also operate during access to information in WM (e.g., Goethe & Oberauer, 2008; Oztekin & McElree, 2007; Szmalec et al., 2010). In short-term recognition, and more specifically in the context of the n-back task, they can be defined as two dissociable processes that operate in parallel during item recognition: (1) a familiarity matching process that, driven by the degree of activation of items in long-term memory, indicates whether a recognition probe matches a representation in memory and (2) a recollection process which guides the retrieval of items from the direct access region of WM[9] and provides more contextual information about when exactly the item was previously encountered (e.g., serial position). The quality of recollection directly depends on the strength of the bindings between the stimulus and the context in WM. Within this framework, PI represents a conflict in WM that is elicited when familiarity matching indicates that an item has been encountered before and thus competes for recognition, while the context-sensitive recollection process specifies that this item is old and does not belong to the to-be-memorized information (Jonides & Nee, 2006; Oberauer, 2005). Here, it is important to note that only the context-sensitive

[9] WM can be conceptualized as the activated part of long-term memory with a region of direct access where information is temporarily maintained in a directly accessible state (Oberauer, 2009).

recollection process depends on serial order (or, equivalently, position) memory in the sense that it involves memory representations of the items in their position of occurrence, whereas this is not the case for familiarity matching that just relies on the level of activation and is not context- or position-sensitive.

## CURRENT STUDY

The aim of the current study was to investigate whether people with dyslexia and normal reading controls cope differentially with task conditions that elicit PI. Knowing that recollection from memory relies on order information and based on the evidence that dyslexic individuals show serial-order memory deficits (Martinez Perez et al., 2012, 2013; Szmalec et al., 2011), we hypothesized that recollection is less efficient in dyslexia and therefore that people with dyslexia will be more susceptible to PI, compared with a matched control group.

We investigated this hypothesis by making use of a 2-back task with black and white line drawings. In the n-back task, PI occurs when a new item does not match the item *n* positions back but does match one of its neighbors (position n+1 or n-1). On these so-called *lure-trials* participants are typically slower and less accurate. The familiarity-matching process signals that the item has been encountered previously, and the recollection process is needed to override the misleading activation from the familiarity process by providing the contextual evidence that the item was not encountered in the targeted n-back position. When the number of lure trials in the task increases, and thus more PI is elicited, participants typically engage in top-down adaptation strategies, such as a stronger reliance on the context-sensitive recollection process than on item familiarity (Oztekin & McElree, 2007; Szmalec et al., 2010). Through these adaptation strategies the susceptibility to PI decreases.

To our knowledge, there have been only two memory studies using the n-back paradigm to investigate WM functioning in people with dyslexia (Beneventi, Tønnessen, Ersland, & Hugdahl, 2010; Sela, Izzetoglu, Izzetoglu, & Onaral, 2012). Using 0-back, 1-back and 2-back variants of the n-back task with letter stimuli, Beneventi et al. (2010) found that children with dyslexia compared with controls had poorer performance on both the 1- and 2-back task, but not on the 0-back task that required to respond to the presence of a single target. Sela et al. (2012) did not find these behavioral group differences when using the n-back task in an fNIR study with dyslexic university students (without phonological impairments) and matched controls, but did demonstrate lower maximum oxygenated hemoglobin levels in the left frontal lobe for the dyslexic group.

These findings point towards a WM deficit in dyslexia but, since WM demands were not further manipulated (e.g., through manipulations of PI by the introduction of lure trials as in our study), the cognitive mechanisms responsible for this decreased WM performance remain to be identified.

In the current experiment, we extend these findings by looking at performance of dyslexic adults on a 2-back picture task and, more importantly, by examining the influence that the introduction of lure trials has on performance. Participants had to complete two blocks of the n-back task: in the first block, only match and mismatch trials were presented; in the second block we introduced n+1 lure trials (see Figure 1). These trials cause PI and therefore in the final block the recollection process is challenged by a competing familiarity signal. We predicted that people with dyslexia will make more errors overall, which would generalize the results in dyslexic children of Beneventi et al. (2010). Most importantly, knowing that the introduction of lure trials necessitates a shift towards recollection and hence imposes higher demands on serial-order memory, we predict that 2-back performance will suffer more from the introduction of lure trials in the dyslexic group than in the matched control group.

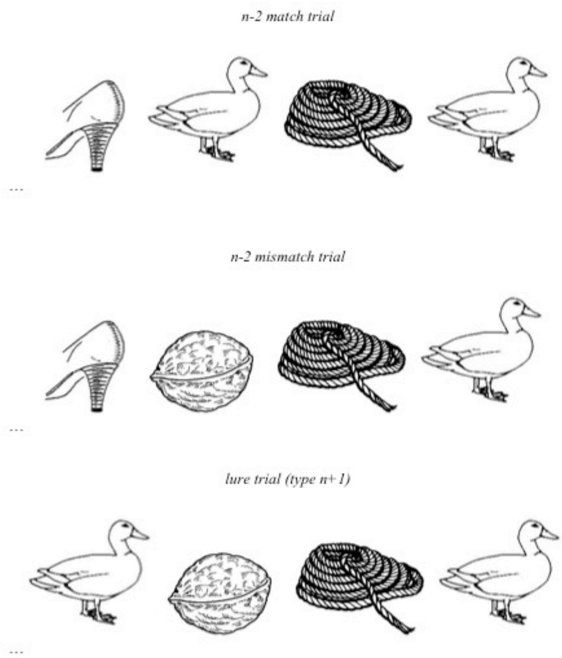


***Figure 1.*** **Visualisation of the three types of trials**.

## METHOD

### PARTICIPANTS

Twenty-five adults with dyslexia and 25 matched controls were paid for participation. All were native Dutch speakers enrolled in higher education. Certificates of dyslexia were obtained from the university's official diagnostic centre. For further validation, we administered the Eén Minuut Test (Brus & Voeten, 1979), assessing word reading proficiency, and the Klepel (van den Bos, Spelberg, Scheepsma, & de Vries, 1994), a nonword reading test. The two groups were matched on IQ using the Fluid intelligence subscales from the Flemish version of the Kaufman Adolescent and Adult Intelligence Test (KAIT; Dekker, Dekker, & Mulder, 2004; see Callens, Tops, & Brysbaert, 2012). Table 1 shows that individuals with dyslexia and controls are matched on age and intelligence and only differed on the reading tests.

***Table 1*. Means per group with standard deviations between brackets**.

| | *Control* (n=25) | *Dyslexia* (n=25) | Group difference |
|---|---|---|---|
| Age | 21.22 (1.50) | 20.60 (1.44) | *ns* |
| KAIT fluid | 109 (9.89) | 106.92 (10.93) | *ns* |
| EMT (words/1 min.) | 101.64 (10.46) | 83.29 (18.92) | $p < .001$ |
| Klepel (nonwords/1 min.) | 65.12 (12.41) | 44.71 (13.03) | $p < .001$ |

*Note.* Ns = not significant. Group differences were tested with a one-way ANOVA on *df*(1,48). KAIT = Kaufman Adolescent and Adult Intelligence Test, EMT= Eén Minuut Test.

## MATERIALS AND PROCEDURE

The n-back task was administered in the third session of a set of experiments. The material of the n-back task consisted of 25 black and white line drawings that provide high naming agreement in Dutch, based on the norming study by Severens, Lommel, Ratinckx, and Hartsuiker (2005). Naming agreement was above 74% for all pictures (M=89.04%) and their dominant name was always a monosyllabic word. Picture names had a length of two to five letters (M=3.84), a frequency range between 1 and 73 (M=30.35), log frequency 1-1.8633 (M=1.36). The selected materials can be found in the Appendix.

The *2*-back task consisted of two blocks of 94 trials each with a pause in the middle of each block (after 47 trials). Because this was a 2-back task, the first two trials of each block did not require a response, so that each block yielded 90 trials for analysis. The first block contained 30 match trials (i.e., the picture matched the picture presented two positions before) and 60 mismatch trials (i.e., the picture did not match the picture presented two positions before). The second block contained 13 n+1 lure trials (i.e., target item does not match the item two positions back but does match the item three positions back). There were 30 match trials, 47 mismatch trials and 13 lures in this last block, which means that we kept the number of yes and no responses equal across blocks. For all mismatch trials, we made sure that no item was repeated earlier than 17 trials after its last appearance, by which the risk for PI from a previous encounter with that item is minimized (Szmalec et al., 2010). The occurrence of a particular drawing on a match, mismatch or lure trial was counterbalanced across all stimuli. Once the list order was created it was fixed and was exactly the same for each participant.

Drawings were presented one at a time, centered on the computer screen. Each picture stayed on the screen for 2000ms and was followed by a blank screen for 1000ms. Participants were required to indicate as fast and accurately as possible whether a presented item matched the one presented 2 positions before by pressing the left (i.e., mismatch) or right key (i.e., match) on a response box. They were not informed about the presence of lures.

A practice block of 47 trials preceded the experiment and was run with the same ratio of mismatch and match trials as block 1, but 25 different (uncontrolled) pictures from the same database were used. This practice block did not contain lure trials.

## RESULTS

Mean reaction times (RTs; correct trials only) and accuracy, averaged over match and mismatch trials, are displayed in Figure 2 as a function of the Block type and Group.

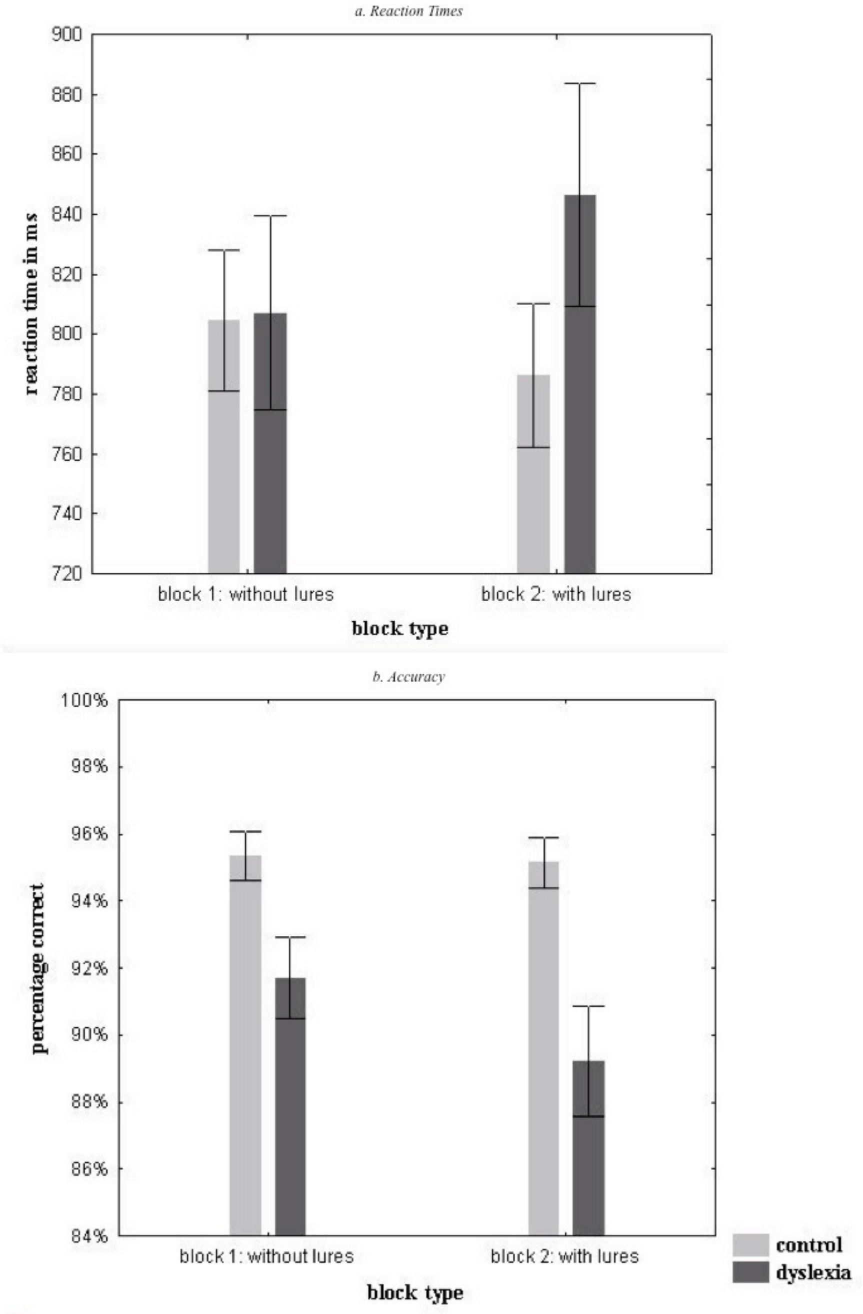


***Figure 2.*** **Graph with mean RTs and accuracies as a function of the block type and group.**

### RTs

RTs were averaged over match and mismatch trials and analyzed by means of an ANOVA with Block type (without lures vs. with lures) and Group (control vs. dyslexia) as predictors. There was no main effect of either Group or Block type (both $F<1$), but there was a significant interaction effect between Block type and Group; $F(1,45)=5.05$, $p<0.05$, $\eta^2=0.10$: the controls did not slow down significantly with the introduction of lure trials, $F(1,45)=1.10$, $p=0.30$, $\eta^2=0.02$, whereas the people with dyslexia did, $F(1,45)=4.40$, $p<0.05$, $\eta^2=0.09$ (see Figure 2a).

Planned comparisons further show no significant Group effect in both the block without lures ($F<1$) and the block with lures; $F(1,45)=1.97$, $p=0.17$, $\eta^2=0.04$.

Comparing RTs to lure trials versus the average of match and mismatch trials (within the block with lures) by means of an ANOVA with Trial type and Group as predictors, we observed a significant lure-effect. This is, slower RTs for lure trials (M=1045.67, SD=245.73) compared to the average of match and mismatch trials (M=814.33, SD=148.96), $F(1,45)=94.30$, $p<0.001$, $\eta^2=0.68$; there was however no main effect of Group nor a significant interaction between Trial type and Group ($F<1$).

### Accuracy

Accuracy was analyzed using the same ANOVA design. This yielded a significant main effect of Group across blocks, $F(1,45)=12.42$, $p < 0.001$, $\eta^2=0.22$: the dyslexic group (M=90.46%, SD=0.036) performed worse than the control group (M=95.24%, SD=0.056). The main effect of Block type was marginally significant, $F(1,45)=3.10$, $p=0.08$, indicating a trend towards worse performance for the block with lures (M=92.36%, SD=0.066) compared to the block without lures (M=93.64%, SD=0.05). Finally, the interaction effect between Block type and Group was not significant, $F(1,45)=2.26$, $p=.14$, $\eta^2=0.06$, but showed a trend similar to the RT results: the controls did not show a significant drop in accuracy with the introduction of lure trials, $F<1$, whereas the people with dyslexia did, $F(1,45)=5.00$, $p<0.05$, $\eta^2=0.10$ (see Figure 2b).

Planned comparisons further show that the Group difference was significant in both blocks: controls ($M_{block1}$=95.33%, $M_{block2}$=95.14%) were more accurate than the participants with dyslexia ($M_{block1}$=91.70%, $M_{block2}$=89.22%) in both blocks; $F(1,45)=7.08$, $p<0.05$ for block 1 and $F(1,45)=4.83$, $p<0.05$ for block 2 (see Figure 2b).

Also in terms of accuracy a significant lure-effect was observed, the accuracy for lure trials (M=77.57%, SD=0.24) being lower compared with match and mismatch trials (M=92.37%, SD=0.066), $F(1,45)=18.45$, $p<0.001$, $\eta^2=0.29$. Similar to the RT data neither a significant main effect of Group nor an interaction with Group was observed ($F<1$).

## DISCUSSION

The current study investigated whether people with dyslexia have problems coping with task conditions that elicit PI. Previous research proposed that the linguistic and non-linguistic problems associated with dyslexia may be best understood in terms of a core serial-order problem (Szmalec et al., 2011; Bogaerts et al., submitted). Since the context-sensitive recollection process that is used to overcome PI in an n-back updating task relies on a representation of the items in correct serial order, we hypothesized that recollection memory would be impaired in adults with dyslexia. In the current experiment, we compared their performance with that of a matched control group on a 2-back picture task with two blocks, one of which involved PI due to the use of lure trials. Importantly, the 2-back picture task has no reading component and also no speeded element (presentation times are two seconds per item with a one second inter-trial interval).

In the first block without lure trials (i.e., only match and mismatch trials were presented), adults with dyslexia showed lower accuracy than controls. This group difference in accuracy could be expected given that familiarity matching and recollection are known to operate in parallel during item recognition and therefore even the block without lures can be assumed to draw on serial-order processing to some extent. Moreover, it is consistent with the results of Beneventi et al. (2010), who investigated WM performance in dyslexic children using 0-, 1-, and 2-back variants of the n-back task, but all without lures.[10] In the second block, lure trials were introduced to increase PI and, as a consequence, increased the demands on order-sensitive recollection memory. In line with the predictions, our results demonstrate that the reading impaired group was more severely affected by the introduction of lure trials compared with the control group: the RTs of the control group did not slow down significantly with the introduction of lure trials, whereas they did for the dyslexic group. This contributed to a reliable interaction between group and task. A similar finding was seen for

[10] While our accuracy results in the block without lures are in line with the study of Benventi et al. (2010), we did not find a RT difference between groups on the 2-back task, whereas they did (see also Sela et al., 2012).

accuracy in as much as the introduction of lures caused a clear drop in accuracy rates only for the dyslexic group; however, the interaction in this case was not reliable. These results suggest that people with dyslexia have a particular problem with order-sensitive recognition memory that is engaged to efficiently cope with the PI introduced by the presence of lure trials in block 2. This is consistent with the predictions based on the hypothesis that dyslexia originates from an underlying deficit in serial-order memory (Szmalec et al., 2011). It also extends the recent findings on impaired short-term memory for order (Hachmann et al., in press; Martinez Perez et al., 2012, 2013) by showing similar problems with order memory within a WM updating paradigm.

Our use of nameable line drawings is a point that deserves some attention in the light of the problems with rapid automatized naming that are found in dyslexia (e.g., Norton & Wolf, 2012). Although it is possible that stimuli were named subvocally, a basic naming speed deficit in the dyslexic group cannot be an alternative explanation for our results. Any naming component is present to the same extent in both blocks of the experiment. If the dyslexic group had basic naming speed difficulties, one would expect a group difference in RT in both blocks, and this was not the case.

In contrast to what one might expect given that the dyslexic group is more affected by the introduction of lures, no significant interaction between Trial type (lure vs. match+mismatch) and Group was found within the lure block. It should however be noted that the lure trials were meant as a between-block manipulation, using only 13 trials of this type. Therefore, the lack of a significant interaction effect might be due to insufficient statistical power. A systematic investigation of the performance of people with dyslexia on lure-trials themselves deserves attention in future research.

We argue that the serial-order approach may be helpful to better understand why dyslexia is often also associated with memory and learning deficiencies outside the domain of language. First, the hypothesis of a deficit in serial-order memory in dyslexia can nicely frame the WM findings in people with dyslexia. Frequently used tasks for short-term memory performance, such as digit span and other serial recall tasks, confound item storage and short-term memory for the order of the respective items. The reports of reduced memory span in dyslexia (e.g., Kibby, Marks, Morgan, & Long, 2004; Smith-Spark & Fisk, 2007) can therefore be framed in terms of a problem with the sequential, or order, component in the task, an explanation that is supported by the recent studies which dissociated the order and item components of WM (Hachmann et al., in press; Martinez Perez et al., 2012, 2013). The results of the current study, suggesting an increased susceptibility to PI in adults with dyslexia, can also well be framed within a general hypothesis relating to serial-order retention.

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# APPENDIX

***Table A1.* Stimulus material.**

| Picture name Dutch | Picture name English |
|---|---|
| bad | bathtub |
| boot | boat |
| tak | branch |
| koe | cow |
| kast | dresser |
| eend | duck |
| ei | egg |
| veer | feather |
| vis | fish |
| spook | ghost |
| geit | goat |
| hak | heel |
| muis | mouse |
| nest | nest |
| peer | pear |
| bord | plate |
| vlot | raft |
| touw | rope |
| roos | rose |
| sjaal | scarf |
| stuur | steeringwheel |
| tent | tent |
| vaas | vase |
| noot | walnut |
| heks | witch |

# CHAPTER 4
## Linking memory and language: Evidence for a serial-order learning impairment in dyslexia[11]

The present study investigated long-term serial-order learning impairments, operationalized as reduced Hebb repetition learning (HRL), in people with dyslexia. In a first multi-session experiment, we investigated both the persistence of a serial-order learning impairment as well as the long-term retention of serial-order representations, both in a group of Dutch-speaking adults with developmental dyslexia and in a matched control group. In a second experiment, we relied on the assumption that HRL mimics naturalistic word-form acquisition and we investigated the lexicalization of novel word-forms acquired through HRL. First, our results demonstrate that adults with dyslexia are fundamentally impaired in the long-term acquisition of serial-order information. Second, dyslexic and control participants show comparable retention of the long-term serial-order representations in memory over a period of one month. Third, the data suggest weaker lexicalization of newly acquired word-forms in the dyslexic group. We discuss the integration of these findings into current theoretical views of dyslexia.

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[11] Bogaerts, L., Szmalec, A., Hachmann, W. M., Page, M. P. A., Duyck, W. (revised manuscript submitted for publication). Linking memory and language: Evidence for a serial-order learning impairment in dyslexia. *Research in Developmental Disabilities*.

## INTRODUCTION

### DYSLEXIA

Developmental dyslexia is commonly defined as a learning disorder characterized by persistent difficulties with reading and/or spelling despite adequate intelligence, education and sensory functions (World Health Organization, 2008; Lyon, Shaywitz, & Shaywitz, 2003). Although the above definition focuses on problems with reading and spelling, the literature on dyslexia reveals a strikingly broad scope of associated nonlinguistic dysfunctions. Examples include impaired short-term memory (e.g., Martinez Perez, Majerus, Mahot & Poncelet, 2012a), working memory (e.g., Gathercole, Alloway, Willis, & Adams, 2006; Smith-Spark & Fisk, 2007), implicit (sequence) learning (e.g., Lum, Ullman, & Conti-Ramsden, 2013; Pavlidou, Kelly, & Williams, 2010; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003), motor functions (e.g., Nicolson, Fawcett, & Dean, 2001) and sensory functioning (e.g., Stein, 2001, but see also Goswami, 2015).

The underpinnings of dyslexia remain a source of controversy. The influential phonological theory (Stanovich, 1988; Snowling, 2000) postulates that an impairment in the representation and processing of phonological information is the core underlying deficit in dyslexia. However, while phonological impairments are indeed found in a clear majority of the studies (Melby-Lervag, Lyster, & Hulme, 2012; Ramus & Ahissar, 2012; Ziegler & Goswami, 2005), the presumption of an etiological and causal role for these phonological problems in relation to reading is not without its critics (Blomert & Willems, 2010; Castles & Coltheart, 2004). Most importantly, there is evidence for a double dissociation between dyslexia and phonological deficits: some individuals with severe reading disability do not show a phonological impairment, while some children with an apparent phonological deficit nevertheless do achieve fluency in (word) reading (Paulesu et al., 2001; Wimmer, Mayringer, & Landerl, 2000). Moreover, it is unclear how some of the nonlinguistic impairments often associated with dyslexia (e.g., implicit learning or motor deficits) may be accounted for by phonological deficits. Perhaps as a result, diverse alternative theoretical accounts of dyslexia have been proposed (e.g., the automaticity/cerebellar deficit hypothesis, Nicolson & Fawcett, 1990; the anchoring-deficit hypothesis, Ahissar, 2007; the magnocellular theory, Stein, 2001) but a unifying framework that addresses the diversity of associated dysfunctions is still lacking (Pennington, 2006; Ramus et al., 2003). A recently introduced integrative hypothesis proposes that several of the associated dysfunctions observed in dyslexia arise from a deficit in memory for serial-order information (i.e., the order in which items are presented within a sequence; Szmalec, Loncke, Page, & Duyck, 2011). The present study builds on this novel hypothesis, which is explained in more detail later.

## SERIAL-ORDER MEMORY AND LANGUAGE

It is well known that both the immediate processing and the long-term learning of sequential information have relevance to language skills (Conway & Christiansen, 2001). First, there is the observation of a clear association between verbal immediate serial recall performance and the learning of novel phonological word-forms (Baddeley, Gathercole, & Papagno, 1998; Gathercole, Service, Hitch, Adams, & Martin, 1999; Gupta, 2003). At the theoretical level, models of short-term memory suggest that the encoding of item identity on the one hand, and serial order processing on the other hand, are distinct and dissociable functions (e.g., Burgess & Hitch, 1999, 2006; Gupta, 2003, 2008; Page & Norris, 2009). These models contend that verbal item-information is stored via temporary activation of long-term phonological and lexico-semantic representations, with a strength depending primarily on the quality of these long-term traces (see also Majerus & D'Argembeau, 2011). In contrast, the encoding of serial order occurs via a system that operates on items, over-and-above those processes used in their individual recognition. Several recent studies by Majerus and colleagues have highlighted the importance of the serial-order processing component of short-term memory (STM), in addition to memory for item identity, in relation to novel word-form learning (e.g., Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus & Bo ukebza, 2013) and literacy acquisition (Martinez Perez, Majerus, & Poncelet, 2012b).

Recently, Page and Norris (2008, 2009) explicitly related word learning to a memory framework by extending their computational model of verbal short-term memory (the primacy model, Page & Norris, 1998) to word-form learning. They proposed that the order-STM processes described above contribute to long-term learning of new phoneme sequences (and by extension novel lexical or orthographic representations) via a mechanism that is also seen operating in Hebb repetition learning (HRL). HRL refers to the observation that when a particular ordered sequence of stimuli is repeated several times over the course of an immediate serial recall task, people show gradually enhanced recall of that sequence —known as the *Hebb* sequence— relative to *filler* sequences in which stimuli appear in a random order (Hebb, 1961). In essence, HRL reflects how, through repeated presentation and recall, an ordered sequence of information in short-term memory gradually develops into a stable, long-term memory trace. In the framework of Page and Norris (2008, 2009), a new word-form is conceived as a familiarized sequence of sublexical components, such as phonemes or syllables (see also Gupta, 2008, for a similar view). HRL of a syllable sequence like "*lo fo du*" is therefore assumed to be functionally equivalent to acquiring the novel word-form "LOFODU", similar to the way in which children learn new words by picking up statistical regularities from the verbal input in their environment (e.g., Saffran et al., 1996). Experimental evidence for the hypothesis that HRL mimics naturalistic word-form acquisition was provided by Szmalec and colleagues (Szmalec, Duyck, Vandierendonck, Barberá-Mata, & Page, 2009; Szmalec, Page, & Duyck, 2012). In these experiments, that included only normal readers, participants typically had to recall nonsense sequences of nine visually presented consonant-vowel syllables (CVs), with each sequence grouped by short pauses into three three-CV groups (e.g., "fi ke da – sa mo pu – vo ti zu"). A Hebb sequence, presented every third trial, always contained the same three three-CV groups, in a random group-ordering. Participants showed clear HRL (i.e., improved recall of sequences whose groups repeated relative to filler sequences). After learning, auditory lexicalization tests showed that the three-CV groups that had been repeatedly presented and recalled, exhibited the properties expected of novel word-form entries in the mental lexicon. In summary, these studies suggest that HRL draws on the same memory processes responsible for representing and learning serial-order information in the service of language acquisition (i.e., novel word-form learning).

## DYSLEXIA AS A DIS-ORDER?

Drawing on the crucial role that serial order plays in language learning and processing, Szmalec et al. (2011) proposed a novel hypothesis relating to dyslexia, that we will call the "SOLID" (Serial-order Learning Impairment in Dyslexia) hypothesis. It offers an integrative account that clarifies how the problems encountered by people with dyslexia, not only in reading but also in other (nonlinguistic) tasks, may originate from a common underlying impairment in memory for serial-order information. Szmalec et al. demonstrated that dyslexic adults show reduced HRL, not only in verbal but also in visuospatial stimulus modalities. These data support the idea that people with dyslexia experience difficulties with serial-order learning and that these difficulties extend beyond the verbal domain (cf. the early work of Corkin, 1974; but see also Gould and Glencross, 1990).

Memory for serial order is also involved in tasks that have been traditionally used in the domain of statistical learning and implicit learning (see Perruchet & Pacton, 2006, for discussion). For example, in the Serial Reaction Time (SRT) paradigm (Nissen & Bullemer, 1987), participants are presented with sequences of visual stimuli, each appearing in one of four locations on a screen. They are required to press a particular key corresponding to a given location, each time a visual stimulus appears in that location. The serial order in which locations are occupied by the visual stimuli is probabilistically determined, and this regularity is learned implicitly by participants, as revealed by faster key-press reaction times for repeated sequences of locations. Memory for order is thus critical for performance in this task and it seems that, at least partly, similar order-learning mechanisms underlie performance in the Hebb repetition task and the SRT tasks (Page et al., 2006). In line with the SOLID hypothesis, a majority of studies using the

SRT paradigm have reported impaired implicit-sequence-learning abilities in individuals with dyslexia (see Lum et al., 2013 for a recent meta-analysis and Pavlidou et al., 2010, for converging evidence in artificial grammar learning).

One fundamental characteristic of most serial-order learning tasks is that they proceed over a relatively extended time period (Hedenius et al., 2013), tapping into the transfer between short and long-term memory. This characteristic is particularly important in the case of the Hebb paradigm. First, a sequence needs to be encoded and temporarily represented in short-term memory. Second, via repeated presentation and recall of the sequence, a long-term memory trace of the item- and order information in a given sequence is gradually established, as shown by increased recall accuracy over successive Hebb trials (for normal readers, learning in a traditional HRL task displays improvements of around 3-4% per repetition; Page & Norris, 2008). Third, with time, the long-term representations that develop throughout HRL become more robust and resistant to interference (i.e., they undergo memory consolidation). Previous studies in normal readers have shown measurable savings from earlier HRL in an unannounced test three months after learning (Page & Norris, 2008), supporting the claim that HRL is indeed long-term learning. In the case of verbal HRL, it is assumed that the learned sequence creates novel entries in the mental lexicon (Szmalec et al., 2009, 2012; see above). Szmalec et al. (2011) explicitly characterized their serial-order account as a ‘learning account’: the dyslexic disadvantage is assumed to exist at the stage of the long-term learning of serial-order information (rather than solely at the stage of short-term representation of this information, although data suggest such a short-term deficit too – see below). It is especially this type of learning that is assumed to be crucial for learning words from sequence regularities in the phonological (and orthographic, when learning to read) input from the environment. Note, however, that the study by Szmalec et al. (2011) focused exclusively on learning within a single session and only looked at learning with a relatively narrow practice interval (using only ten Hebb repetition trials). This leaves open the question of how people with dyslexia perform with more intensive repetition learning, and whether group differences can be found also in how well the learned sequential material is retained in memory over longer periods of time. It is possible that the dyslexic disadvantage affects not only learning, but also long-term retention of sequential verbal material. These questions, regarding performance after the initial learning stage, are addressed by the current study. They are particularly relevant given that people with dyslexia typically show therapeutic resistance (Vaughn, Thompson, & Hickman, 2003) and problems with automatization (i.e., the process by which skills gradually become so fluent that they no longer need conscious control, e.g., Nicolson et al., 2001). One recent study, that was unusual inasmuch as it investigated implicit sequence learning including long practice, is that by Hedenius et al. (2013). They tested the SRT performance of children with dyslexia and matched controls, including a first session with a large amount of practice and a second session on the subsequent day; this allowed them to investigate overnight consolidation. They reported an impairment in initial implicit sequence learning for dyslexics, but even more pronounced group differences in learning after extended practice. No group difference in the overnight retention of the learned material was observed.

Drawing on the assumption that verbal HRL relies on the same memory mechanisms that serve lexical acquisition (Page & Norris, 2008, 2009), and on the recent demonstration of impaired HRL in dyslexia, an additional important question is how an order-learning deficit may account for the language problems that are central to dyslexia, in particular the low reading achievement. Several recent models of reading stress the importance of the temporal alignment of the serial orthographic representations (i.e., letter position and identity) and phonological representations in reading acquisition (e.g., the SERIOL model, Whitney, 2001; the overlap model, Gomez, Ratcliff, & Perea, 2008). When encountering an as-yet-unknown orthographical word-form in an alphabetic language, a reader will typically use a decoding strategy through which s/he converts letters into the corresponding sounds[12], integrating a representation of the entire sequence of sounds into a single word-form (e.g., the dual route cascaded model, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Repeatedly processing the same sequence of letters will then gradually develop a lexical representation in the mental lexicon. The presence of such a representation allows more automatic and proficient processing of the (now known) letter string. In our view, the acquisition of novel orthographical and phonological

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[12] Alphabetic orthographies differ in the consistency of their grapheme-to-phoneme correspondence, ranging from highly consistent or 'transparent' (e.g., Finnish, Spanish) to inconsistent or 'opaque' (e.g., English, French). In the current paper we tested speakers/readers of Dutch. The Dutch orthography is considered relatively transparent since grapheme-to-phoneme correspondences are fairly consistent, but there are notable exceptions (e.g., /t/ written as d at the end of some words). Additionally, the letters a, o, e, and u can indicate either long or short vowels, depending on their location in a syllable (Patel, Snowling, & de Jong, 2004; Ziegler et al., 2010).

word-forms strongly relies on memory for serial information, and as a result, a deficit in serial-order learning would lead to problematic word-form (or lexical) learning. In line with the lexical-quality hypothesis (Perfetti, 2007), Szmalec et al. (2011) argued that if the order of the sublexical constituents of a newly learned word is not optimally consolidated as a single lexical entry in long-term memory, its lexical representation will be impoverished.[13] This, in turn, could impair lexical access for that entry, disrupt normal procedures for mapping grapheme sequences to phoneme sequences (Whitney & Cornelissen, 2005), and hence affect reading accuracy and fluency (Kuperman & Van Dyke, 2011; Perfetti, 2007). However, to our knowledge, no published research has tested whether the impaired long-term learning of verbal serial information for people with dyslexia is indeed associated with difficulties in acquiring novel lexical representations.

## CURRENT STUDY

The aim of the present study is threefold. First, we aim to investigate how resistant people with dyslexia are to serial-order learning: Is the Hebb learning impairment persistent (i.e., an ongoing capacity deficit) or can people with dyslexia, with more practice (in this case, more Hebb

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[13] As noted previously (p. 5), the short-term processing and storage of the (sublexical) item information is sensitive to the quality of verbal long-term memory representations (e.g., Gupta, 2003, Majerus et al., 2008). Less well-defined or noisy representations of the items themselves might therefore also (independently) contribute to difficulties in lexical learning and reading (e.g., Martinez-Perez, Majerus, & Poncelet, 2013).

repetitions), reach the same serial-order learning performance level as control participants, implying that learning is just slower in dyslexia? Second, we aim to distinguish between learning and retention deficits: Are people with dyslexia only impaired in serial-order learning or is the long-term retention of the acquired order representations also affected (i.e., there is faster degradation over time)? Third, we aim to make the link between memory and language impairments explicit, by investigating whether poor verbal serial-order learning in dyslexia also leads to poor lexicalization of the learned verbal sequences. We will, henceforth, refer to these three research goals as *resistance*, *retention* and *lexicalization*.

The present study reports two experiments. Experiment 1 covers the first two goals. It extends the previous examination of HRL in adults with dyslexia (Szmalec et al., 2011) by including not only an initial Hebb-learning session with a much larger number of Hebb repetitions (up to 20 in the current study vs. 12 in Szmalec et al., 2012) but also re-learning on the subsequent day and one month after initial learning. This allows us to estimate the retention of the learned Hebb sequences over time. Because the acquisition of natural language unfolds over time, HRL (as its hypothesized laboratory analogue) should therefore be tested longitudinally. In the control group, we expected to observe the well-replicated HRL effect, as well as significant retention of the Hebb materials across the re-learning sessions (Page & Norris, 2008). For people with dyslexia, we predicted not just slower Hebb learning but also a persistent impairment in HRL, despite the opportunity (in terms of number of repetitions) for substantial overlearning (i.e., we predicted *resistance*). We anticipated that people with dyslexia would be likely to benefit less from initial learning when asked to relearn the same Hebb sequences across sessions (i.e., we predicted lower *retention)*. This prediction is notwithstanding the fact that the only published study on overnight retention of sequential information in dyslexia (Hedenius et al., 2013) did not find such a group difference. Experiment 2 retested long-term retention of serial-order information, investigated in Experiment 1, now also controlling for possible task learning or strategic effects by contrasting the relearning of the previously learned Hebb list with the learning of a new Hebb list. It also addressed our third goal, which was to investigate the lexicalization of word-forms acquired through HRL and, for the first time, test whether, as we tentatively predicted, such lexicalization is worse for people with dyslexia.

## EXPERIMENT 1

## METHOD

### PARTICIPANTS

Twenty-five adults with dyslexia and 25 matched controls (participants were matched as groups) were paid for participation. All were native Dutch speakers enrolled in higher education. All participants with dyslexia had a history of dyslexia that dated back to childhood and had obtained an official diagnostic certificate of developmental dyslexia through a government-approved diagnostic center (vzw Cursief, Ghent, Belgium). Criteria for diagnosis implied a score below the 10th percentile on the Gletschr (De Pessemier & Andries, 2009), a validated instrument for assessing reading and writing abilities in Dutch. Subjects with reported comorbidities were not included. For further validation, we administered the Eén Minuut Test (Brus & Voeten, 1979), the standard Dutch word reading test, and the Klepel (Van den Bos, Spelberg, Scheepsma, & de Vries, 1994), the standard nonword reading test. The Eén Minuut Test consists of 116 words of increasing difficulty. The participant has to read aloud as many words as possible in one minute. Similarly, the Klepel contains 116 nonwords that follow the Dutch grapheme-phoneme correspondence rules. The participant has two minutes to read aloud as many nonwords as possible.

The two groups were matched on IQ using the fluid intelligence subscales (i.e., symbol learning, logical reasoning, secret codes, block patterns, delayed auditory memory, and delayed symbol learning) from the Flemish version of the Kaufman Adolescent and Adult Intelligence Test (KAIT; Dekker, Dekker, & Mulder, 2004; see Callens, Tops, & Brysbaert, 2012).

The order of the KAIT, EMT and Klepel was counterbalanced. Reading tests and KAIT were administered only to participants for whom these data were not available from a prior study (Callens et al., 2012). Two control participants were excluded from analysis: one had previously participated in a similar Hebb study and the other reported problems learning foreign languages. Table 1 shows that individuals with dyslexia and controls only differed on the reading tests.

***Table 1*. Participant Characteristics.** Means per group with standard deviations between brackets. Ns = not significant. Group differences were tested with a one-way ANOVA on df(1,46) for Experiment 1 and df(1,33) for Experiment 2. IQ = estimated total intelligence, EMT= Eén Minuut Test.

| | ***EXPERIMENT 1*** | | ***EXPERIMENT 2*** | | |
|---|---|---|---|---|---|
| | *Control* (n = 23) | *Dyslexia* (n = 25) | *Control* (n = 18) | *Dyslexia* (n = 17) | Group difference |
| Age (years) | 21.34 (1.52) | 20.60 (1.44) | 20.28 (1.02) | 21.35 (2.80) | *ns* |
| IQ | 109.00 (10.11) | 106.92 (10.93) | 108.18 (9.46) | 106.48 (12.13) | *ns* |
| EMT (words/1 min.) | 101.83 (10.44) | 83.29 (18.92) | 93.00 (9.43) | 73.52 (10.53) | $p < .001$ |
| Klepel (nonwords/1 min.) | 65.56 (12.50) | 44.71 (13.03) | 96.11 (11.07) | 62.24 (13.31) | $p < .001$ |

## MATERIALS AND PROCEDURE

### *Hebb learning*

The Hebb learning task was identical in all three sessions. In a Hebb learning block, sequences of nine consonant-vowel syllables (CVs) were presented visually for immediate serial recall. One particular sequence, the Hebb sequence, was repeated on every third trial (similar to Szmalec et al., 2011, 2012). On the other trials, the filler trials, the order of the syllables was randomized. To ensure that the Hebb task was sensitive only to learning order information and not to learning the individual items, all sequences (i.e., repeated and non-repeated) within a Hebb learning block were permutations of the same set of nine syllables. Each participant completed two Hebb learning blocks and thus learned two different Hebb sequences, yielding 6 different (three-syllable) pseudowords. HRL was terminated when the participant recalled two subsequent Hebb trials correctly, with a maximum of 20 Hebb repetitions. The Hebb sequences consisted of three three-syllable groupings that were unique neighbors of existing Dutch words (see Table 2). This allowed us to investigate lexicalization of the Hebb sequences through lexical competition. However, due to technical problems, the lexicalization test could not be performed in Experiment 1 and was therefore postponed until Experiment 2. The order of the CVs within the three-syllable subgroups was kept constant, but not the order of the entire nine-syllable Hebb sequence. For example, a legal Hebb "repetition" of the sequence *la-va-bu-sa-fa-ra-re-si-di* could be *re-si-di-la-va-bu-sa-fa-ra*. This procedure is in a sense more conservative than standard HRL (as the repetitions are not full repetitions) while it resembles more closely the task faced by a word-form learner, who is confronted over and over again with the same lexical elements, in different orders. Hence, the procedure allows participants to extract the three-syllable groupings from the nine-syllable sequences (i.e., statistical learning). In addition, a blank screen was presented for 500ms in between the three-syllable groupings (*la-va-bu* [blank] *sa-fa-ra* [blank] *re-si-di*) to facilitate extraction of the subgroups that overlap with the Dutch base-words. The filler sequences were constructed from the same CVs as the Hebb sequences, but the CVs were presented in a different random order on each trial. Figure 1 shows an example of a possible set of trials. On each trial, the nine CVs were presented for 500ms with an inter-stimulus interval of 0ms within the three-syllable groupings and 500ms between group boundaries. Immediately after presentation, a recall screen showed the nine CVs, arranged randomly in a "noisy" circle around a central question mark. Participants were instructed to recall the order of the CVs by clicking the items in the order of presentation and to click the question mark for omitted CVs. Note that this procedure allows participants to repeat a CV. However, it was not possible to recall an item that was not in the stimulus list. After the participant had clicked nine responses, he or she was able to advance to the next trial by pressing the spacebar.

In each of Sessions 2 and 3 the two Hebb sequences that the subject had learned during Session 1 were relearned. The order of the two Hebb sequences was counterbalanced.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ***F*** | fi | no | bu | ma | va | na | la | di | lo |
| ***F*** | va | la | fi | lo | na | no | di | ma | bu |
| ***H1*** | la | va | bu | fi | na | lo | no | ma | di |
| ***F*** | la | na | ma | bu | no | va | lo | fi | di |
| ***F*** | na | la | ma | va | di | no | fi | bu | lo |
| ***H2*** | fi | na | lo | la | va | bu | no | ma | di |
| ***F*** | va | lo | di | ma | no | na | fi | la | bu |
| ***F*** | fi | lo | no | bu | di | la | na | va | ma |
| ***H3*** | la | va | bu | fi | na | lo | no | ma | di |
| ***F*** | ma | la | lo | va | no | fi | na | di | bu |
| ***F*** | no | lo | la | di | va | fi | ma | na | bu |
| ***H4*** | fi | na | lo | la | va | bu | no | ma | di |
| ***F*** | la | no | di | na | fi | va | ma | lo | bu |
| ***F*** | va | ma | bu | lo | no | la | di | na | fi |

***Figure 1.*** **Visual depiction showing an example of a set of trials in the Hebb learning task.** In this example the learned lexical competitors are 'lavabo', 'finalo' and 'nomadi'. F= filler trial, H= Hebb trial.

***Table 2.* CVCVCV syllable sequences and overlapping base-words.**

| CVCVCV sequence | Base-word | Transcription | English Translation |
|---|---|---|---|
| bi-ki-na | bikini | /biˈkini/ | *Bikini* |
| fi-na-lo | finale | /fiˈnalə/ | *final* |
| fy-si-cu | fysica | /'fizika/ | *physics* |
| ho-re-co | horeca | /ˈhoreka/ | *catering* |
| ka-ra-to | karate | /ka'ratə/ | *karate* |
| la-va-bu | lavabo | /lava'bo/ | *kitchen sink* |
| la-wi-na | lawine | /laˈwinə/ | *avalanche* |
| li-bi-du | libido | /'libido/ | *libido* |
| me-ri-tu | merite | /me'ritə/ | *merit* |
| no-ma-di | nomade | /no'madə/ | *nomad* |
| pa-ra-di | parade | /paˈradə/ | *parade* |
| re-si-di | residu | /rezi'dy/ | *residue* |
| sa-fa-ra | safari | /saˈfari/ | *safari* |
| sa-la-du | salade | /saˈladə/ | *salad* |
| sa-la-mo | salami | /sɑ'lami/ | *salami* |
| sa-ti-ra | satire | /sɑˈtirə/ | *satire* |
| va-li-do | valide | /va'lidə/ | *valid* |
| vi-si-ti | visite | /vi'zitə/ | *visit* |

## RESULTS

### HEBB LEARNING

A CV was scored as correct if it was recalled in the correct position in the nine-syllable sequence. HRL in Session 1 was measured by taking the standardized gradient of the regression line through the points representing the performance on successive Hebb repetitions and comparing it with the corresponding gradient for the intermediate fillers, for each individual participant (see Page, Cumming, Norris, Hitch, & McNeil, 2006). The standardized gradient serves as a measure of the strength of learning (i.e., the steepness of the learning curve over repetitions), independent of the exact number of repetitions (as the number of repetitions was not the same for all participants).[14] Mean gradient values (average of the two Hebb learning blocks) are presented in Table 3. The mean gradient values were entered into an analysis of variance (ANOVA) with Sequence type (filler vs. Hebb) and Group (control vs. dyslexic) as independent variables. The results are summarized in Table 4. Crucially, we found a significant interaction between Sequence type and Group, $F(1,46) = 4.73$, $\eta_p^2 = 0.09$, $p < .05$. Planned comparisons indicate a HRL effect in both groups, however, HRL was significantly stronger for controls. Additionally, we looked at the number of repetitions required to

[14] As outlined by Staels and Van den Broeck (2014) a concern with the gradient measure of Hebb repetition learning is that the learning gradient (i.e., slope) tends to negatively correlate with initial performance (i.e., intercept). Note however that if anything such a negative correlation would work against our hypothesis as initial performance for the dyslexic group is expected to be either lower or comparable to initial performance in the control group.

reach the criterion of two subsequent correctly recalled Hebb trials. The number of repetitions was entered into an ANOVA with Session (session 1 vs. session 2 vs. session 3) and Group (control vs. dyslexic) as independent variables. We found a significant effect of Group, indicating that participants with dyslexia require more repetitions to reach the HRL criterion. Planned comparisons on this measure show that the effect of Group is significant in all three sessions. It is important to note that not all participants reached the criterion within the foreseen maximum of 20 repetitions and that the dyslexic participants reached the criterion less often than the control group. In Session 1, 48.0% of the participants with dyslexia failed to reach the recall criterion for at least one of the two repeating lists, despite considerable opportunity for learning, whereas controls had a failure rate of only 17.4%. In Session 2, this learning resistance was 36.0% and 0.0%, and in Session 3 24.0% vs. 0.0%, respectively.

Performance on the filler sequences (i.e., baseline recall performance, for the non-repeated items, measuring STM for order but not long-term serial-order learning) did differ significantly between groups, with the dyslexic group showing lower average performance (35.7%) than the control group (42.2%), $F(1,46) = 5.46$, $\eta_p^2 = 0.11$, $p < .05$. To test whether the Hebb learning impairment in dyslexia is robust against those baseline filler differences, we compared the Hebb learning effect (i.e., gradient Hebb – gradient filler) as well as the number of repetitions required to reach criterion between the two groups (control vs. dyslexic) in an analysis of covariance (ANCOVA), including average filler performance as a covariate. Because we had precise theoretically grounded predictions regarding the direction of this effect, one-tailed p-values are reported. The group difference in HRL was replicated using both the gradient measure, $F(1,45) = 3.31$, $\eta_p^2 = 0.07$, $p < .05$, and the number of repetitions measure, $F(1,45) = 9.76$, $\eta_p^2 = .18$; $p < .01$), when filler performance was covaried out. This suggests that weaker HRL for people with dyslexia is not, or not only, due to worse baseline (short-term) memory capacity.

***Table 3.*** **Top panel: Mean standardized gradient values for both groups as a function of experiment (experiment 1 vs. experiment 2) and sequence type (filler vs. Hebb). Lower panel: Number of Hebb repetitions, averaged over the two Hebb sequences, for both groups as a function of delay after Hebb learning (0h in Session 1 vs. 24h in Session 2 vs. one month in Session 3).**

| | ***EXPERIMENT 1*** | | ***EXPERIMENT 2*** | |
|---|---|---|---|---|
| | *Control* | *Dyslexia* | *Control* | *Dyslexia* |
| *Gradient* | | | | |
| filler | -0.04 (0.32) | 0.03 (0.25) | 0.03 (0.41) | 0.16 (0.19) |
| Hebb | 0.60 (0.22) | 0.41 (0.30) | 0.57 (0.23) | 0.43 (0.26) |
| *Number Hebb Repetitions to criterion* | | | | |
| Session 1 | 9.41 (5.21) | 13.86 (5.70) | 7.58 (5.91) | 16.58 (6.29) |
| Session 2 | 3.70 (1.90) | 9.30 (7.07) | / | / |
| Session 3 | 4.22 (3.18) | 7.52 (6.09) | 3.38 (2.93) | 7.82 (6.88) |

## RETENTION

In order to estimate retention of HRL, independently of initial learning differences, we subtracted performance on the first Hebb trial in Session 2 from performance on the final Hebb trial in Session 1 for each participant. This difference was divided by the end performance of Session 1 to obtain a proportional measure of saving. The same was done for savings between Session 2 and Session 3. Figure 2a depicts the mean proportion of correctly recalled Hebb items on the different points in time (end performance Session 1 vs. start performance Session 2; end performance Session 2 vs. start performance Session 3) for dyslexic participants and controls. The graph clearly shows learning differences, but the lines for both groups that reflect saving are almost perfectly parallel. Planned comparisons on these two relative retention measures show no significant effects of group, both *F*s < 1, indicating comparable retention for both groups, both 24h and one month after HRL (see Table 4).

One could argue that whereas the two groups show parallel savings (see Figure 2a), the individuals with dyslexia are losing a greater proportion of what they initially attained. A second analysis therefore examined the degree of retention when fully equating the degree of acquisition across the two groups by including only those participants who reached the criterion of two subsequent correctly recalled Hebb trials in the first session ($n_{control} = 20$, $n_{dyslexic} = 12$). Figure 2b shows the retention graphs for these subgroups. Planned comparisons indicate again comparable retention for the two groups, both 24h and one month after HRL, *F*s < 1, which strengthens our conclusion of comparable retention for both groups.

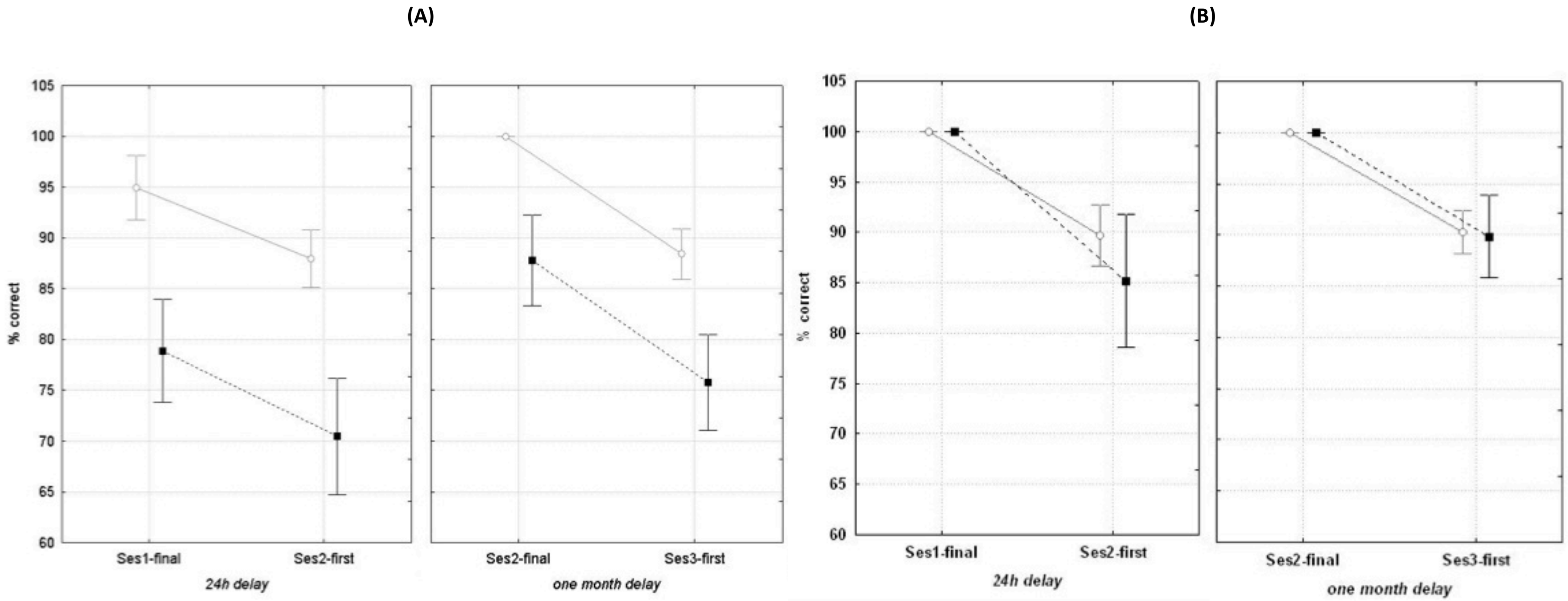


***Figure 2.*** **Retention of the Hebb material.** (A) Mean proportion of correctly recalled Hebb items on the different points of time for dyslexic participants (black squares) and controls (white circles). Error bars denote standard errors. Left panel: final Hebb trial Session 1 vs. first Hebb trial Session 2, right panel: final Hebb trial Session 2 vs. first Hebb trial Session 3. (B) Same retention graphs when including only those participants who reached the learning criterion in Session 1.

***Table 4.*** **Overview statistical tests Experiment 1.** Df(1,46) and df(2,92). Group = control vs. dyslexic; Sequence type = filler vs. Hebb; Delay = 24h vs. one month. °p≤.1; *p≤.05; **p≤.01; ***p≤.001. PC = Planned Comparisons.

| ***Hebb learning: ANOVA with gradients*** | *F* | $\eta_p^2$ |
|---|---|---|
| Group | 1.00 | .02 |
| Sequence type | 74.62*** | .62 |
| Sequence type * Group | 4.73* | .09 |
| ***Hebb learning: PC with gradients*** | | |
| Sequence type in Controls | 56.12*** | .55 |
| Sequence type in Dyslexics | 21.80*** | .32 |

| ***Hebb learning: ANOVA with number of repetitions*** | *F* | $\eta_p^2$ |
|---|---|---|
| Group | 11.52** | .20 |
| Session | 47.67*** | .51 |
| Session * Group | 1.58 | .03 |
| ***Hebb learning: PC with number of repetitions*** | | |
| Dyslexics vs. Controls in Session 1 | 7.91** | .15 |
| Dyslexics vs. Controls in Session 2 | 13.53*** | .23 |
| Dyslexics vs. Controls in Session 3 | 5.41* | .11 |

| ***Retention: ANOVA relative subtraction measure*** | *F* | $\eta_p^2$ |
|---|---|---|
| Group | .50 | .01 |
| Delay | .70 | .01 |
| Delay * Group | .44 | .01 |
| ***Retention: PC relative subtraction measure*** | | |
| Dyslexics vs. Controls for Delay 24h | .37 | .01 |
| Dyslexics vs. Controls for Delay 1month | .60 | .01 |

## DISCUSSION

The aim of Experiment 1 was to examine HRL impairment in dyslexic adults including not only an initial learning session with a large number of Hebb repetitions, but also further learning on the subsequent day and one month after initial learning. This allowed us to investigate how resistant people with dyslexia are to long-term serial-order learning, and also to estimate the retention of the learned Hebb sequences over time.

First, the results of Experiment 1 show that the impairment in serial-order learning is genuine in the sense that people with dyslexia are resistant to Hebb learning of syllable sequences. Our participants with dyslexia needed substantially more repetitions to develop an effective long-term representation of the Hebb sequences and several dyslexics even failed to fully develop this long-term serial-order representation despite the large number of repetitions. Clear group differences were observed, not only for HRL in the first session, but also for further practice on day two and after one month. In contrast to Szmalec et al. (2011), the two groups of the current study did differ in their filler performance, suggesting a group difference in short-term memory for order information. However, when we controlled for this baseline difference by analyzing the results with an ANCOVA, controlling for average filler performance, the finding of impaired serial-order *learning* in dyslexia remained reliable on both measures.

Secondly, dyslexic and control participants showed comparable retention when relearning the Hebb sequences both 24h and one month after initial learning. This suggests that, although serial-order learning is slower and weaker, the representations that are eventually learned seem to stand the test of time rather well, at least for a retention period of one month.

## EXPERIMENT 2

Experiment 2 seeks to replicate the findings about impaired long-term retention of serial-order information observed in Experiment 1, now also controlling for possible task-specific or strategic effects by contrasting the relearning of the previously learned Hebb list with the learning of a new Hebb list one month after initial learning. Furthermore, we assessed lexical engagement of word-forms acquired through HRL in people with dyslexia. With this aim, participants again learned Hebb sequences (e.g., la-va-bu-sa-fa-ra-re-si-di), containing lexical competitors (e.g., lavabu, safara, residi) of existing Dutch base-words (e.g., lavabo [kitchen sink], safari [safari], residu [residue]). Inherent to the use of the lexical competition approach is the requirement that Hebb sequences closely resemble known words represented in the mental lexicon. Importantly, the earlier studies using this lexical competitor approach (Szmalec et al., 2012) have demonstrated that this yields Hebb learning curves (for normal readers) comparable to standard verbal Hebb learning curves (Szmalec et al., 2009, 2011, 2012), suggesting that the learning of syllable sequences derived from existing words does not seem to rely on strong support from these words. This might be due to the fact that the Hebb procedure exposes the participant to individual syllables, presented one by one, while the gradual and implicit grouping of those syllables into pseudoword-forms is only the outcome of the Hebb learning process. Also note that impaired Hebb learning with dyslexic participants has been demonstrated before with Hebb learning of syllable sequences that did not overlap with existing words (Szmalec et al., 2011).

We tested for lexical engagement of the acquired representations immediately and again one month after HRL. Lexical engagement refers to the interaction of a novel word-form with existing entries in the mental lexicon (Gaskell & Dumay, 2003). The current study assesses the lexical engagement of the new phonological representations using a pause detection (PD) task on the overlapping Dutch base-words (Gaskell & Dumay, 2003; see also Szmalec et al., 2012). In a PD task, participants detect an artificially embedded pause in connected speech. Mattys and Clark (2002) demonstrated that the speed at which this artificial pause can be detected, depends on the overall amount of lexical activity caused by the speech preceding this pause. For example, words with a late uniqueness point (e.g., blackberry) that have a pause inserted near the end of the word (blackb_erry), will, during processing of the onset syllables, activate several lexical representations (e.g., blackbox, blackbird, blackboard, etc.). The activation of multiple lexical candidates consumes processing resources that could otherwise be allocated to the detection of the pause. Therefore, the PD time is a function of the number of phonological neighbors (or, by extension, lexical competitors) of the target word, which makes the task a good test of the lexicalization of newly acquired neighbors (Mattys & Clark, 2002; Szmalec et al., 2012).

In line with the results of Experiment 1, we anticipated comparable *retention* of the Hebb materials for both groups. Regarding the test of *lexicalization*, we predicted that the control group should show slower PD times on the existing Dutch base-words, neighbors of the newly created lexical entries, compared with a set of matched control words; this would indicate lexical competition from representations of the Hebb (sub)sequences. Knowing that lexical consolidation of Hebb sequences requires time (Szmalec et al., 2012), we particularly expected lexical engagement effects in Session 2. Finally, we predicted reduced lexical competition from the Hebb sequences for the dyslexic group.

## METHOD

### PARTICIPANTS

Eighteen adults with dyslexia and 18 matched controls were paid for participation. Criteria for inclusion were identical to Experiment 1. We administered literacy with the Eén Minuut Test and the Klepel. The two groups were again matched on IQ using a short-form IQ measure (Turner, 1997), including the subscales Similarities, Comprehension, Block design and Picture completion from the Wechsler Adult Intelligence Scale (3rd ed.; Wechsler, 1998). One dyslexic participant failed to complete Session 2. Table 1 shows that for this sample too, individuals with dyslexia and controls only differed on the reading tests.

### MATERIALS AND PROCEDURE

*Hebb learning*

The materials in the Hebb task were identical to those in Experiment 1. The procedure was almost identical; the only difference was that in Session 1 there was an imposed minimum of 18 Hebb repetitions (i.e., 54 trials in total) that all participants had to complete, independent of their performance. We opted for this fixed minimum in order to boost HRL for the dyslexic group, but keeping the amount of exposure comparable between the two groups in the light of the subsequent lexicalization test. The maximum number of Hebb repetitions was 24 (i.e., 72 trials). In other words, each participant received between 18 and 24 repetitions of the Hebb sequence.

In Session 2, every participant was presented with one old (i.e., previously learned) and one new Hebb sequence. The order of the new and old sequence was counterbalanced and the old Hebb sequences were chosen so that half of the participants relearned the first Hebb sequence from Session1 whereas the other half relearned the second Hebb sequence from Session1. Small changes were applied to the procedure of the Hebb learning task in Session 2 to disrupt, as far as possible, the use of an explicit learning strategy: the first five trials were filler sequences and the Hebb sequence was repeated every fourth trial instead of every third trial. Additionally, the pauses between the three three-syllable subgroups were omitted and the presentation rate of the individual CV's was extended to 1000ms. The minimum number of Hebb repetitions in Session 2 was 12 and the maximum 18.

*Pause detection*

In the PD task, identical to the task used by Szmalec et al. (2012), 50 words were randomly presented once with, and once without, an embedded 150ms pause. Twenty-five words had a CVCVCV structure: the base-words, the control words and filler words. The critical materials were 18 trisyllabic base-words, that is, the lexical competitors of the 18 nonword Hebb sequences. In order to maximize potential (cohort-based) interference effects of the newly learned lexical competitor, the base-words differed from the nonwords only in their final letter (i.e., there was a late uniqueness point) and only words that had no existing lexical neighbors in Dutch were chosen (see Table 2). The 18 base words had a mean frequency of 2.77 (occurrences per million, as per Duyck, Desmet, Verbeke & Brysbaert, 2004). Because two Hebb lists were learned, each containing three 3-syllable nonwords, each participant had 6 base-words. The same words constituted the control condition for some participants, while serving as the lexical competition condition for others. Word frequencies of base- and control words were matched.

The words were presented through headphones (60 dB). The presentation time was 800ms (pause-absent) or 950ms (pause-present), with a 2500ms interstimulus interval (see Szmalec et al., 2012, for further stimulus details). Participants had to decide as accurately and quickly as possible whether a pause was present or not by pressing one of two buttons. In the pause-absent trials, RTs were measured from the same point at which the pause was inserted in the pause-present condition.

## RESULTS

### HEBB LEARNING

The scoring procedure was identical to the one used in Experiment 1: a CV was scored as correct if it was recalled in the correct position in the sequence. Mean gradient values (average of the two Hebb learning blocks in Session 1, the gradient was calculated on performance till the criterion of two subsequent correctly recalled Hebb trials was reached) were entered into an ANOVA with Sequence type (filler vs. Hebb) and Group (control vs. dyslexic) as independent variables (see Table 5 for a summary of the results). In line with the results of Experiment 1, a significant interaction was found between Sequence type and Group, $F(1,34) = 5.52$, $\eta_p^2 = 0.14$, $p < .05$. Additionally, we looked at the number of repetitions required to reach the criterion of two subsequent correctly recalled Hebb trials. Planned comparisons on this measure show a significant effect of Group in Session 1 as well as Session 2, indicating that participants with dyslexia show reliably slower HRL.

In Session 1 not all participants reached the criterion within the foreseen maximum of 24 repetitions, with a clear disadvantage for the dyslexic group: 61.1% of the participants with dyslexia failed to reach the recall criterion before or on repetition 24 (for at least one of the two repeating lists), controls had a failure rate of only 5.6%. For the old (i.e., to be relearned) Hebb list in Session 2, learning resistance was 27.8% for the dyslexic group versus 0.0% for the control group (maximum of 18 repetitions).

Performance on the fillers did differ significantly between groups. Again, the dyslexic group showed lower average performance (41.4%) than the control group (52.1%), $F(1,33) = 9.90$, $\eta_p^2 = 0.23$, $p < .005$. As for Experiment 1, we tested whether the group difference in Hebb learning is robust against the observed filler differences by including average filler performance as a covariate in an ANCOVA. The number of repetitions required to reach the criterion was, as expected, significantly higher for the dyslexic group, while for the gradient measure the group effect just failed to reach significance (respectively $F(1,32) = 6.02$, $\eta_p^2 = 0.16$, $p < .01$. and $F(1,33) = 2.40$, $\eta_p^2 = 0.07$, $p = .05$, p-values both one-tailed).

## Retention

First, we compared initial performance (i.e., performance on the first Hebb trial) on the new versus the old Hebb sequences learned in Session 2. Savings are in this case reflected as better performance on the old compared to the new Hebb sequence. An ANOVA with Hebb List (new vs. old) and Group (control vs. dyslexic) as independent variables, and the initial performance on the Hebb sequence in Session 2 as the dependent variable showed a main effect of group, with lower performance for the dyslexic group ($M(new)_{control} = 77.2\%$ , SD = 27.9, $M(old)_{control} = 92.0\%$ , SD = 13.6 ;

$M(new)_{dyslexia}$ = 56.9%, SD = 30.7 ; $M(old)_{dyslexia}$= 60.1%, SD = 24.2). We observed a marginally significant effect of Hebb List, with on average higher performance for the old Hebb sequence. Crucially, however, we did not find a significant interaction between Hebb List and Group (see Table 5). Second, we looked at the difference of the number of repetitions needed for reaching criterion for the new vs. old sequence. A positive number (i.e., more repetitions for the new Hebb sequence compared to the old) indicates the benefit of re-learning, in other words, savings. No group difference was found whatsoever, $F < 1$ ($M_{control}$= 2.66, SD = 5.42 ; $M_{dyslexia}$= 3.35 SD = 5.11). The results on both measures indicate that retention did not differ for both groups over the period of one month.

## LEXICALIZATION

Mean RTs for the different conditions of the PD task are presented in Table 6. The lexical competition effect (i.e., RTs for base-words minus RTs for control words) is depicted in Figure 3. RTs were averaged across pause-present and pause-absent trials (cf. Dumay & Gaskell, 2007). RTs under 100ms and outliers (+-2.5 SDs) were removed (2.6% of data). Because only the difference between the base-words and control words is of theoretical interest, and we expected the difference to arise only in Session 2, t-tests are reported as a measure of lexical engagement within each session, and for both groups separately. In the control group, we observed evidence for lexical engagement of the Hebb sequences in Session 2, $t(16) = 2.14$, $d = 1.7$, $p < .05$; but not in Session 1, $t(16) = 0.44$, $p = .66$. In the group with dyslexia, there was no reliable evidence for lexical engagement in either of the two sessions, Session 2, $t(15) = 0.68$, $p = .51$; Session 1, $t(15) = 0.001$, $p = .99$. It should be noted that even in Session 2, where we find, for control participants, the reliable lexical competition from newly learned Hebb sequences that we expected based on prior research, the interaction of this competition effect with Group (control/dyslexia) did not reach significance, $F(1,31) = 1.34$, $p = .26$. Given the nature of the competition effect, which is itself difficult to observe, the statistical power available to detect the interaction term is necessarily limited here. For this reason, the lack of a competition effect in either session for the dyslexic group must be seen as suggestive rather than definitive.

Accuracy on the PD task did not differ between the two groups ($M_{control}$ = 83.6%, $M_{dyslexia}$ = 81,8%), $F(1,31)= 2.00$, $p = .16$. No significant accuracy differences between the base and control words were observed, $F < 1$.

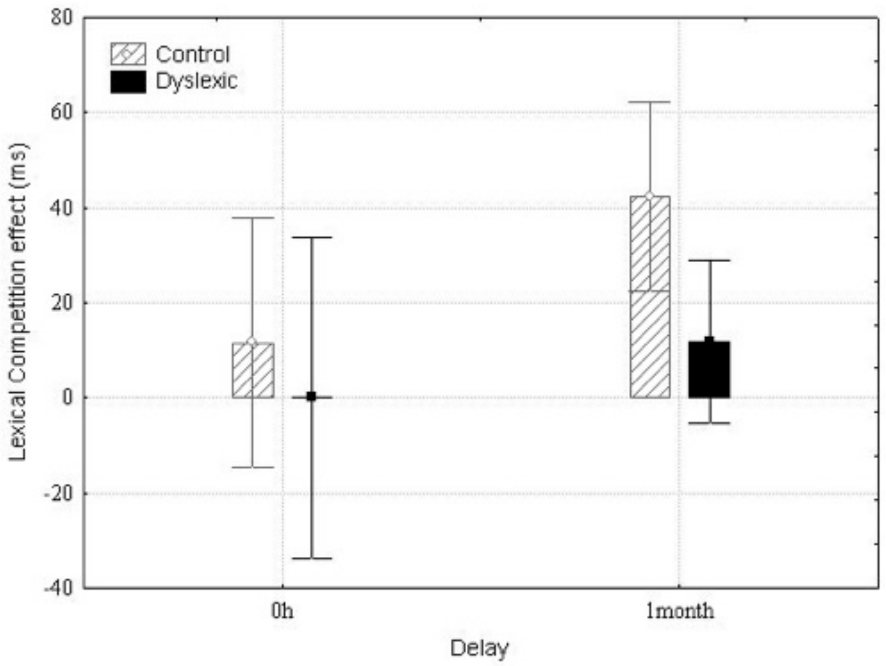


***Figure 3.* The lexical competition effect (i.e., base-words minus control words) in Experiment 2 as a function of group and delay after Hebb learning.** Error bars denote standard errors.

***Table 5.* Overview statistical tests Experiment 2.** Df(1,34) and df(2,68) / df(1,33) and df(2,66) for analysis that include Session 2. Group = control vs. dyslexic; Sequence type = filler vs. Hebb; Hebb List= new vs. old. °p≤.1; *p≤.05; **p≤.01; ***p≤.001.

| ***Hebb learning: ANOVA with gradients*** | *F* | $\eta_p^2$ |
|---|---|---|
| Group | .00 | .00 |
| Sequence type | 50.52*** | .60 |
| Sequence type * Group | 5.52* | .14 |

| ***Hebb learning: ANOVA with number of repetitions*** | | |
|---|---|---|
| Group | 16.13*** | .33 |
| Session | 43.37*** | .57 |
| Session * Group | 5.39* | .14 |
| ***Hebb learning: PC with number of repetitions*** | | |
| Dyslexics vs. Controls in Session 1 | 18.43*** | .36 |
| Dyslexics vs. Controls in Session 2 | 6.27* | .16 |

| ***Retention: ANOVA with initial performance new vs. old Hebb*** | | |
|---|---|---|
| Group | 14.87** | .31 |
| Hebb List | 3.27° | .09 |
| Group*Hebb List | 1.33 | .04 |

| ***Retention: ANOVA with difference in number of repetitions (new-old)*** | | |
|---|---|---|
| Group | 0.15 | .00 |

***Table 6.* Mean reaction times (RT; milliseconds) for base-words and control words as a function of delay after Hebb learning (0h and 1 month) for dyslexic participants and control participants.** Standard deviations are in parentheses.

| | *Control* | | *Dyslexia* | |
|---|---|---|---|---|
| | 0h | 1month | 0h | 1month |
| Base | 514 (173) | 516 (158) | 609 (197) | 577 (122) |
| Control | 503 (153) | 473 (145) | 609 (197) | 565 (117) |

## DISCUSSION

The first aim of Experiment 2 was to further examine the long-term retention of serial-order information in adults with dyslexia and normal reading controls by contrasting the relearning of the previously learned Hebb list with the learning of a new Hebb list. The second aim was to assess the lexicalization of Hebb sequences in people with dyslexia.

First, the finding of impaired Hebb learning, demonstrated in Experiment 1, was replicated. Clear group differences could be observed on the gradient measure of Hebb learning. When looking at the number of repetitions, we observed that people with dyslexia needed almost twice as much Hebb repetitions to reach the learning criterion (i.e., two subsequent correctly recalled Hebb trials) in all of the learning sessions. Second, we measured retention by comparing the initial performance on a new and an old Hebb list one month after HRL and by looking at the difference in number of repetitions needed to reach criterion on the new vs. the old list. We did not observe a group difference on either measure of retention. Third, lexicalization of Hebb sequences appeared to be less robust for dyslexic participants, though this conclusion needs to be qualified by the absence of an interaction moderating the size of the lexical competition across subject-groups. For the control group, the newly learned sequences of syllables (e.g., *la-va-bu, sa-fa-ra, re-si-di)* did not engage in lexical competition immediately after learning, but they did engage in lexical competition with known base-words (e.g., *lavabo, safari, residu*) after one month. This is consistent with previous work in normal reading adults (Szmalec et al., 2012), though the extension to a retention period of one month is novel. In the group with dyslexia however, lexicalization of the Hebb materials did still not occur after 1 month.

## GENERAL DISCUSSION

The present study investigated long-term serial-order learning in dyslexia. We focused on extended learning beyond a short, single (Hebb) serial-order learning session, on the long-term retention of serial-order information in memory, and on the relationship between HRL and lexicalization in a dyslexic population. Overall, our results demonstrate that people with dyslexia are fundamentally impaired in the acquisition of serial-order information. More specifically, dyslexic participants needed more repetitions to develop long-term representations of the phonological Hebb sequences. Moreover, even following more extensive repetition, a substantial number of participants with dyslexia failed to transfer the syllable sequences to long-term serial-order memory. Second, our findings suggest that the difficulty with serial order is indeed related to the initial serial-order acquisition phase rather than to the long-term retention of an acquired serial-order representation. Finally, people with dyslexia seemed to show less robust lexicalization of the newly acquired word-forms, although this effect was statistically less strong. Whereas the newly learned sequences of syllables (e.g., la-va-bu, sa-fa-ra, re-si-di) resulted in lexical competition with known base-words (e.g., lavabo, safari, residu) for normal readers, this lexicalization of Hebb sequences could not be observed in the group with dyslexia.

Natural language is sequential in nature. Typically, a limited number of phonemes or graphemes form different words, depending on their order, and these words in turn are sequentially aligned to form sentences. Long-term acquisition of serial-order information is therefore a critical component for extracting regularities from the phonological (and, by extension, orthographic) input which constitutes a given linguistic environment (see Aslin & Newport, 2012) and for learning new word-forms (Page & Norris, 2008, 2009; Szmalec et al., 2009, 2012). This rationale has been the basis of the Serial-Order Learning Impairment in Dyslexia (SOLID) hypothesis; an integrative account that proposes that both the linguistic and nonlinguistic dysfunctions in dyslexia could reflect a central deficit in serial-order learning. Previous work (Szmalec et al., 2011) indeed reported that adults with dyslexia show reduced HRL, across verbal and visuospatial modalities.

The current study extends the earlier findings of Szmalec et al. (2011) showing that people with dyslexia are fundamentally impaired in the *long-term acquisition* of verbal serial-order information, even following a substantially increased amount practice (i.e., a high number of Hebb repetitions). The finding that dyslexia appears to be associated with a fundamental serial-order *learning* deficit, more than a *retention* deficit, converges with recently reported data showing comparable overnight retention by dyslexic children in the context of the Serial Reaction Time (SRT) task (Hedenius, 2013). A learning, rather than a retention, deficit in dyslexia has also been shown in paired-associate word learning (e.g., Otto, 1961; Messbauer & deJong, 2003).

Our findings point towards a possible theoretical link between impaired Hebb learning and impaired language learning. Within our view, serial-order learning underlies new word-form acquisition. The observation that lexicalization of Hebb sequences was reliable for the control group, but not so for the group with dyslexia, suggests that problems with serial-order learning may be seen as a symptom of dyslexia that leads to impaired lexical representations (we acknowledge again, though, the lack of a reliable interaction here and, therefore, the need to strengthen this statistical claim in future work). This account converges with the reported difficulties of pseudoword learning in dyslexic children (e.g., Otto, 1961; Mayringer & Wimmer, 2000; Messbauer & deJong, 2003) and adults (Di Betta & Romani, 2006). Poor lexical quality, in turn, affects reading and spelling performance (see Perfetti, 2007). A serial-order account of dyslexia can therefore go some way to explaining the problems with reading and spelling characteristic of dyslexia. Interestingly, poor verbal HRL and impaired learning of motor sequences (in contrast to unimpaired performance on non-sequential procedural motor learning) has also been demonstrated in children with a Specific Language Impairment (SLI), diagnosed when oral language lags behind (Hsu & Bishop, 2014). Recent research suggests that SLI and developmental dyslexia can best be treated as distinct, yet closely associated and potentially comorbid, language disorders (see Bishop & Snowling, 2004; Catts, Adlof, Hogan, & Ellis Weismer, 2005). On the one hand, oral language deficits are commonly reported in children with dyslexia (e.g., McArthur et al., 2000; Starck & Tallal, 1988). On the other hand, high rates of literacy problems are reported in children with SLI (e.g., Conti-Ramsden, Botting, Simkin, & Knox, 2001; Haynes & Naidoo, 1991; Tallal, Allard, Miller, & Curtiss, 1997), consistent with the link between lexicality and literacy explained above.

Importantly, the serial-order account (Szmalec et al., 2011) provides a useful perspective for understanding both the language impairments in dyslexia and the variety of nonlinguistic related dysfunctions that have been consistently reported throughout the years. Although not always explicitly recognized, the serial-order learning mechanisms that are the focus of this study, also constitute the basis of the experimental tasks that have been used to assess working memory (e.g., short-term serial recall or span task), implicit sequence learning (e.g., SRT task)[15], artificial grammar learning, or sensorimotor (e.g., forced-choice paradigm) impairments in dyslexia. The current findings demonstrate verbal memory impairments in dyslexia, they are therefore not necessarily incompatible with the idea of a verbal processing deficit (see also Vellutino, 1977) and with the phonological theory of dyslexia (Stanovich, 1988; Snowling, 2000). However, previous demonstrations of sequence-learning impairments for people with dyslexia in non-linguistic tasks (e.g., visuospatial Hebb learning, Szmalec et al., 2011; Bogaerts, Szmalec, De Maeyer, Page, & Duyck, submitted; SRT task, Lum et al., 2013), seem to challenge the view that a selective

[15] Note that the SOLID hypothesis predicts difficulties for persons with dyslexia specifically in implicit learning tasks that require processing of serial-order information, and not in tasks that do not involve serial order. Evidence in line with this prediction was reported by Howard, Howard, Japikse, and Eden (2006). They tested adults with dyslexia on two different implicit learning tasks: a spatial contextual cuing task (in which the global configuration of a display cued the location of a search target), and a variant of the SRT task (in which sequential dependencies existed across non-adjacent elements). Crucially, only the latter task involved memory for serial-order. People with dyslexia showed impaired SRT sequence learning but unimpaired spatial context learning (see also Jiménez-Fernández, Vaquero, Jiménez, & Defior, 2011).

verbal/phonological impairment underlies the full spectrum of symptoms associated with dyslexia. Moreover, serial-order processing seems to be largely a language-independent capacity (Burgess & Hitch, 1999, 2006; Gupta, 2003; see also Parmentier, 2014). We therefore suggest that the verbal-serial-order learning impairment in dyslexia observed in the current study likely reflects a problem with a core ability to represent serial-order information that cannot simply be accounted for by poor phonological representations. Moreover, we hypothesize that the evidence in support of a phonological impairment in dyslexia might, at least partly, be explained in terms of problematic serial-order representation and learning. First, tasks that measure phonological awareness (e.g., phoneme deletion, Spoonerisms) clearly involve serial-order processing, so that participants whose serial representations are compromised would necessarily display poor performance. Second, the dyslexic disadvantages in measures of short-term memory such as digit span and nonword repetition also imply a serial-order deficit, in temporary representation, if not in learning. Our present findings demonstrate how impaired serial-order learning could affect the formation of phonological/lexical verbal–serial representations, an observation that can also account for slow lexical retrieval and worse performance in rapid automatic naming (RAN) tasks reported for people with dyslexia. The serial-order hypothesis is, therefore, compatible with the phonological deficits documented in the literature, and our lexicalization data do suggest a relation between serial-order impairments and wordform-learning impairments.

The precise nature and causal structure of the relationship between reading and sequential learning (see Hari & Renvall, 2001; Hedenius et al., 2013) remains to be elucidated and, accordingly, we recently conducted a longitudinal study that addressed this issue (Bogaerts et al., submitted).

Verbal and visual Hebb repetition learning performance and reading skills were assessed in 96 children (including children at risk of dyslexia) whom we followed from the first through to the second grade of primary school. We observed a positive association between individual order-learning capacities and (later) 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 explained a significant part of the variance in reading performance, above and beyond phonological awareness. This strengthens the claim of the SOLID hypothesis that poor HRL performance in dyslexia is probably not simply a consequence of degraded sublexical representations, but rather represents a genuine cognitive deficiency underlying dyslexia.

One point that deserves more attention is our use of visual (orthographic) representations for the syllables in the Hebb procedure. We opted for visual rather than auditory presentation of the CVs for two reasons: First, this allowed presenting the items simultaneously on the recall screen and therefore permitted a selective measure of serial-order performance uncontaminated by item memory. Second, the visual presentation of the Hebb competitors combined with an auditory PD task allows us to attribute lexical competition effects to abstract lexical representations, rather than just auditory traces in episodic memory. Whereas we acknowledge the slight possibility that the dyslexic subjects had difficulty with the processing of the visually presented CVs, we argue that this is not likely to be the locus of the observed effects. First, only reading of individual CVs was required. Second, problems with phonological processing should arise both on filler and Hebb trials and therefore cannot explain a smaller HRE (i.e., the difference between the filler and Hebb trials). Third, earlier work (Szmalec et al., 2011) on Hebb learning in dyslexia showed that the Hebb learning impairment in the visual-verbal modality is not larger than in the auditory-verbal and spatial modalities.

The current study focuses on the *long-term* learning of serial-order information that, within Page and Norris's (2008, 2009) framework, is crucial when people learn words from sequence regularities in their linguistic environment. However, we do not exclude the possibility that the mere temporary processing of serial-order information is also affected in dyslexia (as put forward by Corkin, 1974; see also Martinez-Perez et al., 2012a; Martinez-Perez, Majerus, & Poncelet, 2013; Hachmann et al., 2014). Indeed, the group difference in filler performance found in the current study even suggest such a difference in immediate-recall performance. As we have mentioned already in our introduction, several recent studies have further highlighted the importance of the serial-order component of STM in relation to language learning and reading (e.g., Leclercq & Majerus, 2010; Martinez Perez et al., 2012b; Majerus & Boukebza, 2013). This suggests that both short-term memory for serial-order and the long-term Hebb learning of lists over multiple trials are strongly implicated in language processing and learning (see also Mosse & Jarrold, 2008). Our data show that when controlling for short-term memory differences, the finding of impaired serial-order learning in dyslexia remains reliable. However, more research is needed to draw firm conclusions about the interrelation of the two memory systems and their relative importance in dyslexia.

## CONCLUSION

In conclusion, the present article draws on the view that language can be regarded as a well-structured environment with an inherently sequential nature and supports the notion that dyslexia is associated with a sequential or serial-order learning impairment. It extends previous research by showing that not only initial HRL in a single session, but also longer-term learning (with more practice) is affected, although the long-term retention of what is eventually learned is unaffected in dyslexia. By assessing lexicalization of verbal sequences in people with dyslexia, we have shown how a serial-order learning impairment may result in language impairment. Our results support the SOLID view positing that dyslexia and its variety of related linguistic and nonlinguistic dysfunctions may be traced back, at least to some extent, to a difficulty with learning serial-order information.

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# CHAPTER 5
## THE INVOLVEMENT OF LONG-TERM SERIAL-ORDER MEMORY IN READING DEVELOPMENT: A LONGITUDINAL STUDY[16]

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.

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[16] Bogaerts, L., Szmalec, A., De Maeyer, M., Page, M. P. A., Duyck, W. (revised manuscript submitted for publication). The involvement of long-term serial-order memory in reading development: A longitudinal study. *Journal of Experimental Child Psychology*.

## 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 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 Oder 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, under review). 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: (1) First, we aim to investigate whether the observation of Hebb learning deficits in dyslexic adults extends to poor-reading[17] 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. (1a) 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).

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[17] 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).

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 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:

(1) 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., under review; 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. (1a) 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 on 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.

*Hebb learning tasks*

*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 percentage of animal words recalled in the correct serial position.

*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 the percentage of lily pads recalled in the correct serial position.

*Intelligence*

The Raven Standard Progressive Matrices (Raven, Court, & Raven, 1992) were 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.

*Reading*

*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 difference between the total number of words read minus the number of reading errors.

*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.

*Other language tests*

*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.

*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., 'spi*n*' [spider] without '*n*'). In the

Spoonerisms task, the first letters of two orally presented words must be switched (e.g., *H*arry *P*otter becomes *P*arry *H*otter). For both tasks the number of total correct answers determines the raw score. A total phonological awareness score was calculated by summing up the raw scores of both tasks.

*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 (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.

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.

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.

***Table 1.* Participant characteristics.**

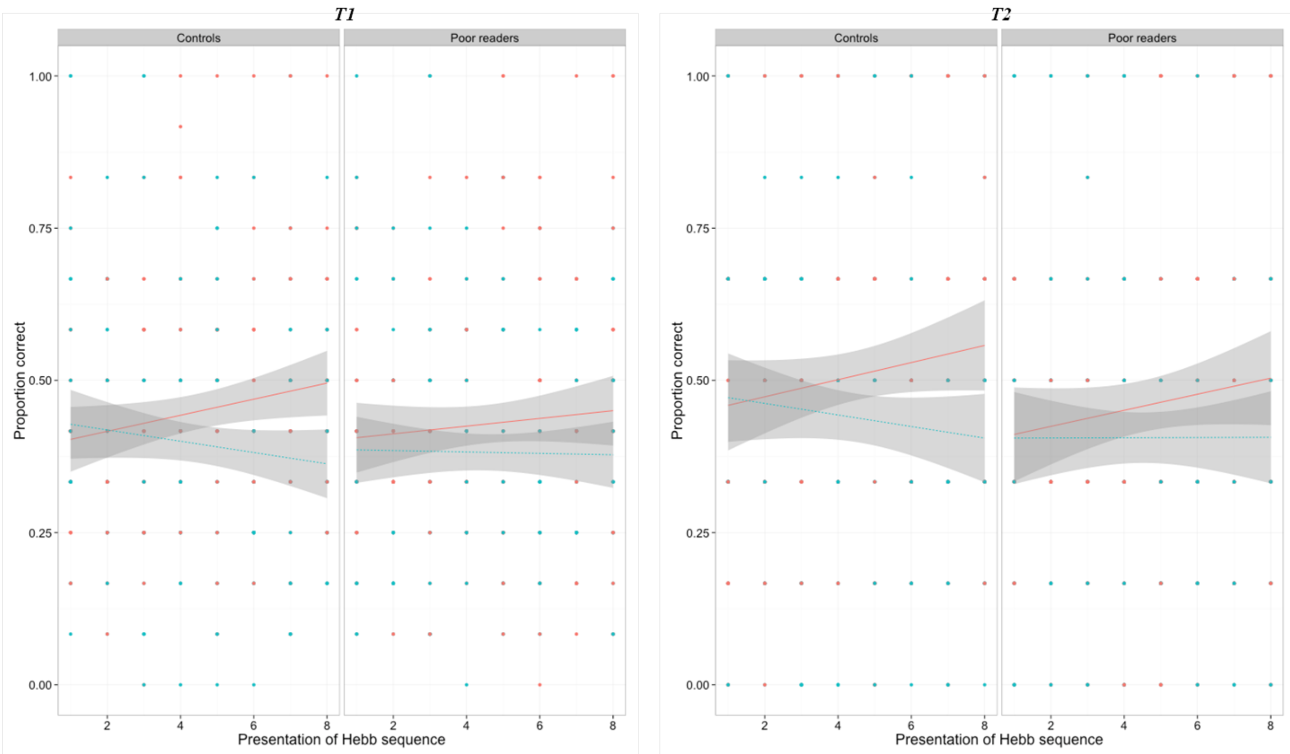
| | EXTREME GROUPS | | | *FULL SAMPLE* |
|---|---|---|---|---|
| | *Poor readers* | *Good readers* | Group difference | *All children* |
| | (n = 23) | (n = 23) | | (n = 94) |
| ***Control variables*** | | | | |
| Age (T2, months) | 95.1 (4.1) | 95.6 (5.6) | *p = .77* | 94.8 (4.6) |
| Raven PM (percentile) | 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.

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

| | | EXTREME GROUPS | | *FULL SAMPLE* |
|---|---|---|---|---|
| | | *Poor readers* (n = 23) | *Good readers* (n = 23) | *All children* (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) |

*Verbal Hebb task*



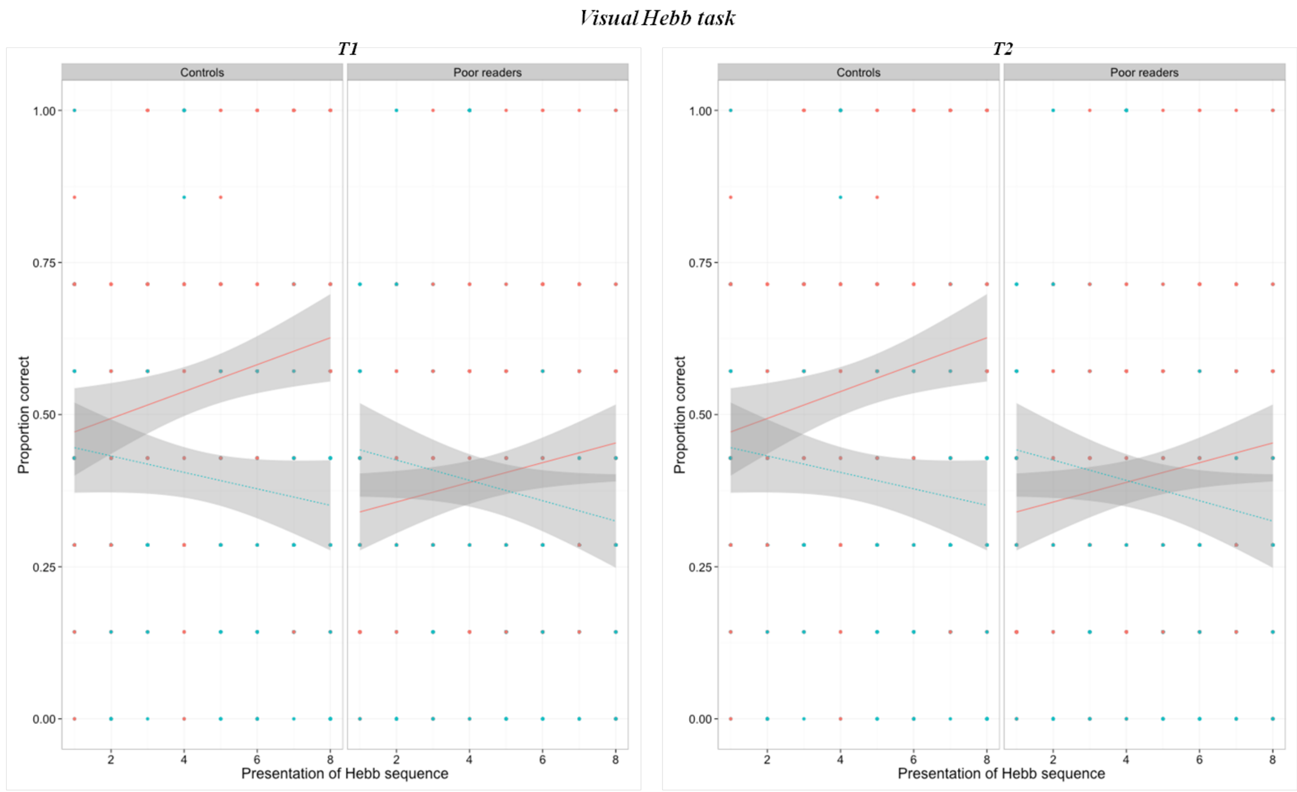



***Figure 1*. Plots of the average proportion correctly recalled items for Hebb (blue) and filler (red) in function of the presentation position of the Hebb sequence.** Grey shading denotes the 95% confidence interval.

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 (verbal/visual) 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.[18] We further included IQ and age as control variables. The model included random effects for subjects and for items. The model including the maximal random effect structure for subject (see Barr, Levy, Scheepers, & Tily, 2013) failed to converge. Therefore, we simplified the random effects structure by removing the random slopes for the intraction terms (leaving a random intercept for subject and a random by-subject slope for Type, Presentation, and Domain). The random effect structure for item, defined as the unique combination of Sequence type and Presentation (i.e., filler1, Hebb1, filler2, Hebb2, etc.), included a random intercept and a by-item slope for group. All continuous predictors were centered. Multicollinearity was low ($r < .21$).

The results of this mixed logit model are summarized in Table 3. We found a significant main effect of Type, reflecting higher performance for Hebb sequences than for the fillers ($\beta = .17$; $p = .01$). A significant interaction of Type by Presentation confirms the presence of a Hebb repetition effect in the

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[17] The inclusion other higher-order interaction terms did not significantly improve the log-likelihood of the model.

developmental sample ($\beta$ = .05; $p$ = .05). A simple slopes analysis revealed that this interaction was driven by a positive correlation between accuracy and Presentation for Hebb trials ($\beta$ = .05; $z$ = 5.79; $p$ < .001) and a negative correlation for filler trials ($\beta$ = -.05; $z$ = -5.231; $p$ < .001). Significant effects for the interaction terms Type:Domain ($\beta$ = -.05; $p$ < .001) and Type:Presentation:Domain ($\beta$ = -.02; $p$ = .007) indicate more learning in the visuo-spatial modality compared with the verbal modality. Crucially, we observed also a significant interaction of Type:Group ($\beta$ = -.05; $p$ = .05) and Type:Presentation:Group ($\beta$ = -.02; $p$ = .013), confirming the predicted weaker Hebb effect for the poor-reading group, compared with the control group (see Figure 1). 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 ($\beta$ = .07; $z$ = 7.28; $p$ < .001) and for the dyslexic group ($\beta$ = .03; $z$ = 3.69; $p$ < .001), suggesting that Hebb learning is present in both groups but to a lesser extent for the poor readers.

When running the same mixed logit model on T1 data only, a significant three way-interaction Type:Presentation:Group was again observed ($\beta$ = -.02; $z$ = -2.615; p< .001). 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 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 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, the crucial result regarding the Type:Presentation:Group interaction remains identical after including average filler performance as an additional control variable in the model, $\chi^2(1) = 6.16$, $p = .013$.

***Table 3.*** **Summary of the fixed effects in the mixed logit model (N= 19136; log-likelihood= -12300.7).**

| ***Predictor*** | *χ2* | *p* | |
|---|---|---|---|
| Intercept | 20.56 | <.00 | *** |
| Raven PM | 7.18 | .007 | ** |
| Age | .58 | .45 | |
| Type | 6.71 | .010 | ** |
| Presentation | .00 | .96 | |
| Domain | .00 | .98 | |
| Group | 2.94 | .09 | . |
| Type:Presentation | 3.81 | .05 | * |
| Type:Domain | 11.68 | <.00 | *** |
| Presentation:Domain | 11.68 | .31 | |
| Presentation:Group | .37 | .55 | |
| Type:Group | 3.95 | .05 | * |
| Type:Presentation:Domain | 7.28 | .007 | ** |
| Type:Presentation:Group | 6.15 | .013 | * |
| Type:Presentation:Domain:Gr | .99 | .60 | |
| Type:Presentation:Group:Lag | 5.47 | .24 | |

In summary, by showing the presence of a clear Hebb repetition effect in the children's group and significantly weaker Hebb learning for poor readers compared with good readers, the analysis presented above 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, and Domain as well as a random intercept for item. All continuous predictors were centered in order to reduce multicollinearity between higher order interactions, which was low ($r < .25$).

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 ($\beta = .0007$; $p = .009$) as well as a significant Type:Presentation:Klepel interaction ($\beta = 0.001$; $p = .005$), indicating stronger Hebb repetition learning in children with higher word- and nonword reading scores. This confirms the subsidiary part of our first prediction (1b, above).

***Table 4.*** **Summary of the fixed effects in the mixed logit model (N = 35008; log-likelihood A = -22688.4 / B = -22685.7).**

**A. Word reading**

| ***Predictor*** | $\chi 2$ | $p$ | |
|---|---|---|---|
| Intercept | 18.97 | <.001 | *** |
| Raven PM | 8.56 | .003 | ** |
| Age | 2.44 | .12 | |
| Type | 7.04 | .008 | ** |
| Presentation | 0.10 | .75 | |
| Domain | 5.63 | .018 | * |
| DMT | 6.95 | .008 | ** |
| Type:Presentation | 2.89 | .089 | ∘ |
| Type:Domain | 19.14 | <.001 | *** |
| Presentation:Domain | 0.22 | .64 | |
| Presentation:DMT | 1.70 | .19 | |
| Type:DMT | 7.87 | .005 | ** |
| Type:Presentation:Domain | 8.97 | .003 | ** |
| Type:Presentation:DMT | 6.77 | .009 | ** |
| Type:Presentation:Domain:DMT | 2.30 | .32 | |
| Type:Presentation:DMT:Lag | 0.49 | .78 | |

**B. Nonword reading**

| ***Predictor*** | $\chi 2$ | $p$ | |
|---|---|---|---|
| Intercept | 19.49 | <.001 | *** |
| Raven PM | 8.63 | .003 | ** |
| Age | 1.54 | .21 | |
| Type | 7.08 | .008 | ** |
| Presentation | 0.10 | .76 | |
| Domain | 5.61 | .018 | * |
| Klepel | 13.34 | <.001 | *** |
| Type:Presentation | 2.91 | .088 | ∘ |
| Type:Domain | 19.10 | <.001 | *** |
| Presentation:Domain | 0.19 | .66 | |
| Presentation:Klepel | 0.08 | .78 | |
| Type:Klepel | 11.25 | <.001 | *** |
| Type:Presentation:Domain | 9.11 | .003 | ** |
| Type:Presentation:Klepel | 7.88 | .005 | ** |
| Type:Presentation:Domain:Klepel | 0.16 | .92 | |
| Type:Presentation:Klepel:Lag | 0.65 | .72 | |

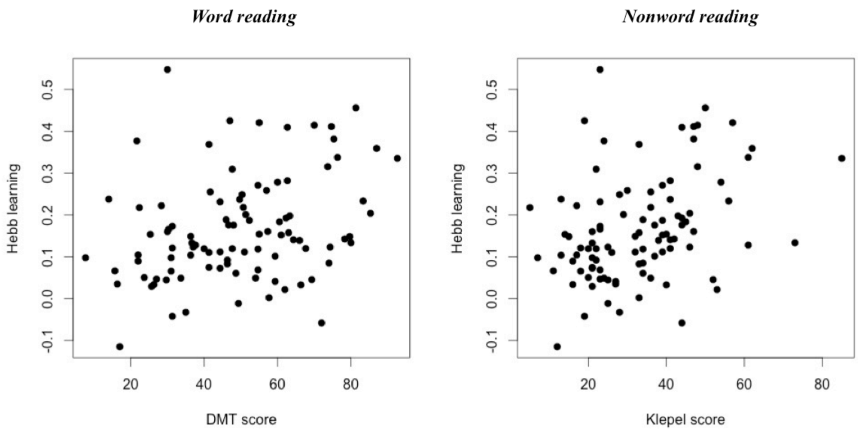


***Figure 2.*** **Scatterplots clarifying the relationship between reading scores and Hebb learning, measured by the coefficient for the Type:Presentation interaction.**

*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 variable[19], 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

[19] The structure of the mixed logit model that we ran to extract the individual coefficient values was identical to the models described above except that we removed all terms that included reading score (DMT/Klepel).

performance and Hebb learning were included as predictors, as well as the control variables IQ and age.

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 this significant unique contribution of Hebb learning, $F(1) = 7.93$, $p = .006$, $\Delta R^2 = .096$, 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 ($\beta = .88$, $t = 7.80$, $p < .001$) and nonword reading ($\beta = .60$, $t = 6.98$, $p < .001$). Hebb learning performance, which did not significantly predict later word reading, is also not a significant predictor of growth in reading ($\beta = 3.01$, $t = 0.27$, $p = .79$). More interestingly, Hebb learning still does reliably predict T2 nonword reading in this more conservative model ($\beta = 20.88$, $t = 2.45$, $p = .02$) and has a unique contribution, $\Delta R^2 = .044$.

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 linear regression results.**

**A. Word reading**

| ***Predictor*** | β | *t* | *p* | |
|---|---|---|---|---|
| Intercept | 48.29 | 21.48 | <.001 | *** |
| Raven PM | .53 | 1.47 | .15 | |
| Age | -.08 | -.17 | .87 | |
| T1 Filler | .94 | .25 | .80 | |
| T1 Hebb learning | 20.91 | 1.35 | .18 | |

**A. Nonword reading**

| ***Predictor*** | β | *t* | *p* | |
|---|---|---|---|---|
| Intercept | 32.38 | 19.90 | <.001 | *** |
| Raven PM | .10 | .37 | .71 | |
| Age | .18 | .49 | .62 | |
| T1 Filler | 3.32 | 1.23 | .22 | |
| T1 Hebb learning | 31.53 | 2.82 | .006 | ** |

*Explaining variance in reading skills.* Finally, we tested our third prediction by evaluating the contributions of filler performance, Hebb learning and phonological awareness in explaining the variance in reading skills. The coefficient for the Type:Presentation interaction, extracted from the mixed logit model, was 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 centered) 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

($\Delta R^2$ phon = .141, $\Delta R^2$ Hebb = .051) and in and nonword reading ($\Delta R^2$ phon = .138, $\Delta R^2$ Hebb = .067), above and beyond all other predictors.

***Table 6*. Summary of the linear regression results.**

A. Word reading

| *Predictor* | β | *t* | *p* | |
|---|---|---|---|---|
| Intercept | 49.22 | 29.01 | <.001 | *** |
| Raven PM | .25 | 0.94 | .34 | |
| Age | .00 | .02 | .98 | |
| Filler | .33 | .11 | .91 | |
| Phon awareness | 1.67 | 4.24 | <.001 | *** |
| Hebb learning | 35.88 | 2.56 | .012 | * |

A. Nonword reading

| *Predictor* | β | *t* | *p* | |
|---|---|---|---|---|
| Intercept | 32.98 | 26.40 | <.001 | *** |
| Raven PM | -.00 | -.00 | .99 | |
| Age | .23 | .83 | .40 | |
| Filler | .284 | 1.28 | .20 | |
| Phon awareness | 1.26 | 4.36 | <.001 | *** |
| Hebb learning | 31.30 | 3.034 | .003 | ** |

## 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., under review, 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., under review; 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 indicate 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., under review). 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).

Finally, 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 remains compatible however 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.

## 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 just began 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 to reliably 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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# CHAPTER 6
## GENERAL DISCUSSION

The overarching aim of this doctoral project was to investigate how those memory systems involved in the short-term processing and the long-term consolidation of serial-order information impact upon reading (dis)ability. In this final chapter we summarize the empirical evidence presented in the four empirical sections, link them to other recent research findings, and discuss the theoretical implications. We conclude this chapter with a discussion of some methodological caveats and possible directions for future research.

## SUMMARY OF CURRENT FINDINGS

Despite an extensive body of research on developmental dyslexia, there is currently no consensus regarding the underlying cause(s) of the disorder (e.g., see Pennington, 2006, for a discussion). The influential phonological deficit hypothesis (e.g., Snowling, 2000; Stanovich, 1988), which postulates that an impairment in phonological processing is the core deficit underlying dyslexia, has been strongly criticized as a single-deficit account. Its main flaw is that not all people with developmental dyslexia who fail to achieve fluency in (word) reading show a clear phonological impairment (Paulesu et al., 2001; Wimmer, Mayringer, & Landerl, 2000). Moreover, it is unclear how some of the non-linguistic memory and learning impairments often associated with reading disability (e.g., De Kleine & Verwey, 2009; Pavlidou, Kelly, & Williams, 2010; Smith-Spark & Fisk, 2007; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003) can be accounted for by a phonological deficit.

The current dissertation is motivated by an alternative theoretical hypothesis, which proposes that both the linguistic and nonlinguistic dysfunctions in dyslexia arise from a common underlying impairment, namely, a deficit in memory for serial-order information (i.e., the order in which items are presented within a sequence; Szmalec, Loncke, Page, & Duyck, 2011). This original hypothesis was grounded on the observation of impaired long-term serial-order learning abilities in adults with dyslexia (Szmalec et al., 2011).

Within the theoretical framework of Page and Norris' (2008, 2009) model of verbal short-term memory, which directly relates word-form acquisition to serial-order learning, we further assumed that learning to read words can be understood as the acquisition of ordered grapheme and phoneme sequences. The central assumption of the theoretical framework put forward by Page and Norris (2008, 2009) is that the link between memory and language learning can be operationalized using the Hebb repetition paradigm. Indeed, it has been shown experimentally that verbal Hebb repetition learning, that is, the repeated recall of a particular sequence of letter or syllable items over the course of an immediate serial recall task (Hebb, 1961), can be considered as a laboratory analogue of acquiring novel phonological word-forms (Szmalec, Duyck, Vandierendonck, Barberá-Mata, & Page, 2009; Szmalec, Page, & Duyck, 2012).

Building on this theoretical framework, and on the study by Szmalec et al. (2011), the present dissertation put forward a memory-based perspective of reading disability. More specifically, we focused on the following theoretical questions:

(1) Is developmental dyslexia associated with a selective difficulty with *order* processing in short-term memory? If so, is this difficulty specific to linguistic materials or is it domain-general?

(2) Does impaired serial-order processing in people with dyslexia involve additional problems in memory functions, such as overcoming proactive interference in recognition memory?

(3) Is dyslexia also associated with a long-term serial-order learning impairment? If so, is the impairment related to the learning itself or to long-term retention? If it is related to learning, is the learning fundamentally impaired or simply delayed?

(4) Can the association between serial-order learning and reading skills also be demonstrated in early-stage readers, and can relative order learning difficulties reliably predict poor reading development?

To address these questions, we carried out four independent studies. The first two studies focused on *short-term order memory*, i.e., the ability to process the order of discrete elements occurring in a sequence. By 'processing' we mean the encoding of serial-order information and the temporary retention of item order. The latter two studies investigated *long-term serial-order learning*, defined as the ability to consolidate sequential information in long-term memory, here operationalized as Hebb repetition learning.

Our experimental work yielded the following findings:

In study 1 (CHAPTER 2) we found that developmental dyslexia is characterized by a specific problem of processing serial order in short-term memory. Moreover, our findings suggest that this deficit is not confined to linguistic material, but extends to non-linguistic material as well. In contrast to the serial-order deficit, memory for item identity was unaffected in adults with dyslexia.
The experiment described in CHAPTER 3 revealed similar order-processing difficulties within a working memory updating (N-back) task. Our results show that adults with dyslexia have difficulties in retrieving information from working memory due to interference from memory representations that were stored prior to the to-be-remembered materials. We have suggested that these difficulties likely stem from a problem with the order-sensitive recollection process that is typically deployed to cope efficiently with proactive interference in recognition memory.

The data presented in CHAPTER 4 support the notion that dyslexia is associated with a persistent serial-order learning *deficit* rather than just delayed learning. Thus, learning remained impaired despite an experimentally induced opportunity, in terms of number of Hebb repetitions, for substantial overlearning. Moreover, the findings suggest that dyslexic and control participants showed comparable retention of the sequences that they *had* learned. This suggests that the eventually acquired representations are not subjected to stronger decay in dyslexia, at least not within the first month after initial learning. By assessing lexicalization of the verbal sequences we have also directly shown, for the first time, how a serial-order learning impairment may result in language impairment.

Finally, the results of the large-sample longitudinal study covered in CHAPTER 5 suggest weaker serial-order learning performance in first graders who develop clinical reading scores one year later, compared with normal reading controls. Moreover, we observed a positive association between order-learning capacities and reading ability, and Hebb learning predicted individual differences in later (nonword) reading skills. Finally, Hebb learning explained a significant part of the variance in reading performance, above and beyond phonological awareness, which confirms that phonological processing may not offer the sole etiological explanation for the development of dyslexia.

In summary, we showed that dyslexia is related to an impairment in the processing and learning of serial order, and our developmental work further suggests that order memory is implicated in reading acquisition. In what follows, we discuss these findings, we situate them within the existing literature, and outline their theoretical implications.

## READING DISABILITY AND SERIAL-ORDER MEMORY: THE EMPIRICAL EVIDENCE

### *Short-term order processing impairments*

There is little value in remembering the digits in a phone number, or the identity of the letters in an orthographic sequence representing a novel word, unless you also remember the serial order in which they appeared. We have argued in CHAPTER 2 that the processing of item identity, on the one hand, and of item order, on the other hand, can be seen as two separable components of short-term memory. We further presented evidence for a specific deficit in order short-term memory (order STM) in developmental dyslexia and we explained how such a deficit may underlie, at least to some extent, reading disability and the phonological problems associated with it.

The relation between reading disability and the two distinct short-term memory components has been the focus of several other recent studies. Table 1 provides an overview of these studies, the tasks they used to operationalize item and order STM, and their findings. The table shows that a dyslexic disadvantage for order STM was consistently found across all four studies[20], independent of the task employed. In summary, the different studies suggest that both the active recall of serial-order information (i.e., reconstructing an ordered list; Martinez Perez, Majerus, Mahot, & Poncelet, 2012; Staels & Van den Broeck, 2014a; Martinez Perez, Majerus, & Poncelet, 2013), and the simple recognition of order (i.e., judging similarity in item-order of two consecutively presented lists; Hachmann et al., 2014, CHAPTER 2) is impaired in dyslexia. Our study, however, was the first also to employ nonlinguistic stimuli, demonstrating that the difficulty with the order

[20] Note that although Staels & Van den Broeck (2014a) found a reliable group difference in order STM, they showed that this group difference was no longer statistically reliable when controlling for item short-term memory (item STM). The authors argued that this was evidence against an order STM deficit in dyslexia. However, because the task that they used for measuring item STM also relies on order processing to a certain extent (as we outline in detail on p. 217), we believe partialling out this variable implies also partialling out order processing, and is therefore not a suitable approach to asses group differences on this variable.

component of short-term memory is domain-general, and thus not limited to linguistic materials.

Unlike the converging findings regarding order STM, the results regarding *item* STM are more mixed. Whereas we observed intact item STM in dyslexic adults —operationalized as item recognition performance for nameable pictures (verbal condition) and visual nonsense stimuli (nonverbal condition)—, others have reported impaired item STM in dyslexic children (Martinez Perez et al., 2012; Staels, & Van den Broeck, 2014a) and adults (Martinez Perez et al., 2013). The question at hand is what can account for these contrasting findings? The first thing to note is that the three studies other than ours made use of a nonword delayed repetition task to measure item STM abilities. We have argued in the discussion of the relevant chapter that nonword recall may not be a pure item task, because it requires participants to remember multiple-letter sequences. Moreover, the retention of item information in this task requires active recall rather than simple recognition, and directly depends on the quality of a phonological representation in long-term memory (Staels & Van den Broeck, 2014a). In our study (presented in CHAPTER 2) we carefully selected verbal material for the item task that does not require serial processing (i.e., nameable images in visual presentation and existing words in auditory presentation). On the basis of our results we speculate that basic item STM seems to be unaffected in dyslexia, and that the item STM deficit observed in the other studies is likely driven by the specific characteristics of the adopted nonword repetition task, specifically the fact that it requires some memory for order information. We acknowledge however that this claim requires additional investigation, using a detailed manipulation of both tasks and stimuli.

***Table 1*. Short-term memory studies with their groups, tasks, and results.** RA = Reading age, CA = Chronological age, (I) = Item task, (O) = Order task.

| | Study | Groups | *N* | Age (years) | Matching characteristics | Tasks | Modality | Group diff |
|---|---|---|---|---|---|---|---|---|
| ADULTS | Martinez Perez et al. (2013) | Dyslexics | 30 | 24.3 | Age, education level, IQ | (I) Single nonword delayed repetition | verbal | yes |
| | | CA Controls | 30 | 23.6 | | **(O) Digit serial order reconstruction** | **verbal** | **yes** |
| | Hachmann et al. (2014) CHAPTER2 | Dyslexics | 21 | 20.8 | Age, IQ | (I) Picture item recognition | verbal | no |
| | | | | | | (I) Nonsense drawing item recognition | nonverbal | no |
| | | CA Controls | 24 | 21.4 | | **(O) Digit serial order recognition** | **verbal** | **yes** |
| | | | | | | **(O) Nonsense drawing serial order recognition** | **nonverbal** | **yes** |
| CHILDREN | Martinez Perez et al. (2012) | Dyslexics | 22 | 10.29 | Age, IQ, receptive vocabulary | (I) Single nonword delayed repetition | verbal | yes |
| | | CA Controls | 22 | 10.08 | | **(O) Animal name serial order reconstruction** | **verbal** | **yes** |
| | | RA Controls | 22 | 8.14 | | (I) Single nonword delayed repetition | | no |
| | | | | | | **(O) Animal name serial order reconstruction** | | **yes** |
| | Staels & Van den Broeck (2014a) | Dyslexics | 30 | 10.53 | Age, receptive vocabulary, IQ | (I) Single nonword delayed repetition | verbal | yes |
| | | CA Controls | 30 | 10.75 | | **(O) Animal name serial order reconstruction** | **verbal** | **yes (a)** |

(a) the effect disappeared after controlling for I performance

We should mention, at this point, that a serial-order processing deficit may explain why dyslexia is often associated with memory deficiencies. Frequently used tasks for short-term memory performance, such as digit span and other serial recall tasks, inherently confound item storage and short-term memory for the order of the stored items. Our demonstration of a dissociation of impaired order STM, on the one hand, but unimpaired item STM, on the other, suggests that the reports of reduced memory span in dyslexia (e.g., Kibby, Marks, Morgan, & Long, 2004; Smith-Spark & Fisk, 2007) may be framed in terms of a problem solely with the sequential component of the task (see p. 55 in the relevant chapter, for further discussion). In this context we refer also to the study described in CHAPTER 3, which further extended the findings on impaired order STM, by showing, for the first time, that impaired order processing in people with dyslexia results in additional problems in memory functioning, such as impaired coping with proactive interference. Interestingly, Lustig, May, and Hasher (2001) demonstrated that performance on memory span tasks is strongly influenced by proactive interference. They suggested that group difference in span size (e.g., age differences, but by extension also differences between clinical and control groups) may be attributed not only to differences in capacity but also to differences in the ability to overcome interference. Moreover, the ability to resist proactive interference was highlighted as a potentially important mediating factor in the relation between the serial recall task and other cognitive tasks, including linguistic tasks (e.g., Gathercole & Baddeley, 1989; Service, 1992; see Lustig et al., 2001).

*Long-term order learning impairments*

Imagine that it does not suffice to remember a sequence of items just for a couple of seconds or minutes. This is true, for example, when learning a phone number by heart, or when learning a new word. According to the dual-store memory model proposed by Atkinson and Shiffrin (1968), memories can reside in the short-term "buffer" only for a limited time. When items are first presented, they enter short-term memory, but due to its limited capacity, as new items are processed, older ones are pushed out. However, each time an item in short-term memory is rehearsed, it is strengthened in long-term memory. Hebb (1961) studied this short-to-long term transfer process and hypothesized that simultaneous activation of cells leads to an increase in synaptic strength between those cells, and that the persistence of repetition of an activation pattern tends to induce lasting cellular changes that add to the stability of a memory trace (making it long-term).

The last two empirical chapters of this dissertation focused on the *long-term learning* (or *consolidation)* of sequential information. In other words, they were concerned with the transfer of serial-order information, initially stored in short-term memory, into stable long-term memory representations. Our experimental work presented in CHAPTERS 4-5 suggests, in line with the earlier study by Szmalec et al. (2011), that dyslexia comprises a problem in order learning. In CHAPTER 4 we further 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. The same study also suggests 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). In our longitudinal study with beginning readers, presented in CHAPTER 5, we further found a positive relationship between serial-order learning skill and reading, and showed that serial-order learning predicts reading skills. This supports the hypothesis of a central role for serial-order learning in reading.

In light of our earlier demonstration of an order impairment in short-term memory, it is worthwhile noting that our data (both in adults and children) show that when controlling for short-term serial recall ability, the finding of impaired long-term serial-order learning in impaired readers remains reliable. This suggests that both short-term memory for serial-order, and the long-term Hebb learning of lists over multiple trials, are (to some extent independently) implicated in successful reading achievement (see also Mosse & Jarrold, 2008). As such, our data can be seen as a behavioral validation of the 2-parameter implementation in Page and Norris's word-learning model. As we have outlined in detail in the introduction, learning a new word-form within the computational model of Page and Norris (2008, 2009) depends on two independent parameters: the short-term (order) representation of a letter/phoneme sequence (i.e., the presence and strength of the primacy gradient), and the weight-change governed by a variable learning rate. The ability to learn sequences by their repeated presentation (and recall) —in the model reflected by the second learning parameter— is assumed to be an ability that differs between individuals: some people are quick learners; others need more exposure and practice in order to learn a sequence. Indeed, Mosse and Jarrold (2008) showed a correlation between the extent of learning, as revealed in the Hebb repetition task, and the ability to learn new words. Consistent with this finding we have shown both that people with reading disabilities show reduced Hebb learning and that there is a positive relationship between the extent of Hebb learning and reading skills in children.

## MEMORY FOR ORDER: A UNIFYING THEORETICAL CONSTRUCT?

As detailed in the introduction, dyslexia research is characterized by a wide diversity in etiological explanations of the disorder (e.g., the phonological theory, Snowling, 2000; the cerebellar theory, Nicolson & Fawcett, 1990; the magnocellular theory, Stein & Walsh, 1997; the anchor-deficit hypothesis, Ahissar, 2007; the visual attention span hypothesis, Bosse, Tainturier, & Valdois, 2007, etc.). Due to the diversity of dysfunctions associated with reading impairment, it has proven difficult to put forward a unifying framework with high descriptive and explanatory adequacy (Pennington, 2006; Ramus, 2003).

We propose that *"serial-order memory"*, as a theoretical construct, provides a useful perspective for understanding pathological reading development, with significant explanatory power. Overall, the results of our four experimental studies highlight the role of memory for serial-order in reading and reading acquisition. They conform with the view that reading disabilities are tied to a deficit in the long-term learning of serial-order information (the "SOLID" or "Serial Order Learning Impairment in Dyslexia" hypothesis), but reveal also the presence of serial-order problems at the short-term processing level. We suggest therefore that "Serial Order Memory Impairment in Dyslexia" would be a more precise term: *Serial Order Memory* refers here to the memory systems involved in both the short-term processing and the long-term consolidation of serial-order information. The main theoretical advantage of this memory-based perspective lies in its explanatory power. It offers an integrative account that clarifies how both linguistic and nonlinguistic dysfunctions in dyslexia can be explained by a single mechanism: a deficit in memory for serial-order.

*The order deficit accounts for the language problems in dyslexia*

Let us first consider nonword decoding difficulties, which are characteristic of developmental dyslexia. Nonword decoding heavily relies on short-term order processing. When encountering a yet unknown orthographic word-form, beginning readers typically convert every letter into its corresponding phoneme, subsequently to produce the full sequence of sounds (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). However, the encoding of the relative position of the letters is critical for correct performance. Moreover, the letters and their corresponding phonemes should be retained in short-term memory for the purpose of production (see also Martinez Perez et al., 2012, 2013). As a consequence, poor order memory might disrupt the normal mapping of grapheme and phoneme sequences for both word identification and nonword production (e.g., Whitney & Cornelissen, 2005). Second, if due to impaired serial-order learning, the order of the individual sublexical items in a sequence is not optimally consolidated as a single entry in long-term lexical memory, this would result in poor quality of lexical representations (Perfetti, 2007). Such impoverished orthographical/ phonological word-form representations would subsequently complicate lexical access. Hence, impaired serial-order memory affects nonword decoding and new word acquisition (see also Di Betta & Romani, 2006), impacting reading accuracy, fluency, and spelling performance (e.g., Perfetti, 2007; Kuperman & Van Dyke, 2011).

*How does an order deficit account for non-linguistic dysfunctions?*

As outlined above, the order hypothesis provides a theoretical link between the language impairments in dyslexia and the nonlinguistic related dysfunctions that have consistently been reported with dyslexic readers. Although not always explicitly recognized, serial-order processing underlies most of the experimental tasks that are used to assess working memory. For example, tasks measuring memory span typically involve the serial recall of item sequences. Moreover, we have shown in CHAPTER 2 that dyslexic difficulties appear to be restricted only to tasks that require processing of order. For our dyslexic participants, short-term memory for item identity was unaffected whereas memory for order was.

In the same vein, the dyslexic disadvantages found in implicit learning tasks, which led to the formulation of the cerebellar deficit hypothesis (Nicolson, Fawcett & Dean, 2001), can also be re-interpreted as reflecting a serial-order learning impairment. Experiments in this domain typically used implicit learning tasks such as the serial-reaction time (SRT) task or artificial grammar learning (AGL). Memory for order is critical for performance in all of these tasks. Note that our serial-order account predicts difficulties for persons with dyslexia in tasks that require the learning of serial-order information, but not in learning tasks that do not rely on the memorization of serial order. And indeed, it has been shown that people with dyslexia who show impaired implicit sequence learning are not impaired in spatial context learning, an implicit learning task that does not involve sequencing of information (Howard, Howard, Japikse, & Eden, 2006; Jimenez-Fernandez, Vaquero, Jimenez, & Defior, 2011). These findings provide cross-validation for our current account.

*How does the order account relate to the phonological theory?*

Although the findings of our four studies are not necessarily incompatible with a deficit in phonological processing, the demonstration of a short-term order deficit in the nonverbal modality (CHAPTER 2) and the previous demonstrations of sequence learning impairments of dyslexics in non-linguistic tasks (e.g., visuo-spatial Hebb learning; Szmalec et al., 2011; the SRT task, e.g., Lum, Ullman, & Conti-Ramsden, 2013; AGL, e.g., Pavlidou et al., 2010), challenge the view that a single core phonological deficit solely underlies the diversity of impairments associated with dyslexia. Next to poor verbal short-term memory, evidence in support of the phonological theory typically encompasses poor phonological awareness and slow lexical retrieval. Our findings presented in CHAPTER 4 demonstrate how impaired serial-order learning can affect the formation of lexical verbal–serial representations. Additionally, we have argued that the tasks measuring phonological awareness, such as phoneme deletion (participants repeat words omitting one or multiple phonemes) and Spoonerisms (the first letters of two orally presented words must be switched) involve serial-order processing as an inherent task demand.[21]

[21] To confirm the interpretation that phonological awareness tasks rely on order processing to a certain extent, there is a statistically reliable correlation between the phonological awareness measure employed in CHAPTER 5 and serial recall ability, measured as the average filler performance, $r = .33$, $p < .001$. However, phonological awareness explained a substantial amount of variance in reading skill after controlling for serial recall ability (and for long-term order learning ability). This suggests that phonological awareness tasks capture also something about the manipulation of sounds that is independent of order processing as we have measured it.

To conclude this section, memory for order emerges as a parsimonious theoretical construct that unifies a series of findings in dyslexia, using a wide range of tasks. However, a word of caution is in order here. In suggesting serial-order as a unifying theoretical construct we do not claim that memory for serial-order is necessarily the *single* core deficit causing reading difficulty. It is possible, that several different impairments interact and eventually result in reading difficulties, as posited by multi-deficit models of reading disability. Indeed, our results presented in CHAPTER 5 hint towards this possibility as both phonological awareness and Hebb learning explained unique and independent parts of the variance in reading ability (with phonological awareness explaining a substantially larger amount of variance).

## THE HEBB REPETITION EFFECT: METHODOLOGICAL CONSIDERATIONS

### THE PROBLEM OF INCONSISTENCY OF FINDINGS

Whereas our own experimental studies have provided consistent results, our literature review of Hebb repetition learning in reading disability reveals a more ambiguous pattern of findings, especially in nonverbal Hebb conditions. Table 2 outlines all Hebb studies also concerned with reading impairment, the tasks and measures they employed, and whether group differences (dyslexics vs. controls) were found. Contrary to the observation of a domain-general learning impairment in dyslexia in the study by Szmalec et al. (2011), the early work by Gould and Glencross (1990) on reading-disabled children aged 11, suggested a Hebb learning impairment in the verbal modality only. More relevant to the present dissertation is the recent study of Staels and Van den Broeck (2014b). In a first experiment, these authors tested adults with dyslexia and matched controls in three Hebb learning conditions very similar to those used in the study by Szmalec et al. (2011): a visual-verbal condition with sequences of syllables presented visually; a verbal-auditory condition with auditory syllable sequences; and a visuo-spatial condition with sequences of dot locations. They found a significant group effect only in their auditory verbal condition. In a second experiment with children (sixth graders), they failed to show a significant dyslexic impairment in any of the Hebb variants that were administered (see Table 2). In their paper, Staels and Van den Broeck (2014b) state: "…. we consider it more likely that it is the finding of a dyslexic Hebb learning deficit in the Szmalec et al. (2011) study that is atypical rather than our null finding" (p. 18). The results of the three experiments presented in CHAPTERS 4-5 show however that the claim that the Szmalec et al. (2011) results are 'atypical' does not hold. Nevertheless, inconsistent results in any research field should be a cause for concern. They require additional discussions regarding the possible source(s) of discrepancy.

We should first emphasize that sample sizes in all studies reviewed above are relatively small, so the heterogeneity of the results, assessed by merely comparing outcomes of significance tests, might be due to noise or to insufficient power. Thus, the Hebb learning impairments might be present across individuals with dyslexia, but sometimes the effect may be too small to reach significance with such small samples (but see our proposal on p. 240 regarding the use of an alternative, more powerful, data-analysis method). However, apart from this possibility, we suggest that the inconsistent findings could be attributed to two additional main sources:

subject variability and factors related to the Hebb task's psychometric characteristics.

***Table 2*. Hebb repetition learning studies with their groups, tasks, measures, and results. CA = Chronological age.**

| | Study | Groups | *N* | Age (years) | Matching characteristics | Tasks | Modality | Measure | Gr. diff |
|---|---|---|---|---|---|---|---|---|---|
| ADULTS | Szmalec et al. (2011) | Dyslexics | 16 | 21.19 | Age, IQ | Auditory syllable sequences - 10 rep | verbal | slope | yes |
| | | CA Controls | 16 | 19.94 | | Visual syllable sequences - 10 rep | verbal | | yes |
| | | | | | | Dot sequences - 10 rep | nonverbal | | yes |
| | Staels & Van den Broeck (2014b) (EXP1) | Dyslexics | 26 | 20.69 | Age, IQ, (attention) | Auditory syllable sequences - 10 rep | verbal | weighted sum (slope) | yes |
| | | CA Controls | 33 | 21.61 | | Visual syllable sequences - 10 rep | verbal | | no |
| | | | | | | Dot sequences – 10 rep | | | no |
| | Bogaerts et al. CHAPTER4 (EXP1) | Dyslexics | 25 | 20.60 | Age, IQ | Visual syllable sequences - 20 rep | verbal | slope | yes |
| | | CA Controls | 25 | 21.34 | | | | | |
| | (EXP2) | Dyslexics | 17 | 21.35 | Age, IQ | Visual syllable sequences - 24 rep | verbal | slope | yes |
| | | CA Controls | 18 | 20.28 | | | | | |
| | Gould & Glencross (1990) | Dyslexics | 20 | 11.25 | Age, IQ | Digit sequences - 10 rep | verbal | early vs. later trials | yes |
| | | | | | | Corsi block sequences -10 rep | visuo-spatial | | no |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | CA Controls | 20 | 11.57 | | | | | |
| CHILDREN | Staels & Van den Broeck (2014b) (EXP2) | Dyslexics | 25 | 10.76 | Age, IQ, (atten-tion) | Digit sequences - 10 rep | verbal | weighted sum (slope) | no |
| | | CA Controls | 32 | 10.41 | | Corsi block sequences - 10 rep | verbal | | no |
| | | | | | | Visual form sequences - 10 rep | | | no |
| | Bogaerts et al. CHAPTER 5 | Poor readers | 23 | 7.93 | Age, IQ | Auditory animal sequences - 8 rep | verbal | raw binary data | yes |
| | | CA Controls | 23 | 7.97 | | Dot sequences (with frogs) - 8 rep | verbal | | yes |

*Subject variability*

The view that developmental dyslexia is a heterogeneous disorder, and that multiple impairments may underlie reading disability, is gaining increasing support (e.g., Bishop, 2006: Menghini et al., 2010; Pennington, 2006; Boets, Wouters, von Wieringen & Ghesquière, 2007, and see our discussion of this view, p. 23). From this perspective, any sample of dyslexics may include individuals, each with several cognitive impairments, with the specific nature of those impairments differing across the group. This may lead to a substantial variance of performance in a particular task given the idiosyncratic characteristics of the sample (Ramus & Ahissar, 2012). We should emphasize that this state of affairs is inherent to most dyslexia research (characterized by the use of relatively small samples and, to complicate things further, the use of different criteria for inclusion in the "dyslexic" sample), and not just to studies about serial-order memory (see for example Lum et al., 2013, for a discussion of subject variability in relation to implicit learning impairments in dyslexia).

One solution to overcome subject variability is to sample more than one group of dyslexics for any given theoretical investigation (i.e., self-replication).

*The task's psychometric characteristics*

Findings that are based on participant's performance in a given task are not independent of the psychometric characteristics of the task. In the present dissertation, as well as all the studies reviewed so far, the theoretical construct "*memory for serial-order"* is operationalized by measuring the strength of "*the Hebb repetition effect"*. The underlying implicit assumption is that participants' performance in the Hebb repetition task reflects a reliable and relatively stable individual capacity for serial-order learning. However, to our knowledge, no published research has tested whether serial-order learning capacities, operationalized by the Hebb repetition task, are indeed stable and reliable measures, and how specific scores relate to typical performance of the entire population. This is different from intelligence, working memory or reading scores, for example, in which (a) an individual's performance level is often determined by situating it relative to norm scores, and (b) for which psychometric characteristics such as test-retest indices, internal validity coefficients, etc. are known.

## THE HEBB REPETITION EFFECT AS A MEASURE OF INDIVIDUAL DIFFERENCES

Any task that aims accurately to measure a given cognitive function must display test-retest reliability. If not, participants' scores in a given session may reflect either situation-specific or error variance (see Siegelman & Frost, 2015, for similar discussion in the domain of statistical learning). Such error variance may compromise the interpretation of the findings. In an attempt to address this problem we have recently initiated an investigation (not reported in the empirical chapters above) to assess the reliability of the Hebb repetition task from an individual differences perspective. Our participants (n = 47), Hebrew-English bilinguals, performed two verbal Hebb repetition tasks; one with sequences of English consonant letters and one with Hebrew (also an alphabetic orthography) consonant letters. They were retested on the same tasks after a period of about six months. This design provides multiple testing of the tasks' reliability. First, we asked whether Hebb repetition learning performance using Hebrew letters correlates with performance using English letters within a given session. Second, we asked whether performance in the Hebb repetition task at time 1, predicts performance at time 2. Our preliminary results are summarized in Table 3. First, we looked at average performance on the filler trials, measuring serial recall ability, and average performance on Hebb trials (left side of Table 3). Note that average Hebb performance cannot be taken as a measure of the Hebb repetition effect or the degree of order learning specifically, because there is no control for filler performance. In order to capture the improvement on the repeated Hebb list relative to performance on fillers we looked at two common measures of learning: the *Gradient* measure and a *Halves* measure (see the right side of Table 3). The gradient measure takes the learning rate on the Hebb trials and substracts from it the learning rate on filler trials. The halves measure compares early and late trials to capture the extent of learning (for a detailed description of these measures we refer to the next section, p. 237). Additionally, we calculated the reliability coefficients also by making use of partial correlations to control for filler performance (thereby avoiding difference scores, which have been argued to be inherently less reliable, see Mosse & Jarrold, 2008). More specifically, we correlated average Hebb performance scores, while controlling for average filler performance (*Partial r* in Table 3).

***Table 3.*** **Test-retest of the verbal Hebb repetition task.** N = 47 at time point 1 (T1) and n = 30 at time point 2 (T2). °p≤.1; *p≤.05; **p≤.01; ***p≤.001.

**(A) Within-session correlations Hebrew-English**

| | ***Average scores*** | | ***Learning measures*** | | |
|---|---|---|---|---|---|
| | *Hebb* | *filler* | *Gradient* | *Halves* | *Partial r* |
| T1 | .58** | .82*** | .09 | .22 | .27° |
| T2 | .59** | .80*** | -.14 | -.01 | .26 |

**(B) Between-session correlations**

| | ***Average scores*** | | ***Learning measures*** | | |
|---|---|---|---|---|---|
| | *Hebb* | *filler* | *Gradient* | *Halves* | *Partial r* |
| | .52** | .80*** | .01 | -.04 | .13 |

As can be seen in the table, the results of our two tests of the tasks' reliability (i.e., the within session correlations between a Hebrew and English version of the task, and the between-session correlations) show an identical pattern: Average filler performance, measuring serial recall ability, has a high reliability coefficient (for comparison, reliability scores of standard cognitive tests are typically about .70 or more). The test-retest reliability of the average Hebb score had a lower value. More importantly, the two commonly used measures of degree of Hebb learning, the gradients of improvement and the halves, had very low reliability. The partial r measure indicated slightly higher reliability, yet both within- and between-session correlations remained low and nonsignificant. This pattern of findings suggest that whereas baseline serial recall performance as measured in the task is a stable capacity of the individual and is reliably measured by the task, the relative degree of learning over repetitions is not.

*What could explain the very low reliability of the Hebb learning measure?*

First, low test-retest reliability could be due to a performance level that is close to either floor or ceiling or, indeed, has insufficiently large variance for any other reason. Figure 1 depicts the distribution of the Hebb learning measures obtained in the English condition at the first test session. Both the Gradient and Halves scores show a distribution that is close to normal, which suggests that the distribution of the scores is not the source of the problem. Another possible account of the low test-retest reliability is the very limited number of observations of Hebb trials. In a typical Hebb paradigm (and the one we have used in the current study) there are 30 trials: 20 filler trials, and 10 Hebb trails. This means that for every 'presentation' (repetitions 1-10), the subject has two data points for filler performance (which are usually averaged), and a single data point for Hebb performance. Psychometrical considerations (in individual differences studies) require a significantly larger number of trials, which can reduce the measurement error and increase the task's sensitivity. An additional factor of complexity is that the potential progression in learning depends on the performance on the very first Hebb trial (see our discussion on p. 238/240), which is by itself highly variable (because it relies on only a single data point).

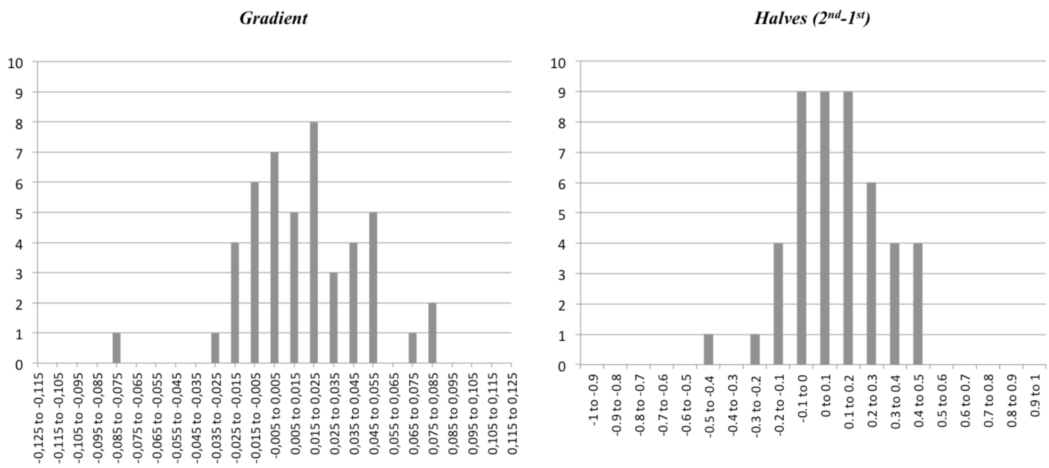


***Figure 1.*** **Distribution of the Hebb learning scores obtained in the Hebb task with English consonants.**

Note that this does not necessarily undermine the theoretical validity of the task in assessing serial-order learning on the group level. Throughout the dissertation, we did obtain and replicate statistically reliable and recurring group differences. It questions, however, the efficiency of specific Hebb learning measures in reliably predicting cognitive abilities at the individual level. We should emphasize that the problem of low reliability in not peculiar to the Hebb repetition task, but extends to most tasks of implicit sequence learning. For example, Siegelman and Frost (2015) very recently demonstrated a relatively low reliability for auditory statistical learning tasks and the SRT task, which are conceptually related and are very similar to the Hebb paradigm. The following discussion thus centers on possible solutions for generating better Hebb learning measures.

## THE NEED FOR AGREEMENT ON THE LEARNING MEASURE[22]

The Hebb repetition effect emerges in a series of immediate serial recall trials, when the performance on a list that is surreptitiously repeated (normally every third trial, for 8-10 repetitions) is shown to improve relative to performance on fillers (i.e., non-repeated lists) presented at approximately the same location in the series of trials. However, researchers have assessed the degree of learning via a range of possible measures. This has led to discussions regarding the “correct” way to assess learning. In what follows, we outline the main measures, and offer what we believe is the optimal solution for assessing the Hebb repetition effect.

### *The Gradient*

Because gradual improvement on the so-called Hebb (repeating) lists is the essence of the effect, we (and many others; e.g., Couture, Lafond, & Tremblay, 2008; Horton, Hay, & Smyth, 2008; Hsu & Bishop, 2014; Parmentier, Maybery, Huitson, & Jones, 2008; Tremblay & Saint-Aubin, 2009) have chosen to measure Hebb repetition learning by looking at the gradient of improvement in serial-recall performance over repetitions, contrasting that with the equivalent gradient over matched fillers. Any non-zero gradient across matched filler lists can be attributed to something like prac-

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[22] Partial adaptation of Bogaerts, L., Szmalec, A., Duyck, W., & Page, M. P. A. Some solid evidence for the SOLID hypothesis, but Staels and Van den Broeck’s (2014) “methodological improvements” are on shakier ground (comment submitted for publication). *Journal of Experimental Psychology: Learning, Memory and Cognition.*

tice effects across trials; any additional improvement across Hebb lists is then attributed to Hebb repetition learning.

*Halves*

This measure, put forward in the developmental Hebb learning studies (e.g., Gould & Glencross, 1990; Mosse & Jarrold, 2008; Archibald & Joanisse, 2012) collapses the presentations of each list type into first and second half scores (e.g., in a task with 8 Hebb repetitions the data from presentations 1 to 4 are collapsed into a first-half score, the data on presentations 5 to 8 into a second-half score). It defines learning in terms of improvements across the two halves of the task. If the difference in performance on the first half versus the second half of repeated Hebb trials is significantly larger than the difference in performance for the first half versus the second half of unrepeated filler trials, then this suggests a Hebb repetition effect. The merging of a few early and late Hebb trials respectively has the advantage that the measures that are entered into the analysis are no longer based on a single datapoint, which reduces noise.

*Weighted sum score*

In their recent paper, Staels and van den Broeck (2014b) claim that the gradient of performance across repetitions is not a good measure of Hebb repetition learning. Their principle objection is that the gradient measure correlates negatively with the intercept of the corresponding regression line. Essentially, if a participant starts with a reasonably high baseline score on the first presentation of the to-be-repeated Hebb list, then they have less headroom to show a gradient of improvement over subsequent repetitions (practically a ceiling effect). This fact, they claimed, makes the gradient (and, so we assume, by extension also a measure like a first-final half difference score) a “poor measure”. They therefore developed an alternative measure, based on a weighted-summed performance across all Hebb repetitions, which they contrasted with summed performance on matched fillers.

Staels and van den Broeck’s method is a little complex, but essentially they did apply linearly increasing weights to scores taken from across the trial series. They derived these weights from an analysis of the mean performance across Hebb and filler trials. Quite apart from the unnecessary complexity involved in the calculation of the weighted sum scores, Staels and van den Broeck’s weighted index of Hebb learning is flawed in several important ways (see our recent reply to this paper, Bogaerts, Szmalec, Duyck, & Page, submitted):

1. First, by failing to divide their weighted sum of Hebb scores by the sum of the weights (often called normalization), the resulting Hebb performance score is not measured on the same scale as the unweighted summed filler score with which it is compared. This is a substantial error.
2. Second, by including an intercept difference in every one of their weights except the first (which is, a priori, set to zero), this intercept difference is built into each weight in a way that fails to acknowledge that any baseline difference between Hebb repetitions and matched fillers cannot be attributed to Hebb repetition learning. Figure 1 gives, on the left hand side, several example scenarios in which even a normalized version of Staels and Van den Broeck’s measure would give the impression that there was Hebb learning when there was none. In the right-hand panel, there is an example where the Hebb list is lower at baseline than the fillers but improves substantially over repetitions, while filler performance remains constant. In this case, no learning would be registered using the weighted sum measure.

3. Third, even if Hebb and filler scores would be normalized to the same scale, and controlled for an intercept difference, the weighted measure would still be inappropriate because the matched filler scores were not weighted in the same way as the Hebb repetition scores.

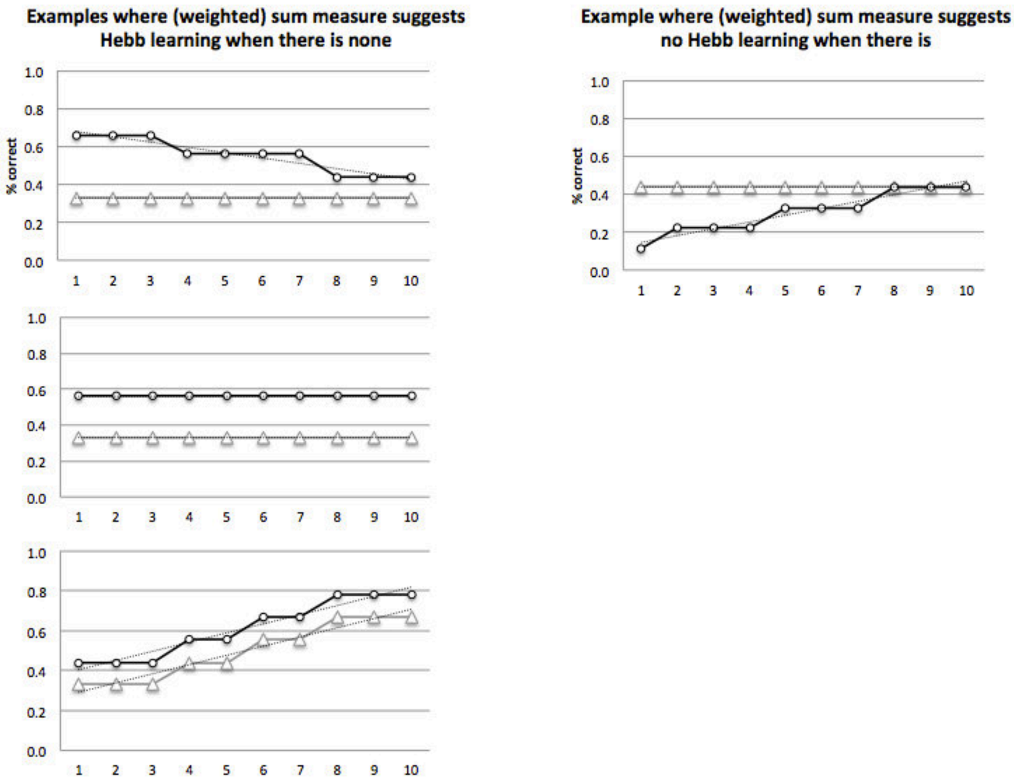


***Figure 2*. Example scenarios in which a weighted sum measure would give wrongly give the impression that there was Hebb learning (left) or that there is no learning (right).**

*Raw binary data*

We have used an alternative data-analysis method designed for categorical data analysis, namely one based on mixed logit models (i.e., generalized linear mixed models with a logit link function, see Bates & DebRoy, 2004; Jaeger, 2008), as outlined in CHAPTER 5. The term 'mixed' refers to the fact that these models allow the inclusion of both fixed effects and random effects associated with, for example, subjects. The logit link function captures the fact that a difference in probabilities close to the upper bound 1, matters more than the same changes around .5. This characteristic seems especially convenient in the particular case of the Hebb repetition paradigm, as there is indeed less room for improvement when initial performance is high. Contrary to all other methods available for the analysis of Hebb learning, the above data analysis method uses the raw binomial data collected during a Hebb repetition task (i.e., the sequence of 1/0 scores, with 1 reflecting that an item was recalled in the correct serial position). An important advantage of mixed logit models over ANOVA or State Trace Analysis (see Staels & Van den Broeck, 2014b) is their greater power (i.e., they are more likely to detect true effects). Our results presented in CHAPTER 5 show that Hebb learning as measured by the LMM method is more powerful in predicting reading skills (our analyses revealed that the traditional Hebb learning measures were not as powerful). This suggests that the LLM measure likely has a higher potential of achieving test-retest reliability than the traditional measures (although further research on this matter is required). Additionally, these models do not make an assumption of homogeneity of variances (an assumption that is often violated in group studies), they can take into account possible baseline serial-recall differences and any other control variable (e.g., IQ, age, version of the task when employing different Hebb sequences across subjects, etc.).

We argue that it is important for future research to converge on a measure, allowing a much more straightforward comparison between studies. We think that the outlined LMM data-analysis offers the most optimal approach for analyzing Hebb repetition learning in future studies.

## FUTURE RESEARCH

Our discussion leads us then to outline some directions for future research.

First, an important challenge for any account of dyslexia is to explain how the supposedly underlying affected memory processes relate not only to impaired but also to normal performance (see Ramus & Ahissar, 2012, for a discussion). We have mostly argued how an impairment in serial-order learning fits patterns of poor performance. Subsequent research should aim not only further to confirm the order-memory hypothesis by showing how dyslexia is impaired in learning tasks involving order, but also by showing that in very similar tasks that do not involve order, dyslexics perform just as normal reading controls do. This offers potential avenues for future studies, where dyslexics are tested simultaneously in settings that involve sequentially ordered stimuli, and conditions where the same stimuli are presented holistically (see for example, Fiser & Aslin, 2001, for a holistic grid presentation of stimuli in testing memory for conjunction of shapes). Moreover, since many accounts regarding the underlying impairment of dyslexia are based on specific experimental tasks, these should be analyzed and retested while controlling whether or not they involve an order component.

Second, memory for order touches upon the vast literature of statistical learning, where sequential stimuli are typically presented in particular orders with different statistical contingencies. There is quite a lot of recent research tying individual differences in reading ability (Arciuli & Simpson, 2012;

Frost, Siegelman, Narkiss, & Afek, 2013) and reading impairment (e.g., Ahissar et al., 2006; Ahissar, 2007) to measures of the ability to register statistical dependencies. Linking the two research areas would provide interesting theoretical advances. In this line of research, the sensitivity of people with dyslexia to transitional probabilities of items within a sequence could be investigated. This may provide complementary evidence in support of a theory involving memory for order.

Third, we believe that our research field would greatly benefit from the development of both short- and long-term order memory tasks and measures that are optimized in terms of their psychometric characteristics, and are based on norms in the normal population. Moreover, the development of highly reliable tasks is important for further research aiming to investigate the predictive value of serial-order memory capacities for (later) linguistic capacities. Indeed, such future studies are needed to clarify the potential causal links between order memory and reading difficulties, thereby providing us with better insights into the clinical significance of impaired order memory in dyslexia (in comparison to, for example, phonological awareness).

Last but not least, the serial-order approach not only offers a theoretical account for further understanding the learning and memory dysfunctions in dyslexia, but also offers directions for future research regarding its possible implications on a more applied level. First, our longitudinal results suggest that it might be useful to include nonverbal tests of order memory in test batteries for early identification of children at risk for reading difficulties (see also Martinez Perez et al., 2012). Second, it would be very interesting to investigate whether serial-order capacities are 'trainable' or whether children can be taught to use them more efficiently. If so, then serial-order processing and learning could possibly serve as a locus for early remediation interventions. These could focus on word-learning strategies that target specifically the order of the letters (and corresponding phonemes) in the sets of words that are repeatedly trained. As an aside, the view of word learning as sequence learning predicts an important role for order processing and learning not only in reading visual word forms but also in producing them in writing (i.e., spelling skills), as well as in speaking, a prediction still open for further exploration.

## CONCLUSION

The four empirical studies presented in this dissertation highlight the role of memory for serial-order in reading and reading disability. We have demonstrated that dyslexia is tied to an impairment in the processing *and* learning of sequential order. Moreover, order memory was shown to make an important contribution to reading development. Overall, the findings presented in this doctoral dissertation contribute to a growing body of evidence regarding the involvement of memory for order in normal and pathological language development (Archibald & Joanisse, 2012; Hsu & Bishop, 2014; Martinez Perez et al., 2012; Martinez Perez, Majerus, & Poncelet, 2012; Martinez Perez et al., 2013; Mosse & Jarrold, 2008; Szmalec et al., 2011).

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# CHAPTER 7
## NEDERLANDSTALIGE SAMENVATTING

In dit proefschrift onderzochten we de rol van het geheugen voor seriële orde informatie bij leesproblemen. We keken daarbij zowel naar de verwerking en kortetermijn opslag van orde informatie (HOOFDSTUKKEN 2-3), als naar het langetermijn leren van geordende lijsten (HOOFDSTUKKEN 4-5). Onze resultaten boden overtuigende evidentie voor de idee dat dyslexie gepaard gaat met een deficit in het geheugen voor seriële orde informatie. De uitkomst van onze longitudinale studie bij kinderen toonde bovendien de belangrijke contributie aan van orde-leren in de vroege leerfase van het lezen. Deze bevindingen werden gekaderd binnen een geheugenaccount voor dyslexie. Tenslotte bespraken we in de algemene discussie (HOOFDSTUK 6) ook enkele belangrijke methodologische kanttekeningen.

## INLEIDING

### LEZEN EN DYSLEXIE

In onze maatschappij is het geschreven woord alomtegenwoordig. Het belang van leesvaardigheid kan dan ook moeilijk worden overschat. Ondanks de complexiteit van geschreven taal leren de meeste kinderen relatief gemakkelijk vloeiend lezen. Ongeveer 5-10% van de totale bevolking ervaart echter ernstige en aanhoudende problemen met lezen en krijgt de diagnose dyslexie (e.g., Wereldgezondheidsorganisatie, 1996).

Volgens de beschrijvende definitie van de Stichting Dyslexie Nederland (2008) is dyslexie "een stoornis die gekenmerkt wordt door een hardnekkig probleem met het aanleren/vlot toepassen van het lezen en/of het spellen op woordniveau". Bovenstaande definitie van dyslexie legt de nadruk op problemen met lezen en spellen. In de literatuur wordt echter bij mensen met dyslexie nog een veel breder spectrum van cognitieve moeilijkheden gerapporteerd. Zo bleken bijvoorbeeld werkgeheugentaken (Smith-Spark & Fisk, 2007), motorische leertaken (Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003) en sensorische taken zoals auditieve en visuele perceptie van snel verdwijnende of snel wisselende stimuli (zie Ramus, 2003, voor een overzicht) problematisch voor dyslectici.

Wat aan de oorsprong ligt van dyslexie vormt tot op vandaag nog steeds het onderwerp van wetenschappelijk debat. Aanhangers van de *fonologische theorie* stellen dat een verstoorde fonologische verwerking de basis vormt van dyslexie (Snowling, 2000; Stanovich, 1988). Problemen met fonologische verwerking werden inderdaad aangetoond met een groot aantal taken, over leeftijden en talen heen (e.g., Ziegler & Goswami, 2005, zie Melby-Lervag, Lyster, & Hulme, 2012 voor een recente meta-analyse). Het oorzakelijk verband tussen fonologische problemen en dyslexie wordt echter steeds meer in twijfel getrokken (e.g., Blomert & Willems, 2010; Castles & Coltheart, 2004).

De observatie dat gebrekkige fonologische vaardigheden niet noodzakelijk resulteren in dyslexie en de vele studies die andere (niet-talige) cognitieve problemen bij dyslexie aantoonden, hebben onderzoekers ertoe aangezet alternatieve theorieën naar voor te schuiven. De *magnocellulaire theorie* (waarvan de auditieve en visuele theorie onderdeel uitmaken) legt het probleem bij de verwerking van snelle temporele informatie (Stein & Walsh, 1997). De ce*rebellaire theorie* stelt voorop dat een dysfunctie in het cerebellum zorgt voor moeilijkheden met de automatisering van vaardigheden, inclusief de automatisering van lezen (Nicolson, Fawcett, & Dean, 2001). Tenslotte werden er in het laatste decennium een groot aantal nieuwe hypotheses geïntroduceerd. Deze focussen op heel uiteenlopende factoren gaande van aandacht-shifting (Hari & Renvall, 2001) en automatische extractie van regelmatigheden tot de visuele aandachtspan (Bosse, Tainturier, & Valdois, 2007) en visuele crowding (Spinelli, De Luca, Judica, & Zoccolotti, 2002).

De meeste theorieën maken de (impliciete) assumptie dat één enkel deficit aan de basis ligt van dyslexie. Het is echter ook mogelijk dat verschillende deficits (bij verschillende individuen) tot leesproblemen leiden (cf. de multifactoriële visie op dyslexie, Bishop, 2006; Menghini et al., 2010; Pennington, 2006).

Enerzijds zijn al deze nieuwe ideeën tekenen van een uiterst actief onderzoeksveld, anderzijds leidt deze pluraliteit tot ertoe dat we mogelijks door de bomen het bos niet meer zien. Een belangrijke vraag is dus of er een onderliggende factor kan geïdentificeerd worden die een rol speelt in de meeste taken waarop dyslectici zwak presteren. Precies deze vraag stellend suggereerde onze onderzoeksgroep recent dat het theoretische construct '*seriële orde*' zo'n integrerende factor zou zijn (Szmalec, Loncke, Page, & Duyck, 2011) en dat de variëteit aan cognitieve moeilijkheden die worden ervaren door mensen met dyslexie mogelijks veroorzaakt is door een onderliggend deficit in het leren van seriële orde informatie. Hieronder bespreken we het theoretisch kader van deze hypothese en zijn empirische evidentie.

## DE ROL VAN HET GEHEUGEN VOOR SERIËLE ORDE IN TAAL

### *Woordleren*

Recent werd veel onderzoek gedaan naar de relatie tussen het leren van seriele orde en woordleren bij normale lezers. Page en Norris (2008, 2009) argumenteerden dat het Hebb repetitie-effect —een operationalisatie van het langetermijn leren van orde informatie— kan gezien worden als het labopendant voor natuurlijk woordleren. Hebb (1961) toonde aan dat, wanneer een welbepaalde geordende reeks van items meerdere malen herhaald wordt in een taak voor Onmiddellijke Seriële Verbale Herinnering (OSVH), dit leidt tot een betere herinnering van de herhaalde sequens (d.i. het Hebb repetitie-effect). Het Hebb repetitie-effect weerspiegelt het langetermijn leren van de orde van items binnen een lijst. Correlationele evidentie voor het idee dat Hebb leren kan gezien worden als een labo-alternatief voor woordleren vinden we bij Mosse en Jarrold (2008). Zij toonden aan dat bij kinderen de grootte van het Hebb leren in zowel een OSVH-taak als in een visuospatiale seriële herinneringstaak, correleert met de prestatie op een nonwoord-associatietaak. Later toonden Szmalec, Duyck, Vandierendonck, Barberá-Mata en Page (2009) op experimentele wijze aan dat een gemeenschappelijk fonologisch procesmechanisme (of ordeningsmechanisme) aan de basis ligt van zowel leren in een OSVH-taak als van verwerven van nieuwe woordenschat. In een eerste experiment werden nonsens-lettergrepen visueel aangeboden volgens een Hebb procedure. Vervolgens voerden dezelfde proefpersonen een auditieve lexicale beslissingstaak uit, waarin nonwoorden werden gebruikt die waren opgebouwd uit de lettergrepen van het eerste experiment. De auteurs observeerden een geïnhibeerde verwerping van de nonwoorden die waren samengesteld uit de herhaalde Hebb sequens, in vergelijking met de nonwoorden samengesteld uit niet-herhaalde fillersequensen. Dit suggereert dat een modaliteitsonafhankelijke langetermijn representatie ontwikkeld wordt gedurende het Hebb leren. Recent werd bovenstaande bevinding gerepliceerd met een meer stringente test van lexicalisatie, die lexicale competitie naging (Szmalec, Page, & Duyck, 2012).

*Dyslexie als een dis-order?*

*Langetermijn orde-leren.* Het bovenstaande theoretische kader verheldert de relatie tussen het geheugen voor seriële orde informatie en het leren van nieuwe woordvormen. Dit kader kan gemakkelijk worden uitgebreid naar het domein van woordlezen wanneer we het leren van een orthografische woordvorm beschouwen als het leren van een geordende sequens van letters of syllaben. Deze visie voorspelt een belangrijke rol voor het geheugen voor seriële orde informatie in het leesproces en de ontwikkeling van leesvaardigheid. Bijgevolg voorspelt de visie dat leesstoornissen geassocieerd zijn met een probleem in orde-leren. Szmalec en collega's (2011) onderzochten deze hypothese en testten volwassenen met een dyslexiediagnose in een Hebb paradigma. Het Hebb repetitie-effect bleek sterk gereduceerd bij mensen met dyslexie in vergelijking met gematchte controleproefpersonen, zowel met verbale stimuli (zowel bij visuele en auditieve aanbieding) als met visuospatiale stimuli (Szmalec et al., 2011). We moeten echter opmerken dat hoewel Szmalec et al. (2011) overtuigende evidentie bieden voor een domein-aspecifiek leerprobleem gerelateerd aan seriële-orde, de resultaten in de literatuur niet eenduidig zijn. Zo vonden Gould and Glencross (1990), bij 11-jarige kinderen met leesproblemen uitsluitend zwakker Hebb leren met verbaal materiaal. Meer recent betwistten Staels en Van den Broeck (2014) de evidentie voor het zwakkere Hebb leren op basis van hun nulresultaten bij zowel kinderen als volwassenen met dyslexie.

*Kortetermijngeheugen voor orde.* De tot hiertoe besproken studies focussen op het langetermijn leren van orde informatie. Echter, het is bijna vanzelfsprekend dat het leren van een sequens niet onafhankelijk is van de succesvolle codering en tijdelijke representatie van die sequens in het kortetermijngeheugen (KTG). Een belangrijke vraag is dus of het orde leerprobleem van dyslectici mogelijks (ook) kan worden toegeschreven aan de tijdelijke verwerking van seriële orde informatie in het KTG. Recente computationele modellen (e.g., Brown, Preece, & Hulme, 2000; Gupta, 2003; Page & Norris, 2009) suggereren dat de verwerking van item identiteit (item KTG) en de verwerking van seriële orde (orde KTG), dissocieerbare functies zijn. Dit werd verder bevestigd in het werk van Majerus en collega's (e.g., Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus, Poncelet, Van der Linden, & Weekes, 2008). We stellen de hypothese voorop dat de demonstraties van een gereduceerde geheugenspan bij dyslexie (Kibby, Marks, Morgan, & Long, 2004; Smith-Spark & Fisk, 2007) mogelijks te begrijpen zijn als een probleem met de sequentiële component van de taak (zie ook Martinez Perez, Majerus, Mahot, & Poncelet, 2012; Martinez Perez, Majerus, & Poncelet, 2013). Dit leidt tot de voorspelling dat mensen met dyslexie in het bijzonder problemen ervaren met geheugentaken die de verwerking of opslag van orde informatie vereisen.

## ONZE BEVINDINGEN

In dit proefschrift hebben we de rol van het geheugen voor seriële orde informatie bij leesproblemen onderzocht. Meer specifiek hebben we ons gericht op vier belangrijke theoretische vragen:

(1) Gaat dyslexie gepaard met een selectief probleem met de orde component van het KTG? Zo ja, is dit probleem specifiek voor taalkundig materiaal of is het meer algemeen (i.e., domein aspecifiek)?

(2) Leiden de problemen met de orde component van het KTG tot bijkomende geheugenproblemen gerelateerd aan de verwerking van seriële orde informatie, zoals het overwinnen van proactieve interferentie?

(3) Is dyslexie ook geassocieerd met een probleem met het langetermijn leren van orde informatie? Zo ja, is het probleem uitsluitend gerelateerd aan het leerproces zelf of ook aan de langetermijn retentie van het geleerde materiaal? Indien het probleem er een is op het niveau van het leren zelf, is het leren dan werkelijk gebrekkig of gewoon vertraagd?

(4) Kan de associatie tussen orde-leren en leesvaardigheid worden aangetoond bij beginnende lezers? En kunnen (relatieve)

moeilijkheden met orde-leren een zwakke leesontwikkeling voorspellen?

Om bovenstaande theoretische vragen te beantwoorden, hebben we vier onafhankelijke studies uitgevoerd die werden gepresenteerd in vier empirische hoofdstukken. We onderzochten zowel de verwerking en de kortetermijn opslag van orde informatie (HOOFDSTUKKEN 2-3) als het langetermijn leren van geordende lijsten —geoperationaliseerd als Hebb repetitie leren (HOOFDSTUKKEN 4-5).

## KORTETERMIJNGEHEUGEN VOOR ORDE MAAR NIET ITEM INFORMATIE IS ZWAK BIJ VOLWASSENEN MET DYSLEXIE

Een eerste experimentele studie, gepresenteerd in HOOFDSTUK 2, ging na of dyslexie gepaard gaat met een algemeen (in contrast tot een domeinspecifiek) probleem bij de verwerking van seriële orde informatie. Een steekproef van volwassenen met dyslexie en een gematchte controlegroep namen deel aan een gedragsexperiment dat de herkenning testte van item identiteit (item KTG) versus seriële orde (orde KTG). In de item KTG taak werd een sequens van stimuli gepresenteerd, gevolgd door één enkel item. De taak van de proefpersoon bestond eruit aan te geven of dit item was voorgekomen in de reeks. In de orde KTG taak werden achtereenvolgens twee sequensen gepresenteerd. Deze waren steeds opgebouwd uit dezelfde items, maar ofwel was ook de seriële-orde van de items identiek, ofwel waren er twee aangrenzende posities gewisseld. De proefpersoon diende aan te geven of de orde van de twee lijsten identiek was. Voor zowel de item als de orde KTG taak was er een verbale conditie, waarin de stimuli (letters, objecten tekeningen) benoemd konden worden, en een non-verbale conditie, welke gebruikmaakte van nonsens tekens. Onze resultaten suggereren dat dyslectici inderdaad een specifiek probleem vertonen met de verwerking van seriële orde in het KTG. Er werd ook met non-verbale stimuli een gereduceerde herkenningsprestatie gevonden in de orde KTG taak. Dit wijst erop dat het gaat om een deficit in de domein aspecifieke vaardigheid om seriële orde voor korte termijn te representeren. In tegenstelling tot het groepsverschil op de orde taak observeerden we dat het KTG voor item identiteit onaangetast is bij volwassenen met dyslexie.

## VERHOOGDE GEVOELIGHEID VOOR PROACTIEVE INTERFERENTIE BIJ VOLWASSENEN MET DYSLEXIE?

In HOOFDSTUK 3 werd onderzocht of de problemen met de verwerking van in het KTG, zoals mensen met dyslexie deze ervaren, leiden tot moeilijkheden bij het overwinnen van proactieve interferentie tijdens werkgeheugen updating. Proactieve interferentie houdt in dat oude herinneringen het herinneren van nieuwe informatie in de weg staat (Jonides & Nee, 2006). Deze vorm van interferentie wordt gezien als een belangrijke bron van vergeten in het langetermijngeheugen (LTM, Underwood, 1957; Wixted & Rohrer, 1993) maar beïnvloed ook de ophaling van informatie uit het werkgeheugen (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) (e.g., Suprenant & Neath, 2009). Volwassenen met dyslexie en gematchte controles werden onderworpen aan een n-back updating taak, waarin interferentie werd uitgelokt. Aangezien het contextgevoelige herinneringsproces (dat gebruikt wordt om proactieve interferentie in een dergelijke werkgeheugen taak te overwinnen) berust op een representatie van een item in de juiste seriële volgorde, voorspelden we meer problemen met het overwinnen van proactieve interferentie bij mensen met dyslexie. Onze resultaten bevestigden deze voorspelling.

### DE LINK TUSSEN GEHEUGEN EN TAAL: EVIDENTIE VOOR ZWAK ORDE-LEREN IN DYSLEXIE

De studie gepresenteerd in HOOFDSTUK 4 onderzocht het langetermijn leren van verbale sequensen bij volwassenen met dyslexie. In een eerste experiment —dat bestond uit drie testsessies— onderzochten we de persistentie van het leerprobleem evenals de langetermijn retentie van het geleerde sequentieel materiaal. Retentie werd nagegaan door één keer 24 uur en één keer een maand na de initiële leerfase de Hebb lijst van het eerste testmoment opnieuw te laten leren. In een tweede experiment werd de lexicalisering van het geleerde verbale materiaal nagegaan aan de hand van een pauze-detectietaak.

De resultaten van deze studie ondersteunen de idee dat dyslexie gepaard gaat met een hardnekkig probleem in orde-leren. Het leereffect van volwassenen met dyslexie bleef immers verminderd ondanks de ruime oefenmogelijkheden (in termen van het aantal Hebb herhalingen). De resultaten suggereren tevens dat de langetermijn retentie van aangeleerde informatie onaangetast is in dyslexie. Tenslotte vonden we zwakkere lexicalisering van het verbale materiaal in de groep met dyslexie. We bieden hiermee voor het eerst directe evidentie dat het geheugendeficit bij dyslectici aanleiding geeft tot problemen met het aanleren en verwerken van taal.

### DE ROL VAN HET GEHEUGEN VOOR SERIËLE ORDE INFORMATIE BIJ LEREN LEZEN: EEN LONGITUDINALE STUDIE

In HOOFDSTUK 5, het laatste empirische hoofdstuk, onderzochten we de betrokkenheid van het geheugen voor orde in de beginnende geletterdheid van kinderen. We gebruikten bij deze studie een longitudinaal design en volgden kinderen op van begin eerste leerjaar tot midden tweede leerjaar.

Een verbale en visuele Hebb repetitie taak, standaard leestesten en enkele testen voor algemeen cognitief functioneren werden afgenomen in een grote steekproef van kinderen, met inbegrip van kinderen met een (familiaal) risico op dyslexie. Een eerste doelstelling van de studie was te onderzoeken of de observatie van een gereduceerd Hebb repetitie-effect in volwassenen met dyslexie kon worden gerepliceerd in kinderen met zwakke leesprestaties. Onze bevindingen suggereren inderdaad gebrekkig orde-leren in eersteklassers die een jaar later klinische leesscores vertonen, in vergelijking met normaal lezende leeftijdsgenoten. Een tweede doelstelling van de ontwikkelingsstudie was na te gaan of er een positieve relatie bestaat tussen de individuele vaardigheid om geordende lijsten te leren en leesvaardigheid, wanneer we kijken naar een ongeselecteerde steekproef van lezers over het volledige lees-continuüm. Deze positieve relatie werd inderdaad bevestigd. Een derde doel van de studie was het exploreren van het potentieel van de Hebb repetitie taak als een voorspellend instrument voor (pathologische) leesontwikkeling. We konden in onze studie aantonen dat Hebb leren inderdaad individuele verschillen in latere (nonwoord) leesvaardigheid kon voorspellen. Tenslotte testten we of de vaardigheid om seriële-orde te leren een uniek deel van de variantie in leesprestaties verklaart, onafhankelijk van de variantie verklaard door fonologisch bewustzijn, een algemeen aanvaarde predictor van leesprestaties. Hoewel fonologisch bewustzijn de meeste variantie in leesprestatie verklaarde, vonden we dat de prestatie op de orde leertaken een unieke en significante voorspellende waarde had.

## ALGEMENE DISCUSSIE

In de algemene discussie (HOOFDSTUK 6) bespraken we de implicaties van onze bevindingen en plaatsten we enkele belangrijke methodologische kanttekeningen.

### GEHEUGEN VOOR ORDE: EEN VERENIGEND THEORETISCH CONTRUCT?

De resultaten van deze vier experimentele studies wijzen op de belangrijke rol van het geheugen voor seriële orde in het domein van lezen. Ze bieden ondersteuning voor de opvatting dat dyslexie geassocieerd is met een probleem met het leren van seriële orde informatie (cf. de "Serial Order Learning Impairment in Dyslexia" of kortweg "SOLID" hypothese, Szmalec et al., 2011) maar onthullen ook de aanwezigheid van orde problemen op het niveau van het KTG. We suggereerden daarom "Serial Order Memory in Dyslexia" als een meer precieze benaming. De belangrijkste theoretische waarde van de orde hypothese ligt in zijn verklarende kracht. De hypothese biedt een integratieve account die verduidelijkt hoe veel van de problemen die voorkomen bij dyslexie —en dan doelen we zowel op de talige als de niet-talige— verklaard kunnen worden door één enkel mechanisme: een deficit in het geheugen voor seriële orde.

*Hoe verklaart een orde deficit de taalproblemen die de kern van dyslexie vormen?*

Ten eerste steunt het lezen of decoderen van een nonwoord in belangrijke mate op korte termijn orde-verwerking. Wanneer een (beginnende) lezer geconfronteerd wordt met een (alsnog) onbekende orthografische woordvorm, zal hij/zij doorgaans elke letter omzetten in het bijbehorende foneem, om vervolgens de volledige reeks van geluiden samen te voegen (Coltheart et al., 2001). De codering van de relatieve positie van de letters is hier cruciaal. Bovendien moeten de letters en de bijbehorende fonemen worden bewaard in het KTG tot productie plaatsvindt (cf. HOOFDSTUK 2, zie ook Martinez Perez et al., 2012, 2013). Ten tweede kunnen we zeggen dat het feit dat de afzonderlijke sublexicale items in een reeks niet optimaal worden geconsolideerd als één lexicale representatie een plausibel gevolg is van de verminderde capaciteit voor orde-leren (cf. HOOFDSTUK 4). Dit zou resulteren in een slechte kwaliteit van lexicale representaties (Perfetti, 2007). Verarmde orthografische en/of fonologische lexicale representaties hebben op hun beurt negatieve gevolgen voor lees- en spellingprestaties (e.g., Perfetti, 2007; Kuperman & Van Dyke, 2011).

*Hoe verklaart een orde deficit de niet-talige problemen die worden geassocieerd met dyslexie?*

Hoewel niet altijd expliciet erkend, ligt seriële orde-verwerking aan de basis van de meeste experimentele taken die gebruikt worden om de capaciteit van het werkgeheugen te beoordelen (e.g., geheugenspan taken waarin een sequens van items in de juiste volgorde dient te worden herhaald). In dezelfde lijn kunnen de dyslectische nadelen, gevonden op impliciete leertaken, worden geïnterpreteerd als een gevolg van een orde deficit. Immers, geheugen voor orde is essentieel voor de succesvolle uitvoering van taken zoals de seriële reactietijd taak of het leren van een artificiële grammatica.

We argumenteerden dat het ‘geheugen voor seriële orde', als een theoretisch concept, een nuttig perspectief biedt voor het begrijpen van de pathologische ontwikkeling van het lezen. Een woord van voorzichtigheid is hier echter op zijn plaats. We willen niet beweren dat het geheugen voor seriële orde noodzakelijkerwijs het *enige* onderliggende deficit is dat leesmoeilijkheden veroorzaakt. De resultaten van de longitudinale ontwikkelingsstudie (HOOFDSTUK 5) toonden aan dat zowel fonologisch bewustzijn als de capaciteit in Hebb leren unieke variantie in leesvaardigheid verklaren. Dit suggereert dat een probleem met orde-leren het best kan worden gezien als *een* (maar niet de enige) belangrijke bron van leesmoeilijkheden (cf. Pennington, 2006, Bishop, 2006).

## METHODOLOGISCHE KANTTEKENINGEN

Terwijl onze eigen experimentele studies convergerende resultaten opleverden onthulde onze literatuurstudie van het onderzoek naar Hebb repitie leren gemengde bevindingen (Gould & Glencross, 1990; Staels & Van den Broeck, 2014). In HOOFDSTUK 6 hebben we de mogelijke redenen voor deze inconsistente resultaten trachten te achterhalen. Ten eerste benadrukten we dat, omwille van de kleine steekproefomvang in alle studies, de heterogeniteit van de resultaten kan worden veroorzaakt door ruis of onvoldoende statistische 'power'. Afgezien van deze mogelijkheid, opperden we dat de inconsistente bevindingen kunnen worden toegeschreven aan twee andere belangrijkste bronnen: 'subject variabiliteit' en factoren die verband houden met psychometrische eigenschappen van de Hebb repetitie taak (met name zijn test-hertest betrouwbaarheid).

Een laatste belangrijke bemerking beschreven in de algemene discussie betreft de precieze maat van leren in het Hebb repetitie paradigma. Er is in de literatuur discussie over wat de "juiste" maat van Hebb leren is. We schetsten de belangrijkste maten die gebruikt werden in voorgaand onderzoek en beargumenteerden het belang van een standaard maat voor toekomstig onderzoek. We opperden tenslotte dat het gebruik van Linear Mixed Models (LMM) als een meer optimale benadering.

## BESLUIT

De vier empirische studies die in dit proefschrift werden voorgesteld benadrukken de betrokkenheid van het geheugen voor seriële-orde bij lezen en bij leesproblemen. We hebben aangetoond dat dyslexie gepaard gaat met een deficit in de kortetermijn verwerking en het langetermijn leren van seriële orde informatie. Bovendien werd het belang van de orde component van het geheugen aangetoond in de vroege ontwikkeling van lezen. Onze bevindingen dragen bij tot de groeiende verzameling aan evidentie voor de betrokkenheid van het geheugen voor orde in zowel normale als pathologische taalontwikkeling (Archibald & Joanisse, 2012; Hsu & Bishop, 2014; Martinez Perez, 2012, 2013; Mosse & Jarrold, 2008; Szmalec et al., 2011).

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# APPENDIX
# DATA STORAGE FACT SHEETS

% Data Storage Fact Sheet

% Name/identifier study: SHORT-TERM MEMORY FOR ORDER BUT NOT FOR ITEM INFORMATION IS IMPAIRED IN DEVELOPMENTAL DYSLEXIA
% Author: Wibke Hachmann (1st), Louisa Bogaerts (2nd)
% Date: 30 May 2015

1. Contact details
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1a. Main researcher
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2. Information about the datasets to which this sheet applies
==========================================================
* Reference of the publication in which the datasets are reported: Hachmann, W. M., Bogaerts, L., Szmalec, A., Woumans, E., Duyck, W., & Job, R. (2014). Short-term memory for order but not for item information is impaired in developmental dyslexia. Annals of dyslexia. DOI:10.1007/s11881-013-0089-5.

* Which datasets in that publication does this sheet apply to?: sheet applies to all data reported in the study

3. Information about the files that have been stored
==========================================================

3a. Raw data
-----------------------------------------------------------

* Have the raw data been stored by the main researcher? [x] YES / [ ] NO
If NO, please justify:

* On which platform are the raw data stored?
  - [X] researcher PC
  - [X] research group file server
  - [ ] other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?
  - [ ] main researcher
  - [ ] responsible ZAP
  - [X] all members of the research group
  - [ ] all members of UGent

```
3b. Other files
-----------------------------------------------------------

* Which other files have been stored?
  - [ ] file(s) describing the transition from raw data to reported results. Specify: ...
  - [X] file(s) containing processed data. Specify: files with processed data as used for
analyses, files regarding the subject characteristics
  - [ ] file(s) containing analyses. Specify: ...
  - [ ] files(s) containing information about informed consent
  - [ ] a file specifying legal and ethical provisions
  - [ ] file(s) that describe the content of the stored files and how this content should
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  - [ ] other files. Specify: ...


* On which platform are these other files stored?
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  - [X] research group file server
  - [ ] other: ...

* Who has direct access to these other files (i.e., without intervention of another
person)?
  - [X] main researcher
  - [ ] responsible ZAP
  - [ ] all members of the research group
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% Data Storage Fact Sheet

% Name/identifier study: INCREASED SUSCEPTIBILITY TO PROACTIVE INTERFERENCE IN ADULTS WITH DYSLEXIA?
% Author: Louisa Bogaerts
% Date: 30 May 2015

1. Contact details
==========================================================

1a. Main researcher
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- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: louisa.bogaerts@ugent.be

1b. Responsible Staff Member (ZAP)
----------------------------------------------------------
- name: Wouter Duyck
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: wouter.duyck@ugent.be

If a response is not received when using the above contact details, please send an email to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.

2. Information about the datasets to which this sheet applies
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* Reference of the publication in which the datasets are reported: Bogaerts, L., Szmalec, A., Hachmann, W.M., Page, M.P.A., Woumans, E., & Duyck, W. (2014). Increased susceptibility to proactive interference in adults with dyslexia? Memory. DOI: 10.1080/09658211.2014.882957.

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3. Information about the files that have been stored
==========================================================

3a. Raw data
----------------------------------------------------------

* Have the raw data been stored by the main researcher? [x] YES / [ ] NO
If NO, please justify:

* On which platform are the raw data stored?
  - [X] researcher PC
  - [X] research group file server
  - [ ] other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?
  - [ ] main researcher
  - [ ] responsible ZAP
  - [X] all members of the research group
  - [ ] all members of UGent

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3b. Other files
-----------------------------------------------------------

* Which other files have been stored?
  - [ ] file(s) describing the transition from raw data to reported results. Specify: ...
  - [X] file(s) containing processed data. Specify: files with processed data as used for
analyses, file regarding the subject characteristics
  - [ ] file(s) containing analyses. Specify: ...
  - [ ] files(s) containing information about informed consent
  - [ ] a file specifying legal and ethical provisions
  - [ ] file(s) that describe the content of the stored files and how this content should
be interpreted. Specify: ...
  - [ ] other files. Specify: ...


* On which platform are these other files stored?
  - [X] individual PC
  - [X] research group file server
  - [ ] other: ...

* Who has direct access to these other files (i.e., without intervention of another
person)?
  - [ ] main researcher
  - [ ] responsible ZAP
  - [X] all members of the research group
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% Data Storage Fact Sheet

% Name/identifier study: LINKING MEMORY AND LANGUAGE: EVIDENCE FOR A SERIAL-ORDER LEARNING
IMPAIRMENT IN DYSLEXIA
% Author: Louisa Bogaerts
% Date: 30 May 2015


1. Contact details
==========================================================

1a. Main researcher
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- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: louisa.bogaerts@ugent.be

1b. Responsible Staff Member (ZAP)
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- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: wouter.duyck@ugent.be

If a response is not received when using the above contact details, please send an email
to data.pp@ugent.be or contact Data Management, Faculty of Psychology and Educational
Sciences, Henri Dunantlaan 2, 9000 Ghent, Belgium.


2. Information about the datasets to which this sheet applies
==========================================================
* Reference of the publication in which the datasets are reported: Bogaerts, L., Szmalec,
A., Hachmann, W. M., Page, M. P. A., Duyck, W. (under review). Linking memory and
language: Evidence for a serial-order learning impairment in dyslexia. Research in
Developmental Disabilities.

* Which datasets in that publication does this sheet apply to?: sheet applies to all data
reported in the study



3. Information about the files that have been stored
==========================================================


3a. Raw data
----------------------------------------------------------

* Have the raw data been stored by the main researcher? [x] YES / [ ] NO
If NO, please justify:

* On which platform are the raw data stored?
  - [X] researcher PC
  - [X] research group file server
  - [ ] other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?
  - [ ] main researcher
  - [ ] responsible ZAP
  - [X] all members of the research group
  - [ ] all members of UGent
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3b. Other files
----------------------------------------------------------

* Which other files have been stored?
  - [ ] file(s) describing the transition from raw data to reported results. Specify: ...
  - [X] file(s) containing processed data. Specify: files with processed data as used for
analyses, files regarding the subject characteristics
  - [ ] file(s) containing analyses. Specify: ...
  - [ ] files(s) containing information about informed consent
  - [ ] a file specifying legal and ethical provisions
  - [ ] file(s) that describe the content of the stored files and how this content should
be interpreted. Specify: ...
  - [ ] other files. Specify: ...


* On which platform are these other files stored?
  - [X] individual PC
  - [X] research group file server
  - [ ] other: ...

* Who has direct access to these other files (i.e., without intervention of another
person)?
  - [X] main researcher
  - [ ] responsible ZAP
  - [ ] all members of the research group
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% Data Storage Fact Sheet

% Name/identifier study: LONGITUDINAL STUDY LINKING MEMORY AND LANGUAGE: EVIDENCE FOR A SERIAL-ORDER LEARNING IMPAIRMENT IN DYSLEXIA
% Author: Louisa Bogaerts
% Date: 30 May 2015

1. Contact details
==========================================================

1a. Main researcher
----------------------------------------------------------
- name: Louisa Bogaerts
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: louisa.bogaerts@ugent.be

1b. Responsible Staff Member (ZAP)
----------------------------------------------------------
- name: Wouter Duyck
- address: Henri Dunantlaan 2, 9000 Gent
- e-mail: wouter.duyck@ugent.be

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2. Information about the datasets to which this sheet applies
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* Reference of the publication in which the datasets are reported: Bogaerts, L., Szmalec, A., Hachmann, W. M., Page, M. P. A., Duyck, W. (revised manuscript submitted for publication). Linking memory and language: Evidence for a serial-order learning impairment in dyslexia. Research in Developmental Disabilities.

* Which datasets in that publication does this sheet apply to?: sheet applies to all data reported in the study

3. Information about the files that have been stored
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3a. Raw data
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* Have the raw data been stored by the main researcher? [x] YES / [ ] NO
If NO, please justify:

* On which platform are the raw data stored?
  - [X] researcher PC
  - [X] research group file server
  - [ ] other (specify): ...

* Who has direct access to the raw data (i.e., without intervention of another person)?
  - [ ] main researcher
  - [ ] responsible ZAP
  - [X] all members of the research group
  - [ ] all members of UGent

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3b. Other files
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* Which other files have been stored?
  - [X] file(s) describing the transition from raw data to reported results. Specify: R
scripts
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analyses
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  - [ ] files(s) containing information about informed consent
  - [ ] a file specifying legal and ethical provisions
  - [ ] file(s) that describe the content of the stored files and how this content should
be interpreted. Specify: ...
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* On which platform are these other files stored?
  - [X] individual PC
  - [X] research group file server
  - [ ] other: ...

* Who has direct access to these other files (i.e., without intervention of another
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% Data Storage Fact Sheet

% Name/identifier study: THE HEBB REPETITION EFFECT AS A MEASURE OF INDIVIDUAL DIFFERENCES
% Author: Louisa Bogaerts
% Date: 30 May 2015


1. Contact details
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3. Information about the files that have been stored
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3a. Raw data
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* Have the raw data been stored by the main researcher? [x] YES / [ ] NO
If NO, please justify:

* On which platform are the raw data stored?
  - [X] researcher PC
  - [ ] research group file server
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Processing, Hebrew University (Department of Psychology), Social sciences building, 0605,
Jerusalem

* Who has direct access to the raw data (i.e., without intervention of another person)?
  - [X] main researcher
  - [ ] responsible ZAP
  - [ ] all members of the research group
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  - [ ] other (specify): ...
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3b. Other files
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* Which other files have been stored?
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  - [ ] main researcher
  - [ ] responsible ZAP
  - [X] all members of the research group
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Louisa Bogaerts
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Ghent University
Henri Dunantlaan 2
B-9000 Ghent

Kaiserslautern, March 4th, 2015

Subject: First author consent

To whom it may concern,

I herewith confirm that Louisa Bogaerts can use our article in her dissertation that is entitled “Short-term memory for order but not for item memory is impaired in developmental dyslexia” and that was published in Annals of Dyslexia, Vol. 64, pages 121-136 in the year 2014. I am the first author of this article which is a result of our common work.

All the best,

W. Hachmann

Wibke Hachmann