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Ph.D. Dissertation

Investigating domain-general short-term memory for order versus specific item memory in developmental dyslexia

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Abstract

Recent findings suggest that people with dyslexia experience difficulties with the learning of serial order information during the transition from short- to long-term memory (Szmalec, 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 work aims 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. In three studies, dyslexic children in Italy, good and poor reading school children in Germany and a sample of adults in Belgium participated in 2 x 2 experiments in which short-term recognition performance for order and item information was assessed, using both verbal and nonverbal material. The findings indicate that, irrespective of the type of material, children and adult 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 dyslexic groups. This work concludes with the assumption that dyslexia is characterized by a selective impairment of serial order short-term memory and discusses the implications of these findings for current theoretical views on dyslexia and its associated dysfunctions.

I. Chapter: Introduction

1. Dyslexia and the issue of definition

About 7% of school children experience problems learning how to read and spell up to a level that allows automatic processing (Peterson & Pennington, 2012). These problems usually concern word level decoding and persist through development, although sometimes changing the patterns of symptoms, for example from slow reading to fluent reading but poor spelling (Bishop & Snowling, 2004). According to the *Diagnostic and Statistical Manual of Mental Disorders (DSM-IV)* of the American Psychiatric Association – the 4th edition that at the time of writing this work is still the official state of the art – problems to acquire written language are diagnosed as dyslexia if reading accuracy and fluency fall substantially below expectations based on age, intelligence and education, and if these problems are not attributable to sensory dysfunction or co-morbidity with other developmental disorders (DSM-IV-TR, 4th ed. text rev., American Psychiatric Association, 2000). In the new version DSM-5, that is about to be released in May 2013,[1] the critical problems of dyslexia are proposed to lie specifically in decoding skills and not for example in comprehension. Also the World Health Organization (WHO) achieves a revised 11th version of the *International Classification of Diseases (ICD-10)*, currently inviting researchers and medical and educational experts to participate in a large revision process. Dyslexia occurs independently of intelligence quotient (IQ) in individuals with very high as well as those with very low intelligence scores, which in the latter case makes it difficult to distinguish from delayed development due to overall low intellectual ability. On the other hand, especially verbal IQ measures obscure diagnostic criteria, introducing a potentially affected and individually very variable standard to compare reading ability to (for detailed discussions of the definition of dyslexia see Bishop & Snowling, 2004, and Lyon, Shaywitz, & Shaywitz, 2003). Consequently, the *discrepancy criterion*, which means that reading must diverge significantly from intelligence measures, was suggested to be replaced by the requirement that the reading problem must be unexpected according to a wider range of general intellectual abilities (DSM-5, proposal). As a compromise, many researchers use the nonverbal part of IQ-measures for a discrepancy cutoff.

[1] American Psychiatric Association (2012). Diagnostic and Statistical Manual of Mental Disorders (5th ed., DSM-5). See project website at http://www.dsm5.org/Pages/Default.aspx, Nov. 12th, 2012.

Amongst all these approaches to a definition, the term dyslexia encloses various degrees of a large diversity of phenomena that can be described as a gradual transition from rather moderate variations in literacy to almost complete illiteracy in spite of adequate schooling in a modern literate society.

Although the definitions strongly focus on the linguistic symptoms, many nonlinguistic impairments have been associated to dyslexia. One of the most debated questions is whether the causes of dyslexia are of specifically verbal 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 visual attention deficits (Bosse, Tainturier, & Valdois, 2007; Facoetti et al., 2009; Romani, Tsouknika, di Betta, & Olson, 2011; Vidyasagar & Pammer, 2009), working memory and executive impairments (Brosnan, Demetre, Hamill, Robson, Shepherd, & Cody, 2002; Kibby, Marks, Morgan, & Long, 2004; Smith-Spark & Fisk, 2007), perceptual anchoring problems (Ahissar, Lubin, Putter-Katz, & Banai, 2006; Banai & Yifat, 2012) or implicit learning difficulties (Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003). The relative importance of predictors for reading ability as well as the specific error patterns vary between languages, for example in relation to orthographic transparency, but nonetheless there are substantial common features associated with dyslexia across different languages: poor phonological awareness and slow serial naming (Peterson & Pennington, 2012).

Forty years ago, researchers considered that those tasks that show deficits in dyslexia all involved the processing of stimuli in sequential order, which promised to be an elegant solution to unite conflicting theories. But with regards to whether or not the problems were specific for linguistic material or found across domains,[2] their results were contradictory. While in some studies, sequence reproduction of dyslexic participants was inferior when faced with linguistic content (Bakker, 1970, cited and reviewed in Vellutino, 1977; Katz, Shankweiler, & Liberman, 1981), other studies report domain-general problems in dyslexia that were common for verbal and non-verbal material (Bryden, 1972; Corkin, 1974, both cited and reviewed in Beaton, 2004, p. 115ff).

[2] To avoid confusion of *domain* with the distinction between sensory *modalities* like the visual versus auditory modality, I will use the term *domain* here to dissociate processing of verbal from that of nonverbal material. Most of the stimulus material in the studies reported below was presented visually and some of it auditorily, while an experimental factor, called *domain*, varied verbal versus nonverbal content.

2. *Phonology and the problem of causality*

More and more research then pointed towards a key role of phonological processing as the best predictor for later reading development. At the same time, performance on phonological processing measures has been shown to often be impaired in dyslexia and consecutively, the general debate focused on a phonological processing deficit (Katz, Shankweiler & Liberman, 1981; Ramus & Szencovits, 2008; Snowling, 2001; Swan & Goswami, 1997; Ziegler & Goswami, 2005). The most established measures for phonological processing are tests of *phonological awareness* (omission and reversion of letters/phonemes) and *rapid serial naming* tasks (naming a repeating sequence of objects, colors or letters as fast as possible). According to the phonological deficit hypothesis, neurobiological preconditions cause individual differences in the phonological awareness of pre-school children (Shaywitz et al., 2002) that for some individuals impede the use of phoneme codes and finally letter to sound mappings, leading to impaired reading and spelling.

The developmental origin and causal role of phonological deficits, though, are highly controversial (Castles & Coltheart, 2004; Melby-Lervåg, Lyster & Hulme, 2012; Morais & Kolinsky, 1994). The main point of critique fosters the understanding that orthography is used as the core representational framework to develop and interact with phonological knowledge during literacy acquisition (Morais, 1991).[3] Phonological awareness and the concept of subdividing speech into phonological elements have been shown to develop in interaction with reading (Morais, Gary, Alegria & Bertelson, 1979; Morais & Kolinsky, 1994). As a consequence, the way we perceive spoken words is influenced by orthography: orthographically similar pairs of physically similar spoken words are easier to recognize than pairs for which the orthographic code differs (Ziegler, Ferrand, & Montant, 2004). This orthographic consistency effect could also be shown in school children of 2-4th grade, for whom the transition from sublexical to lexical reading is ongoing (Pattamadilok, Morais, de Vilder, Ventura, & Kolinsky, 2009).

Finally, coding with the aid of phonological awareness depends on the type of language involved, which is supported by recent findings that point towards a relative importance of phonology in literacy acquisition. For deep orthographies like English for example, in which the matching of phoneme to written form is very often ambiguous, phonological skills seem to play a more important role in dyslexia than in languages that have a much more transparent phoneme-grapheme-code, like for example Italian (Ramus, 2011). Skilled readers of deep orthographies

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[3] For a summary of the debate see the book of Brady & Shankweiler (1991). *Phonological Processes in Literacy. A tribute to Isabelle Y Liberman*. New Jersey:Lawrence Erlbaum.

show an earlier transition from single phonemes to lexical reading, most likely to avoid phonological ambiguity (Frith, Wimmer & Landerl, 1998). For languages with shallow orthographies like Italian on the other hand, rapid serial naming is a better predictor for reading and writing skills than phonological awareness (Brizzolara et al., 2006; Wimmer, 1993).

Not only the interactive nature of phonology and orthography during literature acquisition but also a double dissociation of dyslexia and phonological deficits impose constraints on etiology in this domain. In most studies, there are a constant number of dyslexics for whom there is no report of a phonological deficit as measured with tests of phonological awareness. On the other hand, some children who show a phonological deficit seem to show normal development in written language acquisition (for a summary see Peterson & Pennington, 2012). Boets, Wouters, Wieringen & Ghesquière (2007) argue that the phonological deficit is neither a necessary nor a sufficient criterion for dyslexia (p. 1616 also for the above).

Although phonological skills therefore constitute the best predictor for reading performance, investigating its origin and developmental basis should be inherent with the question of causality in reading development.

Alternatively, dyslexia has been attributed to a magnocellular deficit (Facoetti et al., 2009; Stein & Walsh, 1997). In this theory, the specific symptoms represent an outcome related to phonological decoding problems that arise as a developmental result of a deficient visual attention mechanism, which is insufficiently controlled by magnocells in the dorsal visual stream (Stein & Talcott, 1999). But even more than the phonological deficit theory, the magnocellular theory seems to describe a subgroup of dyslexic individuals, mostly in cases in which there is less of a phonological deficit (for a detailed experiment see Plaza & Cohen, 2006). Successively, the common agreement turned towards a multiple deficit view of dyslexia (Boets, Wouters, von Wieringen & Ghesquière, 2007; Menghini, Carlesimo, Marotta, Finzi & Vicari, 2010; Pennington, 2006) in which most of the variance is explained by phonological problems, a third of cases by the magnocellular theory and some by other, for example motor or executive function impairments. Still, the largest body of evidence report phonological deficits and slow serial naming.[4] But most importantly and as introduced by Bryden (1972) and Corkin (1974), phonological awareness tasks and rapid naming can be argued to substantially demand order processing.

[4] This pattern was confirmed by Franck Ramus in a talk in Milano, Italy, Feb 7th 2011, reporting data from NeuroDys, a large Europe-wide research project on dyslexia.

3. Reclaiming sequence processing

Recently, Szmalec, Loncke, Page and Duyck (2011) renewed the claim that many of the experimental tasks that show impaired performance by dyslexics involve sequentiality, i.e. the processing of serial-order information, and that the cognitive tasks that do not rely on sequentiality often appear unaffected in dyslexia. Convincing evidence in support of this claim was reported by Howard, Howard, Japikse and Eden (2006) from the field of implicit learning, who observed that people with dyslexia experience difficulties only with implicit learning tasks that involve complex sequential stimulus presentation, but not when there is no sequentiality involved. Howard et al. conclude 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. 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). Testing this hypothesis, they found that a sample of adults with diagnosed 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.

The Szmalec et al. (2011) findings show that people with dyslexia have problems with the transfer of serial-order information from short-term to long-term memory, operationalized as Hebb repetition learning. Within the computational models of Hitch, Flude & Burgess (1999) and 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 amongst individual items in a short-term serial recall sequence. In the model of Page and Norris, both the quality of the order representation and its influence on the recognition and production layer determine learning (see Figure 1, Page & Norris, 2009, p. 3742). A new stimulus list causes the units of the order layer to respond with the highest activation for the first item, a little less for the next one and so on, to form a primacy gradient representing serial order in that particular list. This order layer activation is copied into the connection strengths of the occurrence layer, which forms the input for the recognition layer. Here, a repeated list will first activate the same primacy gradient, that however then will emphasize its influence on the occurrence layer in a similar way for a second time, thereby strengthening the same connection settings in the recognition layer. Accordingly, the production layer, which represents the final list retrieval, will receive copies from the units of both the order and the recognition layer. This way, every repeating sequence within a certain time range strengthens recognition of the same primacy gradient and the according list retrieval, leading to better performance with ever repetition, as is the case in Hebb learning.

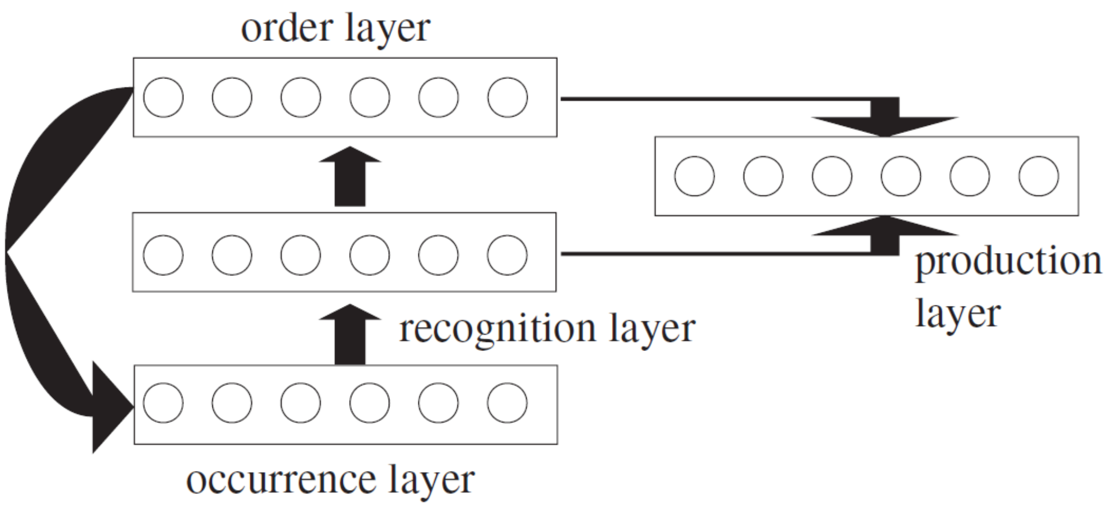


Figure 1: Architecture of the connectionist model of short-term memory by Page and Norris (2009, p. 3742).

Note that the whole learning mechanism "depends heavily on both the presence and the strength of the primacy gradient" (ibid., p. 3745). 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, and is closely related to the acquisition of new phonological word forms (Gupta, 2003; Szmalec, Duyck, Vandierendonck, Barbera Mata, Page, 2009). This concurs with the finding of Howard et al. in two ways: impaired performance in dyslexic individuals 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. Interestingly, one of the most striking findings in the field of higher order cognitive functions in dyslexia is that of a low memory span.

4. Involvement of short-term memory

Several studies reported a reduced memory span in dyslexia, mostly related to 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). The role of verbal memory in new word learning has been well established (see Majerus, Poncelet, Elsen, & Van der Linden, 2006, for a review), and it correlates high with phonological processing, which makes it a good candidate for a common causal role in dyslexia (Johnston & Anderson, 1998; Castles & Coltheart, 2004, but see also Hulme, Snowling, Caravolas, & Carroll, 2005). But whether this common origin describes a verbal or domain-general function, and how either contributes to dyslexia, is still a matter of debate (Kramer, Knee & Delis, 2000; Pennington et al., 1991). As stated by Howard et al. (2006), the involvement of general short-term memory functions such as needed for span tasks and other complex sequential processing seems to be critical in dyslexia. As long as the task involves implicit motor sequence learning (Waber et al., 2003) or the implicit detection of bigram frequencies (Roodenrys & Dunn, 2008), dyslexics perform at the same level as good readers. But if the task requires complex sequences of stimuli, even if the content is purely non-linguistic, dyslexics seem to perform worse than good readers (Howard et al., 2006).

Contrary to this account, Nithart et al. (2009) argue that it is specifically verbal working memory that is impaired in dyslexia. Like many researchers before, Nithart et al. interpreted their findings of impaired verbal short-term memory in a serial recall task in dyslexic children in favor of a phonological deficit, stating that this deficit could also be a co-evolution of deficient phonological processing.

Serial recall tasks as the most widely used task for short-term memory performance, however, address item storage together with the order of the respective items, therewith confounding two potentially different functions. The distinction of order and item processing in short-term memory might be able to answer the debate about domain-specificity in findings of low memory span in dyslexia, and at the same time directly investigate the question of serial order processing asked exemplary by both Szmalec et al. (2011) and Howard et al. (2006).

5. Order versus item information in short-term memory

Current models of short-term memory (STM) allow disentangling sequence from item processing (Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Farrell & Lewandowsky, 2002; Majerus et al., 2008; 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 available for all memory content of different domains (Majerus et al., 2009a). The distinction between short-term memory for item and order information has been used in a number of studies (Majerus et al., 2006; 2008; 2009a; Majerus, Heiligenstein, Gautherot, Poncelet & Van der Linden, 2009b; 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 to new word learning and verbal serial recall tasks, such that order appears to be a better predictor for the speed and quality of new word learning (Majerus et al., 2006), whereas item information rather predicts language-specific knowledge, phonological skills as for example previous exposure to the phonology of a foreign language (Majerus et al., 2008) or lexical frequency (Saint-Aubin & Poirier, 1999). In an integrated framework of mechanisms that contribute to immediate serial recall of verbal material (Figure 2), Majerus et al. (2009b, p. 82) propose that the interaction of lexical and sublexical language knowledge in the form of long-term memory entries constitutes the item function, whereas order detection and maintenance is a separate crucial instance of short-term memory, mediated by selective attention.

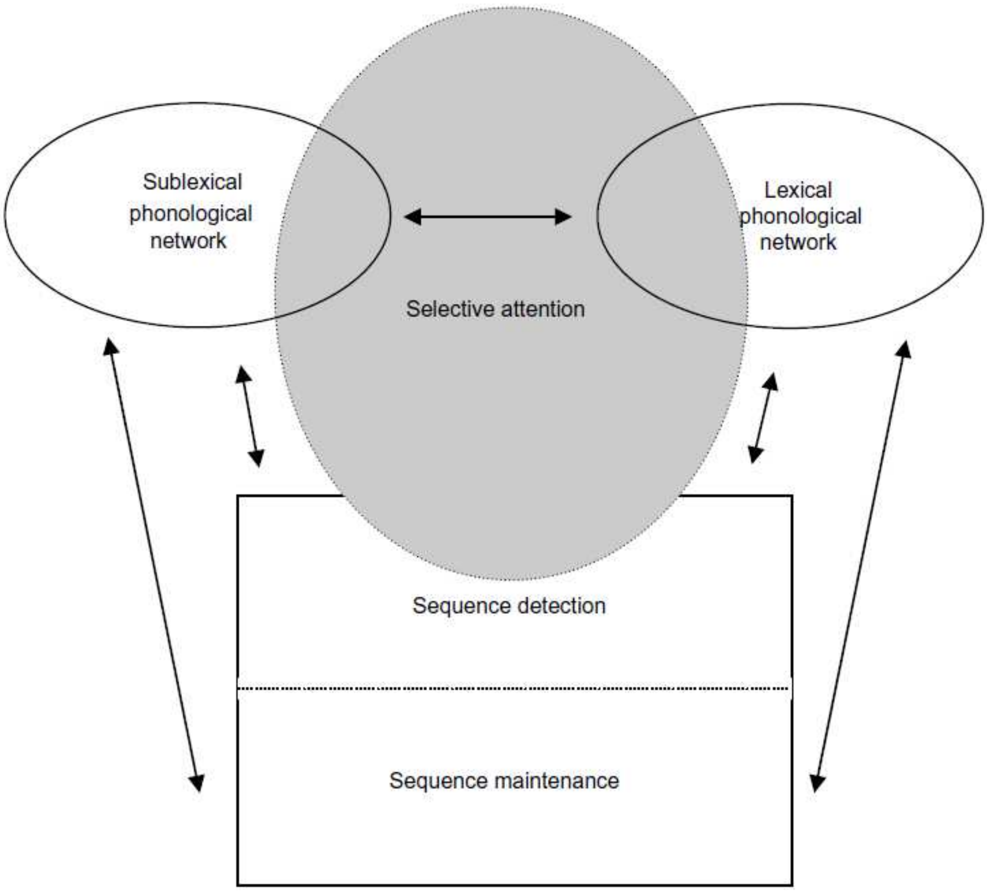


Figure 2: framework of serial order STM, language knowledge and selective attention, Majerus et al. (2009b), p. 82.

Also neurologically these two functions of short-term memory have been dissociated. Majerus et al. (2009a) showed that a network of domain-general executive and attentional functions responded to order tasks, whereas regions specific to 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 showed activation (Majerus et al., 2009a).
Majerus et al. emphasize the difference between a domain-general order function and it´s modality specific item counterpart and describe short-term memory processing as an emergent function of serial order or other executive requirements operating on items that are stored in long-term memory.

If dyslexia is characterized by impaired representation of serial order information in short-term memory and therefore in the processing and learning of ordered information (Szmalec et al., 2011), this may in consequence lead to poor manipulation of phonemes and other serially ordered material, to insecure reading showing increased saccadic eye-movements to previous parts of words or text (Rayner, 1998) and finally result in severely impaired written language acquisition. By investigating this question, the present work may provide a novel and detailed insight into memory and learning that could account for language problems as well as other associated cognitive dysfunctions in dyslexia.

6. Aim and hypothesis

This work hence explores the precise locus of impaired short-term memory in dyslexic individuals by making the explicit distinction between the representation of item and order information in short-term memory tasks and at the same time investigating this distinction both in the verbal and the nonverbal domain. Using the terminology of Page and Norris´ (2009) model, the *primacy gradient in dyslexia* will thus be the subject of investigation of this work.
To this end, the present studies probe the hypothesis that dyslexia is characterized by an impairment of short-term memory that is selective for serial order, and that this impairment includes the verbal and the nonverbal domain, as described by the models presented above. An assessment of short-term memory order processing in dyslexics was also recently reported by Martinez Perez, Majerus, Mahot, & Poncelet (2012). They administered a verbal order

reconstruction task with animal names and pictures and found that dyslexic children compared to both reading age and chronological age matched controls performed worse on this task. This follows Szmalec et al.'s (2011) earlier claim that a serial order learning deficit underlies dyslexia, and is consistent with their own account that new word learning relies on the basis of a domain-general short-term memory for order.

But short-term memory for items, that in the same models is conceived as addressing existing long-term knowledge of single memory entries, should be unaffected in dyslexia. For item memory, however, Martinez Perez et al. (2012) recently reported results that are inconsistent with this hypothesis on first view, but could prove to be an interesting argument in favor of it. Martinez Perez and her group found inferior performance in dyslexic children compared to chronological age matched controls also for verbal item information, using a delayed repetition task of single 3-phoneme nonwords. This task though may not be optimally suited to solely tap into item processing, because it might require some order processing at least during the decoding phase, given that nonwords do not allow semantic or visual coding. As such, the drop in performance of the dyslexic group in the item task reported in the study of Martinez Perez et al. might still be due to an underlying order requirement in the nonword repetition (item) task. Under these assumptions the hypothesize holds that 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 or deficient as a consequence of impaired acquisition of written language.

To test this hypothesis, the present work focused on designing item and order tasks that clearly dissociate the item and order processing in short-term memory, in the sense that item tasks rely as little on order storage as possible, and vice versa. In the item tasks, the order in which stimuli appeared was completely irrelevant to the task, and in order tasks items were predictable and well-known in all cases except for Study 3, in which set size played an important role and hence, also in order tasks the respective items of a series were not predictable. Other than in previous tasks (and unlike Martinez Perez et al., 2012), recognition was used instead of recall in all tasks to 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, (see Pennington, Bennetto, McAleer, & Roberts, 1996, for task distinction or Smith-Spark & Fisk, 2007, for both storage and executive functions investigated separately in dyslexia). In both task conditions verbal as well as nonverbal material was used in order to directly investigate whether any dyslexic impairment in one of these functions surpasses the linguistic domain. This is important because only nonverbal experimental conditions may demonstrate a central dysfunction independent of possibly affected encoding in a sample of participants with a circumscribed language impairment. Also, there are two more theoretical reasons to include nonverbal material: First, an increasing number of studies suggest that the mechanisms responsible for short-term representation of serial order information are domain-general (for a review see Majerus et al., 2009a). Mosse and Jarrold (2008) for example found 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. Second, since all lexical items or combined phonological entities (i.e. words, but also nonwords) by definition imply sequences of phonemes (Page & Norris, 2009; Szmalec, Page & Duyck, 2012), visual stimulus material in the form of nonsense drawings promised to be yet a purer measure of item memory.

This approach resulted in a full-factorial 2 (controls/dyslexics) x 2 (order/item) x 2 (verbal/nonverbal) design that was used with slight variation throughout all three studies. The two item tasks included one with nonsense figures and one with nameable color pictures and words, and the order tasks were matched accordingly with one comprised of another set of nonsense figure and one with verbal material.[5] Over all three studies, this design was evaluated and adapted continuously to improve task validity and difficulty levels for the different participant populations.
According to the hypothesis of an impaired short-term memory function for order, dyslexics are predicted to perform worse than controls on both order tasks, for verbal but also for nonverbal material. For either of the item tasks on the contrary, no difference between groups was expected.

7. Overview

The first study was run as a general initial evaluation of the newly developed design with a sample of 45 high and low proficient readers of school children in Germany in collaboration with Sandra Loosli, who at the time worked at the Medical Center of the University of Freiburg. This first evaluation of the newly developed design was administered in the paradigm of a span task, to be

[5] This latter task, the verbal order task, was adapted several times across three studies, as will be described in the respective material sections of each study. It varied from letters (Study 1) to numbers (Study 2) to another set of nameable pictures and words (Study 3).

able to compare it to existing measures (Nithart et al., 2009; Majerus et al., 2006). This measure was later abandoned and replaced by a pure recognition task of a fixed list length to avoid the particular span-test behavior and associated interference effects that evolve when participants receive lists of increasing length.

Study 2 was conducted at Ghent University in Belgium in collaboration with Arnaud Szmalec, Wouter Duyck and Louisa Bogaerts with an adult sample of 26 formally diagnosed dyslexic individuals and 26 matched controls (Hachmann, Bogaerts, Szmalec, Woumans, Duyck, & Job, submitted). The scope of this study was to investigate whether the findings of impaired order memory persist through development by extending research into an adult population, and to replicate the results showing that even in the verbal domain, item memory remains unaffected also in tested dyslexic individuals. Martinez-Perez et al. (2012) had at this point reported impaired short-term memory performance for an order task in dyslexic children. But for a measure of item memory, their results showed impaired performance in the same population. The differences between the two studies and theoretical implications are discussed in this chapter.

Study 3 instead was conducted with Italian school children who had a formal diagnosis of dyslexia and will further be administered to matched controls for chronological and for reading age. Thsi experiment was part of a larger project about language impairments, and was conducted in collaboration with Francesca Postiglione (Fondazione Marica Di Vincenzi ONLUS), Nathan Maurice Cashdollar (University of Trento) and the public service centre A.P.S.P. Beato de Tschiderer in Trento, and for controls collaborating with elementary schools in Rovereto. Data reported here have to stay preliminary because the study has just begun and after a piloting phase, at this point the experiment was administered to a restricted sample of dyslexic children only.

Besides administering the adapted and tested design finally to a child population that had been properly diagnosed and investigating the dissociation of item and order processing in younger age, this study addresses alternative explanations for the previous results of studies 1 and 2. According to the perceptual anchoring theory (Ahissar, Lubin, Putter-Katz & Banai, 2006; Banai & Yifat, 2012) for example, repetition of a closed set of items would cause heavy interference in the process of anchoring each item to a specific context in every trial, and therefore cause impairments in the dyslexic groups. Also, the effects in study 2 could have been explained by mere task difficulty, since the order tasks were more difficult than the item tasks. The design therefore was adapted in study 3 such that a possible order task effect in the dyslexic group would be independent of task difficulty and set size and be controlled for attentional resources and naming speed.

II. Chapter: Study 1

Young high and low proficient readers of German

This first study was conducted to test the newly developed design of order and item tasks in the verbal and nonverbal domain. With an order as well as an item task adapted from a span task (see Nithart et al., 2009, and Majerus et al., 2006, for comparison), order processing was investigated in high and low proficiently reading children of an elementary school in the south-west of Germany. As described above, the tasks comprised a 2 (verbal/nonverbal) x 2 (items/order) recognition task including: a) two order tasks, one with known letters and one with nonsense figures that were taken from foreign alphabets, and b) two item tasks, one with nameable pictures and words, and one with a different set of nonsense figures. The second set of nonsense figures was created on this occasion and included 200 hand-made doodle drawings. Counterbalancing the order of all four conditions, the tasks were presented to 45 children of 2nd to 4th grade of elementary school, including two classes of children who received special teaching to improve their low reading and spelling skills.

If the rationale of short-term memory for order holds as a broad predictor of reading performance, low proficient readers should perform worse than good readers on all sequencing tasks, be it for verbal or for nonverbal material. For item tasks on the contrary, there should be no difference between groups of reading proficiency.

1. *Method*

1.1 *Participants*

In total, the experiment was carried out with 45 participants aged between 6;6 (6 years and 6 months) and 10;8 (mean (M) = 9;4, standard deviation (SD) = 0;11) of whom 26 were males. The study was conducted in two elementary schools in the south-west of Germany in the south black forest close to the border with France. Parents had given written informed consent and all children who were eager to participate were included. Out of all participating children, 21 received special teaching in place of the regular German language courses of their class, because they had been identified by the last annual evaluation of learning achievement as needing more focused care in the field of reading and writing. The schools provide special courses for children who showed underachievement in comparison to their class peers. These courses are taught by personnel who followed specific training in the area of dyslexia and written language acquisition and comprise about 5-20% of each class. Each end of a school year the schools carry out a writing test (Hamburger Schreibprobe (HSP) [Hamburg writing probe], May, Vieluf & Malitzky, 2001) and those children who performed below the 40^{th} percentile or those who show difficulty during the school year received special teaching, with the consensus of children and parents. The schools approach includes no formal diagnosis if not needed in particular cases, so that the classes were composed of children who had various difficulties with reading and writing. As is the usual case with a so-called "garden-variety of poor readers" (Bishop & Snowling, 2004), also here reasons varied widely as to why some children performed below age and class expectations in the HSP writing assessment. For this collaboration, especially children of these sub-classes were encouraged to participate.

1.2 *Procedure*

The experiment was carried out in two sessions during which each participant was tested individually in a quiet room in the collaborating school. The four experimental tasks were carried out in the first session, while additional testing of reading performance and a short IQ measure was applied in the second session.

First session

Each task started with a probe phase of 6 trials to let the participant get used to the task and the environment. If the child performed well on the probe trials and felt comfortable and ready to start, the experiment proper began.

The four tests manipulated a) stimulus domain with verbal versus nonverbal material and each domain was b) run with two different tasks, an order and an item task. In the verbal domain material comprised letters for the verbal order task and pictures of objects (Rossion & Pourtois, 2004) for the verbal item task. For the nonverbal counterparts, material consisted mostly of self-made nonsense drawings, but for the order task 7 letters from old Greek, Thai, Arabic and Russian were chosen to make the nonverbal order task as comparable as possible to the verbal order task. In the order tasks, participants were instructed to decide by button press whether two sequences of stimuli were the same, whereas in item tasks, instructions asked participants to decide whether an item had been in the previous list or not. Figure 3 depicts the four tasks in the 2 x 2 design with examples of stimuli.

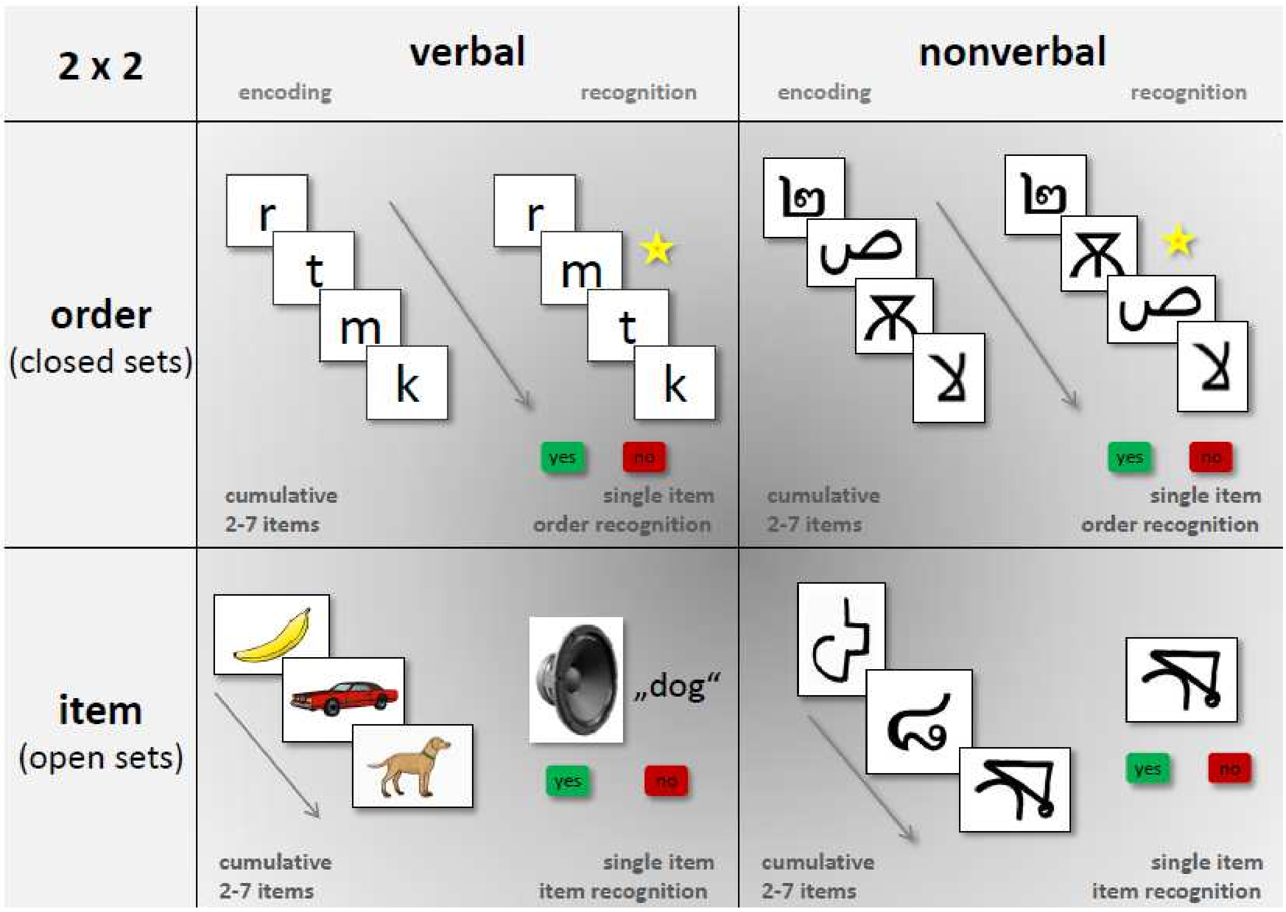


Figure 3: 2x2 experimental design and example stimuli of short-term memory tests for item and order information with verbal and nonverbal conditions respectively.

The lists of stimuli increased in length by one item, starting from a list length of 2 items trough 7. For each step in list length, there were 6 trials comprising one block, making 36 trials in total. Encoding lists were presented cumulatively at a pace of 1 second (sec) per new item from left to right on the upper third of the screen. The following test list in the two order tasks consisted of a temporal sequence in single presentation with a duration of 1 sec per item in the center of the screen. The different loci for encoding and retrieval list in the upper third and in the center of the screen respectively were chosen to avoid visual masking between both lists. Participants were instructed to press a red *no*-key as soon as the order of the second list differed from the first. For correct order, they were asked to press the green *yes*-key (see Figure 3). In item tasks the encoding phase was equal, but for recognition, a single item was probed as target, that in 50% of the cases had been part of the list, counterbalanced across all list positions. The other 50% were made of new target items that had not appeared in any of the encoding lists. In the verbal item condition, targets were presented auditorily to encourage verbal processing and avoid that participants performed mere visual picture matching. This strategy, however, was useful and desired in the nonverbal item task. After each block, a message appeared to tell the participant that the next block would start with one more item in the list. Participants started the next block with a key press, but within blocks, the lists appeared automatically 2 seconds after response.

Reaction times and accuracy were registered as dependent variables. In total, the experiment lasted 45 minutes, comprising 7 minutes per task plus short breaks and a short questionnaire about reading habits. The order of the four tasks was counterbalanced across participants.

Second session

Additional tests were administered that included the Perceptual Reasoning Index and the digit span test of the WISC-VI (HAWIK-IV, *Hamburg-Wechsler-Intelligenz-Test für Kinder*, Petermann & Petermann, 2010 [German version of the Wechsler Intelligence Scale for Children]) and a one-minute standardized reading test for words and non-words in German (subtest of the *Salzburger Leseprobe*, Landerl, Wimmer & Moser, 1997 [Salzburg reading probe]).

2. *Results*

All data were extracted from E-prime and analyzed in R, free software for statistical analysis and mathematical computing. Accuracy data were analyzed as raw binomially distributed data with linear mixed models. For correlations and for plotting, data was aggregated to means by participant for each of the four experimental conditions. The sample that was provided by the schools was more heterogeneous than expected. It included very good readers in the poor readers group as well as poor readers in the supposed control group, and different levels of multilingualism, sensory problems and comorbidities (ADHD).

2.1 *Participants and groups*

Two datasets of participants were excluded because they had not carried out the experiment as instructed or abandoned participation earlier due to motivational reasons. Further, three datasets of left handed and ambidextrous participants were discarded to avoid an influence of inhomogeneous dominance especially on the order tasks. The remaining dataset was formed of 40 participants aged between 6;9 and 10;8 (M=9;5, SD=0;9), 23 of which were males.

This data then was used to form groups by reading performance. In the attempt to extract the most reliable grouping, two grouping parameters were used: 1) the one that the schools had provided and that was based on reading and writing assessments of 10 months prior to this study, and 2) one based on the test results and information that had been collected during this study. Note that besides the difference in testing time, the test that the school had administered was a writing assessment, while the one used here was a reading test. For reading performance, grouping was made by taking only the best and worst readers, leaving out the middle range and matching these two groups approximately for age and IQ measures. Those who performed below a percentile rank (PR) of 30 on the reading test comprised the low performing reading group (LR), while all participants who performed above PR 60 were taken into the high performing reading group (HR). This way, HR and LR groups were formed of 15 and 17 datasets, whereas the remaining 8 datasets of the middle range between PR 30 and 60 formed the medium reading group (MR). For writing performance no further test data was available so that the groups by writing performance were formed according to membership in the special teaching classes (high writing performance = HW, no special teaching, and low writing performance = LW, special teaching).

Table 1 shows the three reading groups by demographic data, reading performance (percent range by age), forward and backward digit span scores and the mosaic test of the WISC-IV, which is the best match with general IQ among the tests of perceptual reasoning. Some children needed more time than one school hour to perform the second session which led to omissions of the test for picture concepts. Hence, the index of perceptual reasoning could only be calculated for slightly more than half of the participants, which is why the values of the mosaic subtest (points by age range) will be used here instead.

Table 1: descriptive data and test results by groups of reading performance

n = 40		LR, n=17		HR, n=15		MR, n=8	
		mean	sd	mean	sd	mean	sd
demographic data	grade	3.29	0.59	3.00	1.00	3.00	1.04
	reading age	1;9	0;6	3;11	1;1	2;10	1;3
	chron. age	9;7	0;6	9;5	1;1	8;9	2;7
	gender	7 (f)	10 (m)	7 (f)	8 (m)	3 (f)	5 (m)
word reading	words PR	10.50	8.32	82.43	13.71	48.55	21.23
	nonwords PR	20.06	13.62	86.30	14.53	61.57	27.01
digit span test	forward	4.82	0.81	5.20	0.94	4.43	1.26
	backward	3.71	0.77	4.07	0.96	3.84	1.47
WISC	mosaic	9.38	2.06	10.30	2.22	9.08	2.71

2.2 *Reaction times*

Accuracy data is the main dependent measure of interest in this study. The analysis on reaction times was run to ensure that an effect of accuracy would not be due to a speed-accuracy trade-off. Participants had been allowed to respond not only after each trial, but especially in the order conditions, had been encouraged to press a button already during list presentation. Each reaction time measure was therefore calculated after the onset of the first wrong target item, which in the order tasks is the first wrong position in mismatch trials and the last position in match trials, but just any target in item task conditions. Reaction times shorter than 350msec in the order conditions were supposed to originate from a reaction to the previous target position, so that the time elapsed during that position was added (1000msec), and for a later analysis by list position (see last part of point 2.3 on page 29 and Figure A15 in the appendix), the respective position number was updated. Psychologically relevant answers could be given seconds after the last target offset, so that there was no reason to discard late reactions. Also to allow an exact match of this data with accuracy, all reaction times were used for this analysis showing a mean response latency of 1361msec (within a range of min. 350msec and max. 9617msec).
These data were subjected to a linear model for Gaussian distributions on the fixed factors domain and task. The model revealed a main effect for the groups HR (SE=42.74, t= -4.138, p<.0001) and MR (SE=51.27, t=3.58, p<.001) and for order tasks (SE=41.21, t= -13.59, $p<2e^{-16}$). There were interactions between order tasks and the verbal domain (SE=58.27, t= -2.14, p<.05) and between the verbal order task and group MR (SE=72.72, t= -2.182, p<.05). Means by group and conditions according to the linear model effects are displayed in Table 2.

Table 2: effects table of reaction times by task and domain

n = 40	item		order		
	verbal	nonverbal	verbal	nonverbal	Mean
LR	1729.53	1674.45	1044.86	1114.67	1390.88
HR	1590.31	1497.59	987.39	1031.40	1276.67 ***
MR	1754.17	1857.77	956.73 *	1241.17	1452.46 ***

Reactions to order tasks were faster, and within order tasks, the verbal order task showed the shortest response latencies. Collapsed over all tasks, the high proficient readers responded faster than average, and medium proficiency readers responded significantly slower. Results about the medium reading group have to be interpreted with caution, taking into account that this group counts half as many members as both other groups.

Most importantly, low readers as a group in relation to the other groups are not the faster to react on stimuli in the order task conditions, they indeed show no significant deviation from mean response latencies in any condition. A hypothesized decrease in accuracy for order conditions in this group, therefore, is unlikely to be due to a trade-off with response speed.

2.3 *Accuracy*

Raw binomial accuracy data were analyzed with generalized linear mixed models for logistic regressions. None of the participants performed at or below chance level collapsed over all span list lengths, so that all data of 40 participants was included. As a first step, task difficulty was evaluated in an omnibus model of accuracy by the two experimental fixed factors task and domain and the random factors participant and target item (trial in the order conditions). It revealed a main effect of domain (E=1.121, SE=.265, z=4.227, p<.0001) that interacted with task (E= -.701, SE=.280, z= -2.507, p<.05). Effect tables show that with 93.5% correct, performance was highest for the verbal item task (Mean proportion Correct, MC= .935) and with 73.7% correct it was lowest for the nonverbal order task (MC=.737), while for nonverbal item and verbal order overall performance was about the same (MC=.824 and .810 respectively).

To investigate group differences, two models on task and domain were run, one time adding the grouping according to writing assessments (school grouping) and the other time the reading performance grouping (experiment grouping).

The model on school grouping revealed a main effect of domain (E=.983, SE=.292, z=3.372, p<.001) and an interaction with task (E= -0.769, SE=.316, z= -2.433, p<.05) similar to the omnibus model. Further, it showed a tendency for a main effect of writing group (E= -.251, SE=.151, z= -1.661, p=0.097), in which high proficiency writers were less affected by the overall task difficulty. There were no further significant effects or interactions in the model on school grouping. Figure 4 shows a box plot of accuracy by the model´s fixed effects task and domain. Mean proportions correct per participant and condition as single data points are collapsed over two tasks in each box.

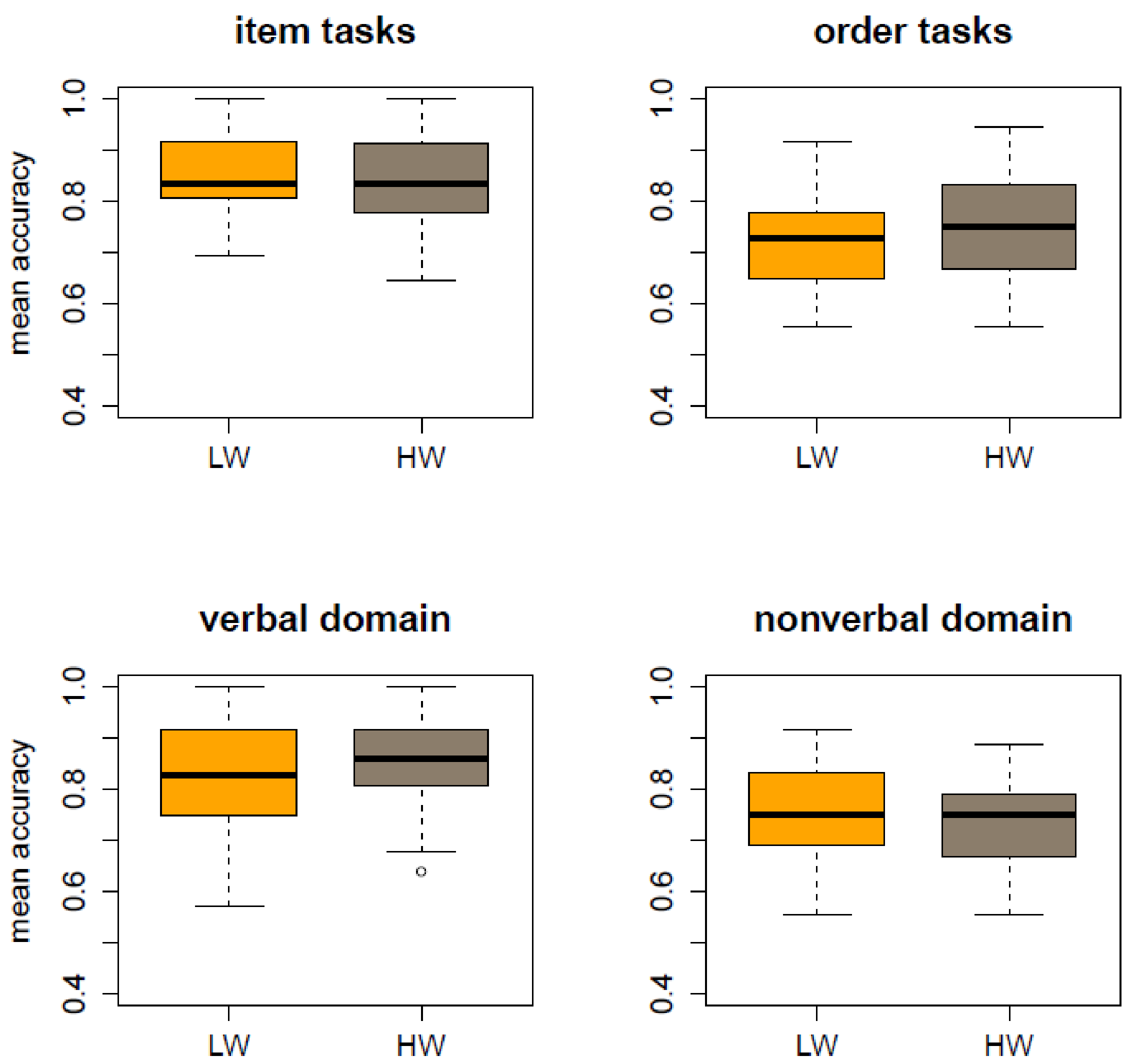


Figure 4: box plot of accuracy on school grouping (writing performance 10 months prior to this experiment), and on the fixed factors task and domain. The thick lines denote median values and the surrounding boxes mark the interquartile range with 1.5 times that range depicted by the whiskers. Data points outside 1.5 times interquartile range are shown as single dots.

High proficient writers perform a little better in order and verbal tasks than their low performing colleagues. This difference was most evident in the verbal order task, while in all other tasks, low proficient writers performed at least as good as high proficient writers. None of these differences, however, was strong enough to reach significance in the regression model. It showed no interaction of school grouping with either domain or task (both $p>.2$).

Figure 5 depicts bar plots for spelling groups (A) and reading groups (B) to compare accuracy for each group by condition. The most evident difference between groupings occurs in the nonverbal order task. Here, good and bad spellers show no difference, but when split into three different groups by reading performance, diverse performance on the nonverbal order task emerge.

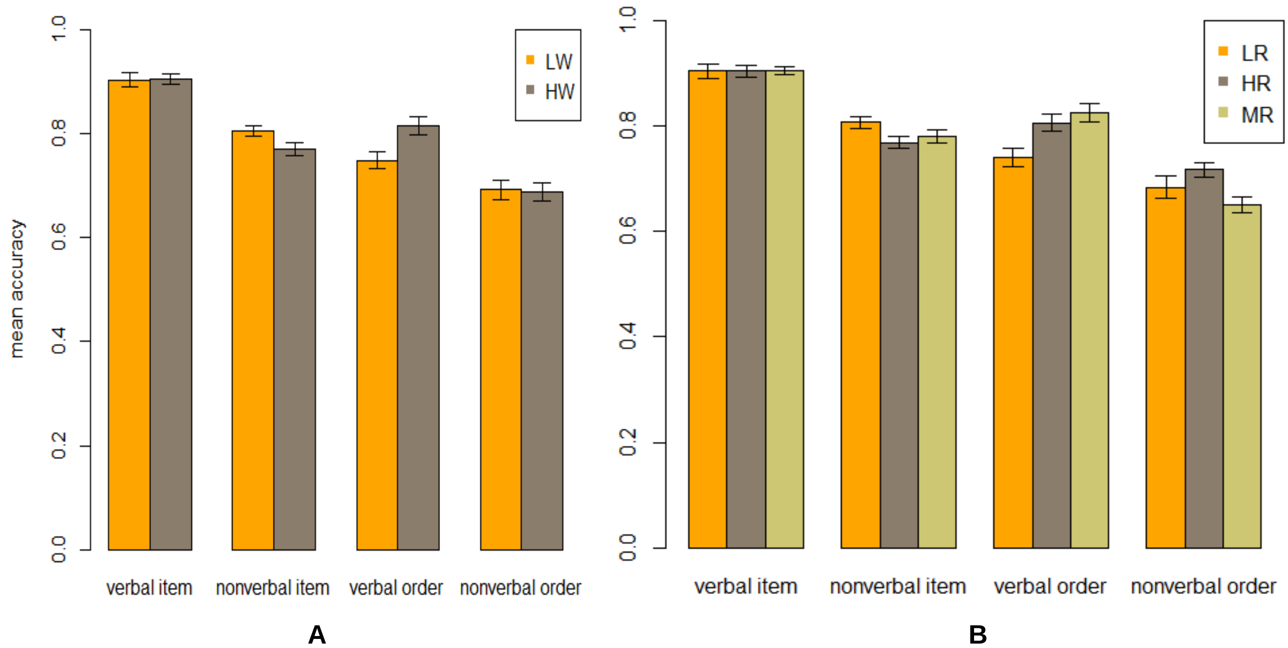


Figure 5: bar plot of mean accuracy on writing test grouping (A) and reading test grouping (B) by task and domain. Error bars depict 1.96 SD from group and condition mean.

The respective model on experimental grouping according to participant´s reading performance showed a main effect of domain (E=0.985, SE=0.301, z=3.278, p<.01) and an interaction of domain and task (E= -0.772, SE=0.328, z= -2.356, p<.05) as both previous models. In addition, there was an interaction of group and task (E=0.404, SE=0.207, z=1.953, p=.0508), denoting inferior performance of low proficient readers in both order tasks. No other effect or interaction showed a tendency or significance.

Planned comparisons of accuracy in order tasks revealed a main effect for group (E=.248, SE=.113, z=2.189, p<.05) and an interaction of group MR and domain (E=.628, SE=.241, z=2.608, p<.01). Low proficient readers performed worse on both order tasks, while for this small sample of medium readers, only the nonverbal order task was particularly difficult. For item tasks there was a main effect of domain (E=1.002, SE=.315, z=3.183, p<.01) and no significant interactions.

As can be seen in Figure 6, low proficient readers performed worse both in order tasks and in verbal tasks, but for the grouping by reading performance, the difference in order tasks was bigger than for the grouping according to the writing test (see Figure 5B). The interaction of reading group with domain was not significant (p=0.326).

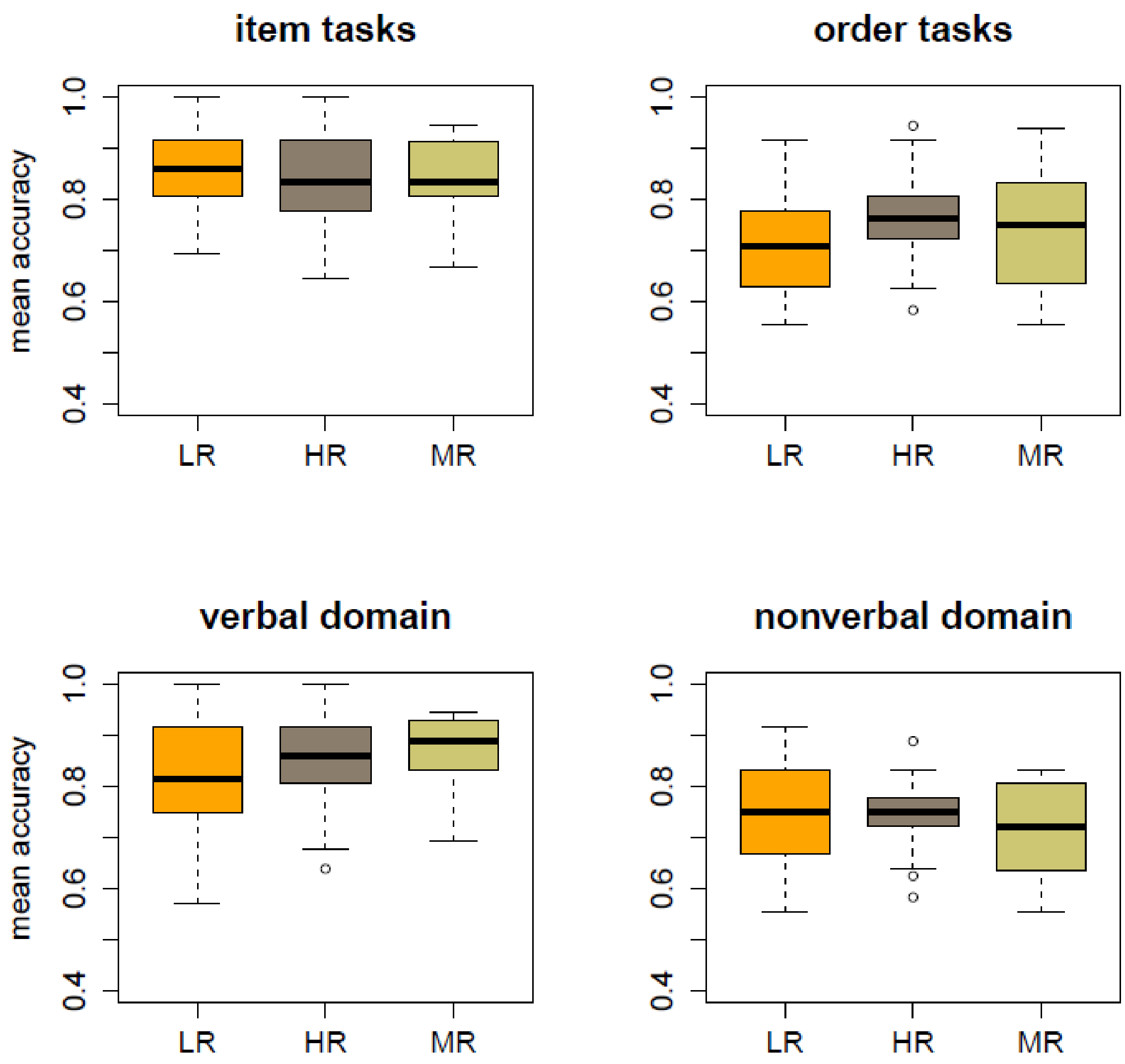


Figure 6: box plot of mean accuracy on reading grouping (tested in this experiment) by the fixed factors task and domain.

Interestingly, the pattern of responses in the reading grouping during presentation of order trials diverges between groups (see Figure A15, appendix). The place of mismatch of the target order lists was counterbalanced within tasks and denotes the place at which the first wrong position of two swapped items occurs. While for the HR group accuracy drops rather monotonously the later the first wrong item occurs, the LR group shows a surprising recovery of accuracy at the latest mismatch position (position 6) in both order tasks up to the level of accuracy in response to correct list repetitions (here depicted as position *0* in green). In item tasks on the contrary, all reading groups performed equally well across target item match positions (Figure A16). This task difference in mismatch and match positions was not found for the grouping according to writing performance.

Performance in order tasks positively correlated with nonword reading ($t=2.2918$, $p<.05$, $r^2=.251$), revealing that participants who had shown high performance in order tasks also performed better in nonword reading as assessed in the one-minute reading task. There was no significant correlation of accuracy with any other of the reading, digit span or WISC-IV measures that had been collected during this study.

3. Discussion

Although the sample comprised a very inhomogeneous combination of reading and writing difficulty, the requirement to remember the order of a serial recall list versus remembering single items seemed to having made a significant difference in performance. This difference was evident in all children in an interaction of domain and task, such that the advantage to use a verbal strategy, that children supposedly adopted in the verbal item task compared to the nonverbal item task, was not as efficient any more in the order tasks. This supports the notion of order memory as a domain-independent function, whereas item measures tap domain-specific long-term memory content.

Low performing readers showed inferior performance in both order tasks, evidenced by a significant interaction of reading group and task. The main effect of domain though did not interact with reading group, suggesting that the verbality of the material itself did not significantly contribute to inferior reading performance. The main effect for domain was similar in the model on writing performance grouping, but neither task nor domain interacted with this grouping. It could be concluded that order task performance is a better predictor for reading than for writing ability. But from these data it is not possible to tell whether this difference in grouping is due to the actual tests of reading versus writing ability or to the time elapsed since testing. Ten months difference from one test to the other mean a lot at the age of second through fourth grade in which children learn at their individual pace, and the stability of assessments for reading impairments are low (see Shaywitz, Escobar, Shaywitz, Fletcher & Makuch, 1992), so that these data cannot easily be compared. Still, it might make sense to assume that for writing ability, long-term knowledge is even more important than for written language encoding, so that a difference in order versus item tasks would be weaker in a grouping according to writing performance.

The correlation between nonword reading and order task performance suggests that serial order processing may play a role in nonword reading, as suggested by Page and Norris (2009) and Mosse and Jarrold (2008). This relation will be examined further in study 2 and in the general discussion.

Other than in the study of Martinez-Perez et al. (2012), there was no difference in item tasks in either of the groupings, making it unlikely that poor reading or writing is related to verbal impairments per se, to fast naming or attention shifting. Fast naming deficits in the low reading group should have impaired also verbal item performance as compared to the high reading group, if it had contributed significantly to reading. Similarly, if attention shifting was impaired in this sample, it should have affected both types of tasks equally, because the encoding phase was the same throughout all tasks. But neither increasing list length nor the difference between verbal and nonverbal item tasks showed any tendency for group differences in the item tasks.

Overall task difficulty resulted in lowest performance for the nonverbal order task. On the one hand it can be argued that low performing readers showed worst performance not on this task, but in the verbal order task, so that a pure effect of overall task difficulty mirrored in the LR group could be ruled out. But the verbal order task on the other hand was conducted with known letters that heavily rely on long-term knowledge of specifically verbal single item decoding skills, so that the increased effect of inferior performance of LR in the verbal order task might be a confound between order and item requirements. Both explanations would be possible within the models of Page and Norris (2009) and Majerus et al. (2009b). In the next studies, the type of material used for the verbal order task and overall task difficulty will be addressed.
Accuracy in the verbal item task almost touches ceiling for some participants, while for longer lists in the nonverbal order task, performance drops below the theoretical 50% chance rate (see appendix, Figure A17 and Figure A18). This could be explained by requirements of the tasks and the according material themselves. On the one hand, the nonsense drawings used here are never completely nonverbal because anything can potentially be given names, and some children reported to having done so. But for most participants, every nonverbal item was a newly to be remembered complex visual entity, while pictures and words in the verbal item task can be integrated into pre-existing long-term knowledge of various modality. For the nonverbal order task on the other hand, the items are not well-known, so it is not a strict order task in the sense of Majerus et al. (2008). Participants still have to remember the items and are not as familiar with them as with letters or numbers, which makes the nonverbal order task much more demanding on the item level than the verbal one.

At the last position of mismatch in order tasks, low proficient readers showed spontaneous recovery from the increasingly lower performance over previous list positions (see appendix, Figure A15). It looks like an equivalence to a recency effect, but another interpretation would be that LR have a shorter chunking ability or memory span for order (as reflected in lower digit span measures), so that they abandon the previous memory entries and focus on the last part of the list as a new order chunk. This performance may also be consistent with a strategy of waiting until the end of the list to process the whole list instead of every item position separately. In this case, however, also medium list positions would show better recognition. Two participants of the LR group responded only at the very end of each list in either order task. They had been reminded several times that it is possible and desirable to respond as soon as they detect a wrong item, but proved reluctant to this strategy. In item tasks on the other hand, the position at which a target item of matching trials had been in the encoding list did not contribute much to performance (see appendix, Figure A16). If target match position played a role in item tasks, it may be observed only in the nonverbal item task, but the pattern is the same for both high and low reading groups. This suggests again that a visual attention span or sluggish shifting (Bosse et al., 2007; Hari & Renvall, 2001) could not have caused this pattern of results, because in that case item task performance would rely more on memory traces for order positions and would be more likely to also show group effects.

The findings of this first study confirm that generally the differentiation of order and item short-term memory plays an important role for written language acquisition. But this experiment itself cannot answer whether or not order processing contributes specifically to developmental dyslexia. The material used here make the task comparable to the studies of Majerus et al. (2008) and Nithart et al. (2009), but need refinement to answer more specific questions. Being aware of subgroups of reading and writing performance and including formal diagnostic testing has to assure that the present results can be related to dyslexia in particular. These questions will be addressed in the studies 2 and 3.

III. Chapter: Study 2

Serial order memory in adult dyslexics

During a collaboration with the department of Experimental Psychology at Ghent University in Belgium, this study with formally tested adult dyslexics was carried out to investigate the exact locus of serial order short-term memory in dyslexia compared to controls in analogy to the quality of representations in the order layer of the computational model in Page & Norris (2009). The procedure of a span task was abandoned in favor of a more simple recognition task, because span tasks foster a slightly different strategy in memory retention from one list length to the next, which might influence performance in different ways between groups. Accordingly, the tasks had to be matched for difficulty to avoid bottom and ceiling effects, now lacking its original adaptivity.
To avoid that participants somehow verbalized the repeated nonsense figures in the nonverbal order task, a verbal suppression task following the procedure for visual working memory tasks in Luck & Vogel (1997) was added.

1. *Method*

1.1 *Participants*

Fifty four students, all native Dutch speakers, with a mean age of 21 years (SD = 1;6 years, range 18;2 to 25;6) from all faculties of Ghent University and four University Colleges in Ghent volunteered for the study.
All of the 26 participants of the experimental group (16 males) had a history of dyslexia that dated back to childhood and they had received their most recent full evaluation of a formal diagnosis not longer than two years ago by Cursief, the support center for students with disabilities in Ghent (diagnostic standard: *Gletschr. Test voor Gevorderd Lezen & Schrijven* [Gletschr. Test for Advanced Reading & Writing], De Pessemier & Andries, 2009). 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 of at least six months duration. Co-morbidities 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.
The control group consisted of 26 regular non-dyslexic students (14 males) who were enrolled in the bachelor or master program at the same University and Ghent University Colleges at the time

of participation. To match groups in addition to formal diagnosis, all participants were administered the same standardized tests, two reading tests and IQ testing, either less than two years before or during participation.

1.2 *Material & Procedure*

The memory tasks reported here were administered in a session one day before all other tests. The order of the four memory tasks was counterbalanced so that each rotation was used at least once in every group.

1.2.1 Nonverbal Item Task

The material consisted of 171 drawings of nonsense symbols (9 items x 18 trials + 9 new targets), see Figure A19 in the appendix for stimulus examples. On each trial, 9 symbols were displayed in consecutive single presentation at a rate of 1000 milliseconds (msec) next to each other positioned along a horizontal axis in the upper third of the computer screen. The list was preceded by a fixation cross of the same duration at the position in which the first item would appear. The number of items in one list (list length) was determined in a pilot study that was run with 18 researchers prior to the actual study. The list length for each condition was chosen so that at least 10 of the piloting participants performed at around 75% over all 18 trials at that length. After each list, a central fixation cross indicated the target item and consecutively, one symbol was displayed alone at the center of the screen, paced at a rate of 1000msec, and followed by a question mark. Participants were asked to respond *no* or *yes* with buttons on a response box, indicating whether the target symbol had been in the list that was presented before or not. With this open item list none of the symbols was ever displayed twice. List selection was randomized and counterbalanced across participants. Two familiarization trials with identical procedure to the experimental trials but with a different set of items were administered at the beginning of the task.

1.2.2 Verbal Item Task

Nameable pictures and auditorily presented words were presented in the verbal item task so that within the verbal domain, items were addressed both through the visual and auditory modality. A subset of 234 pictures from the set of colored object drawings by Rossion & Pourtois (2004) formed 18 lists of 13 pictures each. They were selected randomly and displayed in consecutive single presentation on one long horizontal axis on the computer screen in the same way as in the nonverbal item task. Each list was followed by a delay of 1000 msec after which a word was presented auditorily that either did or did not name one of the objects depicted in the list before. As target pictures those were chosen that represented objects named by disyllabic words in Dutch within a restricted frequency range, somewhat towards the higher end of the scale (2 to 52 times less frequent than the most frequent word of the underlying corpus (Celex), log frequency range=.6-1.7, M=.982, SD=.408). Mean age of acquisition for displayed 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 used were *vliegtuig* (*airplane*) and *sleutel* (*key*), respectively. Importantly, all words had a name agreement of 100%. The task was the same for both item tasks, namely to decide by button press whether the target – here a word – had been in the list that was displayed before or not. No picture or target word was ever repeated across the experiment. To familiarize participants with the task, one trial with different items was used before the beginning of the experimental trials.

1.2.3 Nonverbal Order Task

Four nonsense symbols constituted the material for this condition. To make the task perceptually easy at the item level, care was taken to draw the symbols in such a way that they are easy to distinguish while maintaining their nonverbal character.

The four symbols were repeatedly rotated across all four order positions to form 18 lists. To familiarize participants with the task, four of the lists were displayed at the beginning of the task. 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. List selection was randomized as was the order of familiarization trials. Participants had to constantly 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 symbols (see p. 6 of the *Introduction*). List presentation was exactly the same as in the item tasks.

Preceded by a fixation cross at the position of the first list item, a list of the 4 symbols was displayed in single presentation one by one for the duration of 1000 msec each in a horizontal row in the upper third of the screen. The list was followed by a second fixation cross in the center of the screen, after which the same list repeated in single presentation with each item being presented centrally on the screen for 1000 msec, one by one. Figure 7 shows the procedure of the task with an example of a mismatch trial. The items shown here were the same throughout the whole task.

For half of these target lists, two neighboring positions were swapped, counterbalanced across all list positions. If the second list had the same order as the first, participants had to press the green button for *yes*. If the order of the second list differed, they were instructed to press the red button for *no* as soon as they recognized the difference. A response during presentation of the second list terminated that trial.

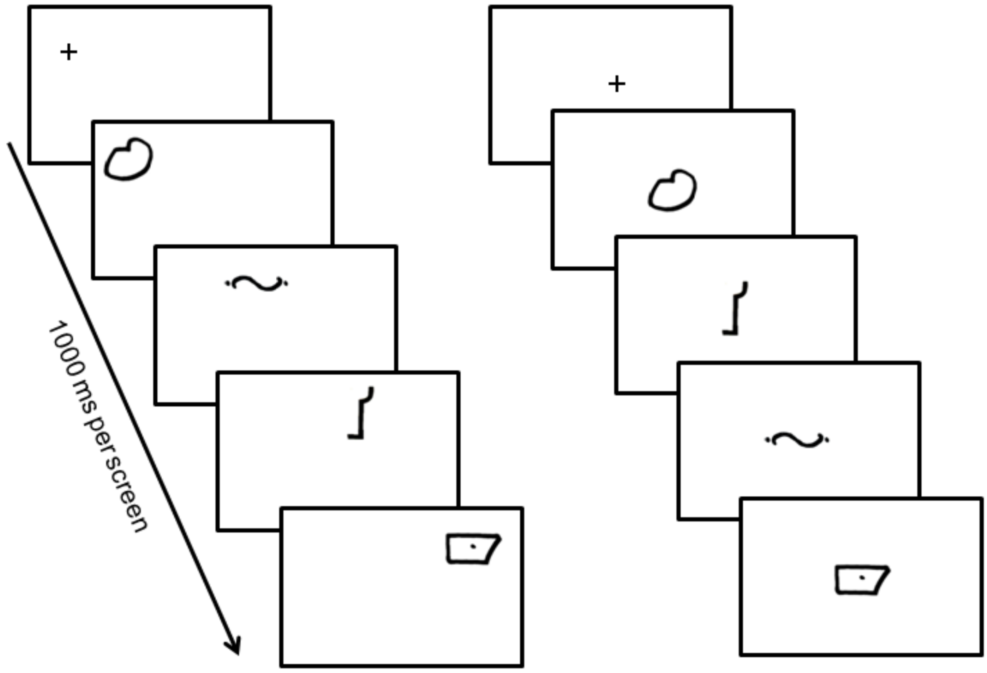


Figure 7: procedure of the nonverbal order task, example of a mismatch trial. Participants could press a response key during presentation of the second list, in this case a fast and correct response would be *no* during the second screen of the second list.

1.2.4 Verbal Order Task

The same procedure (but without articulatory suppression) was used for the verbal order task. The material used in this condition were the numbers 1 to 9 that were rotated in 9 list positions to form 18 lists, each of which was made of all numbers from 1 to 9. Participants saw the numbers in single presentation on a horizontal line preceded by a fixation cross and with the same timing as in all other conditions, and again in single presentation centrally for a second time as in the nonverbal order condition. During presentation of the second lists, in half of the trials two adjacent positions were swapped and these swaps were counterbalanced over all list positions. Participants had to decide whether the order of the second list was the same as the one of the first list and were asked to press the *no* button as soon as they noticed a difference, also during the presentation of the second list. To familiarize participants with the procedure, one trial of the same length and material preceded the experimental trials. Also here, trial selection was randomized. In all tasks, each trial was followed by a question mark providing response time for a maximum of 10 seconds, if it was not terminated by a response before.

1.2.5 Reading and Intelligence test

The same reading and intelligence tests that earlier studies with dyslexics from the University's diagnostic centre (Cursief) had used (Callens, Tops, & Brysbaert, 2012; Tops, Callens, Lammertyn, Van Hees, & Brysbaert, 2012) were administered to all participants. These included the short version of the Kaufman Adolescent and Adult Intelligence Test (KAIT) in Flemish (Dekker, Dekker, & Mulder, 2004), a one minute word reading task in Dutch ("Éen Minuut Test" (EMT), Brus & Voeten, 1979) and a Dutch nonword reading task for children (De Klepel. Een test voor de leesvaardigheid van pseudowoorden [A test for the reading ability of pseudowords], Van den Bos, lutje Spelberg, Scheepsma, & de Vries, 1994) that was shortened to one minute instead of two for this adult sample to avoid ceiling effects in the control group. In each reading test, the participant was asked to correctly read aloud as many words as possible in one minute.

1.2.6 Digit span test

We recorded a female Dutch native speaker's voice on lists of digits, spliced to one digit per second, spoken in a natural but very regular fashion with end-of-sentence prosody on the last digit of a list (as described in the manual of the respective Wechsler Intelligence subtest (WAIS)). List length varied from 3 to 10 in increasing order, providing two trials per list length. The experimenter paced presentation onset of every list and the participant was asked to repeat all digits in correct order while the experimenter checked the answers manually on a prepared sheet that was hidden from participants view. If a participant failed to correctly repeat both trials of a list length, the test was abandoned and the last list length at which the participant repeated at least one list correctly was stored as the individual digit span score.

2. Results

Four participants were excluded from analysis - one male and one female in each group – due to self-reported sleep deprivation, medication that impaired attention, unrelated language problems and insufficient grouping criteria, in this case mild dysorthography with no other reliable criteria for dyslexia, leaving a sample of 24 participants per group.

2.1 *Group characteristics*

Table 3 sums the two groups by age, reading performance, digit span scores and KAIT Intelligence scores. Group differences were only evident in reading performance both for word (EMT) and nonword reading (Klepel), and in digit span.

Table 3: characteristics of participant groups

n = 2 x 24	dyslexic group			control group			t-test (paired, 2-sided)
	mean	median	sd	mean	median	sd	p
age (years; months)	20;7	20;8	1;5	21;3	21;0	1;6	.2
KAIT total IQ	108	107	9.3	111.6	112	8.4	.193
word reading (EMT)	83.4	88	19	101.6	103	10.5	< .001
nonword reading (Klepel)	44.8	41.5	13.1	65.1	63	12.4	<.0001
digit span	5.5	5	.9	6.4	6	1.2	< .01

2.2 *Accuracy data*

Data of the four memory tasks were analyzed in R, free software for statistical analysis and mathematical models. To correct for outliers, the modified non-recursive procedure of Van Selst and Jolicoeur (1994) was applied, who proposed a moving criterion cutoff to account for sample size and diverging skew. The criterion, i.e. the maximum number of standard deviations from group and condition mean, is calculated for different sample sizes “by anchoring the mean to that generated by the simple non-recursive procedure with a criterion cutoff of 2.5 *SD* at a sample size of 100” that includes both a less skewed and a highly skewed distribution of the same population (idm, p. 641). Criterion for cutoff in this case was 2.414.

For descriptive purposes, for outlier analysis and for correlations, average accuracy proportions were calculated across all 18 trials per condition for each participant. Three dyslexic participants showed performance inferior to a cutoff of 2.414 SD below group and condition mean in one of the item conditions, which approximately corresponds to chance level performance (50% correct). After controlling for the fact that in all of the other variables word- and nonword reading, short IQ and digit span, none of those three participants showed values that differed from the standard variation of their group peers, the datasets of these participants were discarded, which resulted in a data reduction of 6.25%. Mean proportions correct of the 45 remaining datasets are presented in Figure 8, showing a box plot with median values and quartiles for each group and condition.

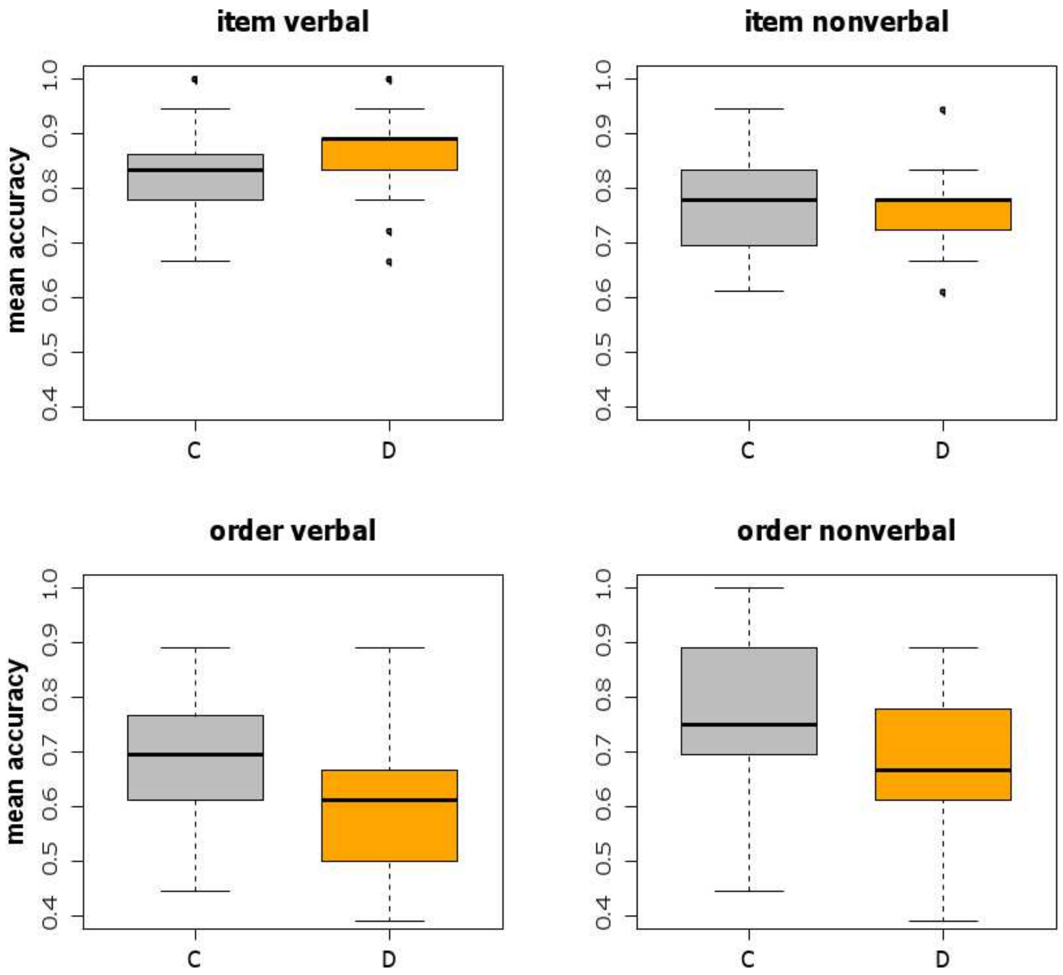


Figure 8: Box plots of mean accuracy by group (dyslexic=D, control=C) for each condition.

The raw accuracy data were submitted to a generalized linear mixed model (lmer) for binomial distributions with the dependent variable accuracy on the fixed factors 2 (group) x 2 (task: item/order) x 2 (domain: verbal/nonverbal) and participant and item as random factors. This overall analysis of the complete design revealed a main effect of domain (E=.942, SE=.338, z=2.789, p<.01) and an interaction of task and domain (E= -1.336, SE=.371, z=-3.598, p<.001), indicating that performance was significantly highest in the verbal item task. There was no significant interaction with group, neither two-way with domain (z= -1.574, p=.116), nor three-way with domain and task (z=1.169, p=.242).

2.2.1 Accuracy in order and item tasks by groups

To evaluate the effect of task on group, the same model was run with accuracy on group and task. It revealed a main effect for task (E= -1.143, SE= .270, z= -4.238, p<.001) which was qualified by an interaction effect of task and group (E=.443, SE=.172, z=2.581, p<.01), confirming that performance on order tasks was significantly lower for dyslexics compared to controls, but equal for both groups in the item tasks. Nineteen of the 21 dyslexic participants performed below the average of the control group in either one of the order tasks. For any of the two item tasks, 10 out of the 21 dyslexic participants performed below control group mean. Figure 9 shows the interaction effects plot of group and task, deriving average accuracy proportions for each group and task from the model. Running the same model on group and domain for comparison showed a marginal effect of domain (z= -1.820, p=.069) and group (z=1.733, p=.083), and no significant interactions.

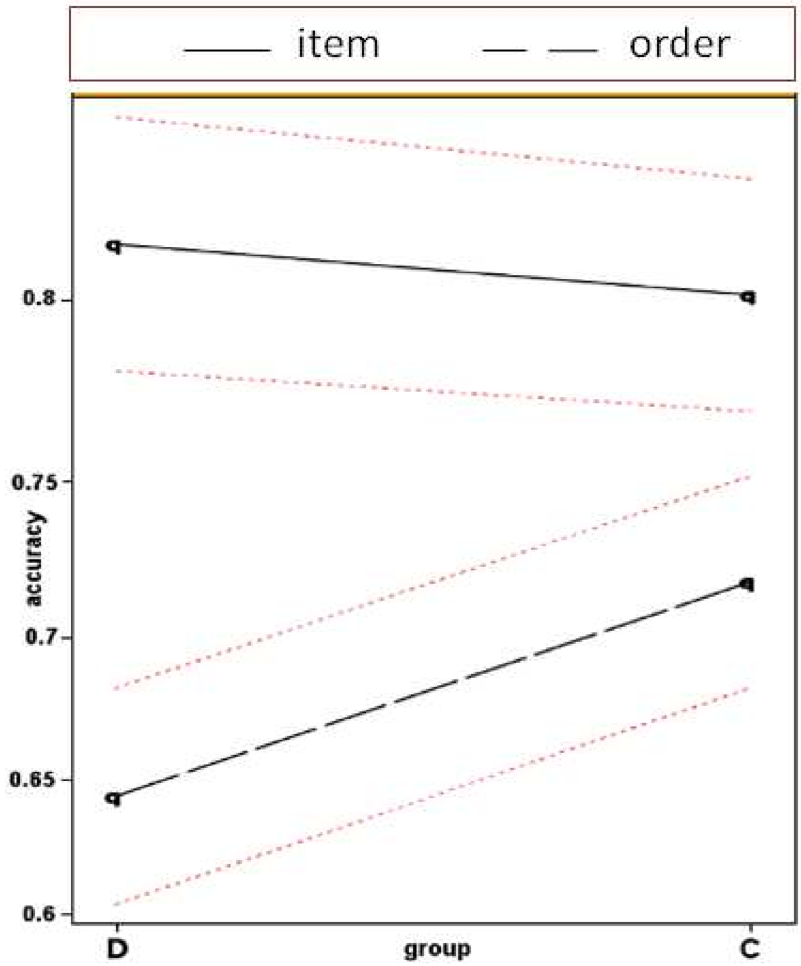


Figure 9: effects plot of the linear mixed model for accuracy on group (dyslexic=D, control=C) and task, depicting the interaction of both factors. The small dotted lines depict confidence bands (limiting level=95%).

Planned comparisons over both item tasks (accuracy of the subset of both item conditions on the factors group and domain) revealed a main effect of domain (E=1.018, SE=.425, z=2.393, p<.05) with no significant interactions (domain : group yielded z= -1.593 with p>.1) and no effect of group (z=.464, p>.5), confirming that there was no group difference in the item tasks, even if there was a tendency for dyslexics to perform better than controls in the verbal item task. For order tasks, there were a main effect of group (E=.362, SE=.180, z=2.015, p<.05) and a main effect of domain (E= -.387, SE=.154, z= -2.518, p<.05) and no significant interactions.[6]

2.2.2 List positions

In order to assess performance within lists, accuracy was analyzed on list position in the verbal order task to the extent that is possible with the actual design. For those trials in which the order of the second list differed from the first (*no*-trials) I calculated the mean accuracy by place of mismatch (list position) for each group. Note that these trials represent only half of the data, namely those trials for which the correct answer would have been *no*. Errors in this case mark *misses* but leave out *false alarms*. As can be seen in Figure 10, performance of the dyslexic group dropped immediately after position 1, while the control group kept performance up until the fourth position of mismatch.

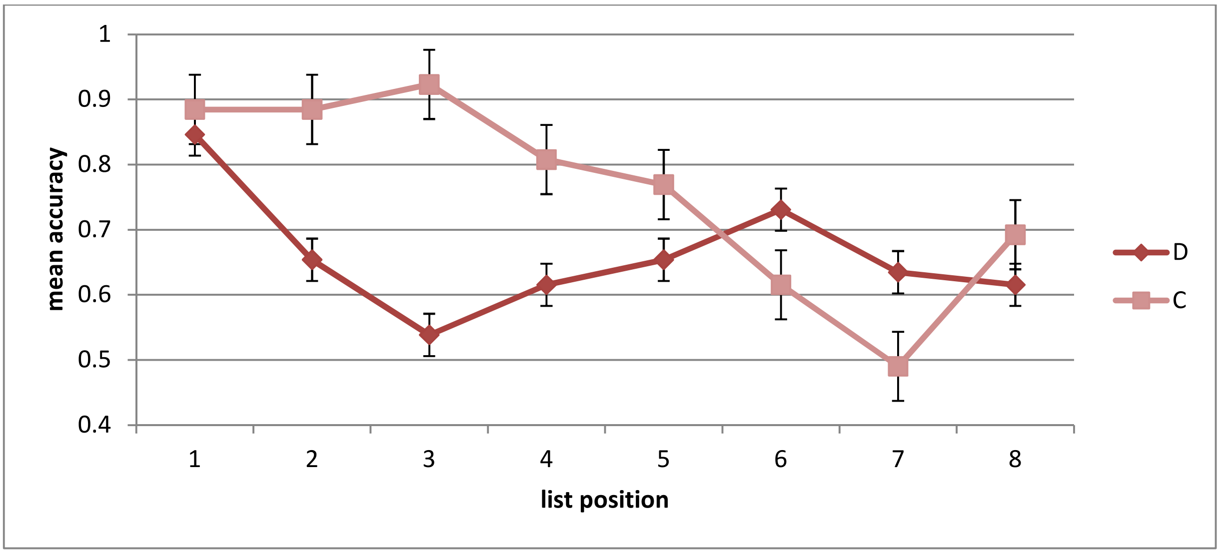


Figure 10: mean accuracy by group over positions of mismatch (*no*-trials) in the verbal order task. Whiskers depict standard errors. Note that these are only half of all trials and errors mark *misses* to reject the wrong order of the second list.

[6] Without outlier elimination the main linear mixed model shows the same effects (domain: E=0.7540, SE=0.3102, z=2.431, p<.05, interaction of domain and task: E=-1.0724, SE=0.3426, z=-3.130, p<.01). The model on task and group shows a task effect (E=-0.90117, SE=0.25166, z=-3.581, p<.001) but no more significant interaction of group and task (z=1.398, p>.1). Planned comparisons for item tasks confirm no group effect (z=0.828, p>0.4), whereas for order tasks, the factor group was marginally significant (z=1.780, p=.075).

2.2.3 Individual digit span and performance in order and item tasks

To control for the influence of individual span on performance in order and item tasks, span was included as a random factor in the generalized linear mixed model of accuracy on group and task, as described above. There was again a main effect of task (E= -1.10380, SE=.26885, z= -4.106, p<.001) that interacted with group (E= .410, SE=.17632, z=2.325, p<.05), indicating that the observed interaction was significant beyond the influence of individual span to task performance. For this small sample size though, span values that are more seldom have almost no influence on the model. To control for sample size in this model, I ran a bootstrap validation, sampling with replacement over the random factor span in 2500 runs and using the same formula for generalized linear mixed models of the dependent variable accuracy on group and task per sample (see Baayen, 2012, p. 307 for bootstrapping linear mixed models for binomial distributions). Table 4 shows median and confidence intervals of model estimates for the single model on the experimental sample as calculated above, for the same model including span as a random factor, and for the bootstrap sample distribution. Both the effect of task and the interaction of task and group yielded sufficiently similar estimates in all three models. Crucially, the confidence intervals for both the effect of task and the interaction of task and group in the bootstrap estimates do not cross the mean of the opposite factor level (set to 0),[7] confirming valid effects.

Table 4: Median of estimates for the generalized linear mixed model of the dependent variable accuracy on group and task, the same model with the additional random factor span, and mean estimates and confidence intervals (5%) for the same model for each of 2500 random bootstrap samples over the factor span.

	lmer (n=45)		+ random factor span		Bootstrap of lmer (n=2500)		
	50%		50%		2.5%	50%	97.5%
Intercept	1.753	***	1.746	***	1.513	1.725	2.174
Group	-.094		-.063		-.616	-.063	.157
Task	-1.143	***	-1.104	***	-1.110	-1.038	-.837
Group :Task	.443	**	.410	*	.329	.395	.459

Significance codes: ***.001 **.01 *.05

[7] Read the estimates from 2.5th quartile to the 97.5th quartile: they should not cross 0, if both samples actually stem from different distributions. For example in the factor *group* here, the estimates finally cross 0 instead of staying on one side of 0 only. This factor was not significant as a main effect also in the experimental sample model.

2.2.4 Correlations between reading scores, intelligence and performance in order and item tasks

Correlation analysis on average accuracy proportions showed that for both groups, mean performance in the order tasks correlated with reading in both the word and the nonword reading test ($r2=.214$, $p=.047$; $r2=.236$, $p=.029$). Mean performance on the item tasks showed no correlation with reading on either task ($r2=.120$, $r2= .110$, neither significant) but a positive correlation with IQ ($r2=.283$, $p<.01$), as can be seen in more detail in the regression tree model in the appendix (Figure A22).

3. Discussion

The aim of this study was to investigate whether dyslexia is characterized by impaired short-term memory for serial-order, but not item information. This hypothesis had been derived from recent findings showing that people with dyslexia have difficulties to learn sequential information in the transition from short- to long-term memory (Szmalec et al., 2011). In line with this hypothesis, the current results show that people with dyslexia performed significantly worse in short-term memory tasks that tapped into processing stimulus order, but not in equivalent processing of item information. This dyslexic disadvantage generalized across verbal and non-verbal stimulus domain. Ultimately, 90% of the dyslexic participants showed performance that was inferior to the control group’s average in one of the two order tasks, indicating the incidence of the problem. In both item tasks on the contrary, dyslexics performed equally well, with even a small majority (55%) of dyslexic participants performing above the control group’s mean. The advantage for dyslexics in the verbal item task, in which 90% of them performed slightly above control group mean, was not statistically significant. This advantage may in part be due to the noticeable eagerness and motivation of some dyslexic participants to contribute to the study by performing as well as they could. In any case, this slight advantage in item tasks corroborates the robustness of the measure for the observed order memory impairment.

Our findings support the hypothesis that dyslexia is characterized by a problem to process ordered information in short-term memory, which is independent of memory content and persisting through development even after therapeutic intervention, as demonstrated here with an adult sample. Because both order tasks proved to be more difficult for dyslexics in this sample, whereas item performance was at the same or even slightly higher level compared to controls, it can be concluded that this short-term memory impairment indeed specifically concerns a domain-general serial ordering function.

The findings in the order condition concur with the current findings of Martinez Perez et al. (2012) in school children, and therefore generalize the impairment in serial-order short-term memory to dyslexia at the age of adulthood. In the verbal item task however, the results of Martinez Perez and colleagues show inferior performance for dyslexic children as well, which is not in line with the data of this study. As such, only the present study shows a dissociation between an order disadvantage, but not an item memory disadvantage for dyslexics. A tentative explanation for the different findings in verbal item short-term memory could be that here, existing words were used, whereas Martinez Perez and colleagues used nonwords (consonant-vowel-consonant structure) in their item task. 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 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 separate activation of representations corresponding to the individual items in the initial sequence. This means that recall of a nonword is likely to demand more serial-order processing relative to recall of a word that has an existing entry in lexical long-term memory, since nonwords as compared to words have no long-term content else than single phonemes and their associated transition frequencies. The fact that Martinez Perez et al. observed impaired memory for delayed nonword repetition may therefore be due to the larger serial-order involvement in their task, relative to ours. In this view, nonword recall may be less suitable to investigate dissociations between order and item memory.

In the item condition here, also visual stimuli were tested, and the finding that also short-term recognition of these stimuli was unimpaired in the dyslexic group further supports the conclusion that the cognitive basis of item short-term memory seems to be relatively unaffected in dyslexia.

3.1 *List positions*

A tentative analysis of list positions (see Figure 10), showed that performance of dyslexic participants dropped immediately after the first list position and did not recover to show a reliable recency-effect. For a sublist of six items, though, dyslexics showed a tendency for a reduced u-shape. For the control group, performance on the last position might be interpreted as recovery due to recency, taking into account the sequence of all nine items as a whole list. As far as interpretable in the present design, the length of list-anchoring (Farrell & Lelièvre, 2009) is restricted to the span level of the dyslexic participants, showing a shorter list effect than controls in the verbal order task, in that the curve for dyslexics follows a different pattern than that of the controls. If this effect would be due to a reduced attentional window (Romani et al., 2011), it should be evident in item tasks as well. As far as these data of match trials in item conditions show, there was no such difference in the position curves between dyslexics and controls (see Figure A20 and Figure A21:, appendix), but both curves are remarkably similar. Note, however, that interpretation of this kind of data needs to be treated with caution because it concerns only that half of the data that represent order mismatch and respectively item match trials.

3.2 *Contribution of digit span*

After accounting for digit span, the interaction of group and task remained significant, although weakened somewhat. This can be related to confounding a general order function with a specific verbal item component in the digit span measure, as described by Majerus et al. (2006). In holding the item requirements constant, the order tasks reported here seems to capture something more of an order function than the digit span task.

3.3 *Reading performance and short-term memory for order*

The hypothesis of a general order impairment in dyslexia on the one hand and spared item performance on the other hand was further confirmed in showing that word and nonword reading were related to performance in order tasks but not to performance in item tasks.

The relation between nonverbal tasks and nonword reading in control participants is not surprising, given that all three tasks deal with sequences of symbols that have no semiotic reference. It supports the notion that nonword reading apart from a grapheme-phoneme matching task attains much from specification in visual processing, as proposed by McCandliss, Cohen and Dehaene (2003). For good nonword readers, performance on order tasks was high and domain did not enter as a discerning factor, but it did so for medium and bad nonword readers (see regression tree in Figure A22 in the appendix for illustration).

More striking though than the finding in the control group is the absence of this correlation in the dyslexia group (r^2=.032, not significant). This lack of association points towards different mechanisms for nonword reading in dyslexics. As suggested by Barca, Burani, Di Filippo and Zoccolotti (2006), dyslexics might remain longer in an early reading phase of single grapheme-phoneme matching and therefore rely more on verbal processing in nonword reading, while experienced readers automatically recognize letter-groups by transition frequencies and highly trained visual familiarity of occurrences of letter-patterns (McCandliss et al., 2003). Nonword reading in dyslexics may under this assumption represent a skill that is impaired as a consequence of diverging reading development rather than directly reflecting the cause of this impairment.

IV.Chapter: Study 3

Order memory in Italian dyslexic school children assessed with a double probe task

The findings of study 2 emphasize the problem of serial order processing in dyslexia beyond a verbal phenomenon (Hachmann et al., submitted). Taken together with the recent publication by Martinez-Perez et al. (2012), this characteristic of dyslexia spans from childhood into adulthood. Still, the prediction for item performance differs between the findings of Martinez Perez and colleagues and the hypothesis presented here and the design that was developed in this work had not yet been administered to school children with a formal diagnosis of dyslexia. Moreover, the findings of studies 1 and 2 could have been explained by two alternative reasons.

Firstly, the perceptual anchoring theory (Ahissar, Lubin, Putter-Katz & Banai, 2006; Banai & Yifat, 2012; but see also DiFilippo, Zoccolotti, & Ziegler, 2008) predicts problems for dyslexic individuals when faced with repeating material of a small closed set in comparison to bigger set sizes or even open lists, in which no item is used in different contexts again. In “standard psychophysical testing protocols”, Benai and Yifat (2012, p. 2) argue, “typical readers make automatic and implicit use of the information that is embedded in the repeated reference stimulus that is characteristic of such protocols”. Their results show that performance of normally developing children in a phonological awareness task, in verbal memory span and in letter knowledge correlated only when assessed with a small sample of stimuli, compared to the same tasks with the same participants when tested with a larger stimulus sample. Under these assumptions, failure of dyslexic individuals in such tasks would be caused by a problem to perceptually anchor each instance of a repeated item in its surrounding. This would lead to increased interference between reoccurring instances of the same item and make the task over-proportionally more difficult. Di Filippo et al. (2008) though could not replicate the findings of Ahissar et al. (2006), and it remained open whether visual attention or anchoring contributed more to dyslexia. Still, anchoring might have played a role in the previous two studies. Here, the information that needs to be anchored with each instance of an item is the respective list position, but only in the order conditions. In item conditions, every item appeared only once to focus entirely on the identity of the single element, thereby confounding task difference with material set size. The anchoring approach differs from the short-term memory approach in that it assumes the problem not in serial order per se, but in the competition of repeating instances of an element in changing context. Within alphabetic languages, both approaches would predict very similar problems in the acquisition of orthographic word forms, one because for every word knowing the exact order of letters is crucial, and the other because with a set of about 30 letters, every letter necessarily repeats in varying contexts to produce the potentially infinite linguistic expressiveness. The crucial difference, however, lies in the hypothesized cause of this learning problem. The present study 3 will address this question by using a fixed set of 24 items throughout all four conditions, thereby eliminating confounds with set size between tasks.

Secondly, the most important finding of Study 2 – stronger drop in performance for order tasks in the adult dyslexic population - could have been confounded with the difficulty level of the order tasks with respect to item tasks. Order tasks overall proved to be more difficult despite initial piloting and the adaptation of list lengths. This argument of mere task difficulty can´t be applied to other studies that point into the same direction of impaired order memory as Howard et al. (2006) or Martinez-Perez et al. (2012), but it cannot be ruled out as an explanation for the main interaction in study 2.

The scope of study 3 accordingly was to replicate the findings of studies 1 and 2 in a formally tested dyslexic children population and to additionally address these two flaws in particular. The main changes to the experimental design of study 2 concerned the size of stimuli sets and the retrieval phase. As described above, fixed set sizes of 24 items each were used for all four conditions. To equalize the retrieval phase in all conditions, a double probe task was used that was similar to the task for order and item memory reported by Hsieh, Ekstrom and Ranganath (2011). Instead of probing one item only in the item conditions but presenting the whole list in the order conditions, in this study two items were probed throughout all conditions. Now, only the task differed for these two target items, such that in item tasks, participants had to judge whether both items had been in the list, whereas in order tasks, participants had to decide whether the two targets had been in correct consecutive order.

A further change in this third study was to better control difficulty levels by making the item tasks slightly more difficult than the order tasks. This was achieved by using longer lists and shorter presentation times for item compared to order tasks. With these settings, the item tasks with respect to the order tasks of this study provide a number of parameters that could be viewed as particularly difficult for dyslexic children: a) children who have slower processing times overall

(Shanahan et al., 2006) would find both item tasks more difficult due to the shorter presentation times. This fact controls for a general effect of performance drops in clinical populations due to fatigue with task compilation. Particularly the verbal item task addresses further approaches to dyslexia reported in the literature by requiring considerable b) naming speed and c) the ability to process verbal material from the visual to the auditory modality in general. If any of these abilities were impaired (Hari & Renvall, 2001; Swan & Goswami, 1997), processing would be slowed down and finally lead to omissions in the verbal item task. This task requires naming of each of six two-syllable items within a non-spaced timing of 1 second each. Also visual familiarity matching is not possible, since after visual presentation of the encoding picture list, target words are presented auditorily. Individuals who efficiently use linguistic codes should benefit from a verbal strategy in this task. Finally, d) higher load on visuo-spatial attention shifting should be required in the item tasks with respect to order tasks, this way addressing magnocellular functions (Bosse et al., 2007). Fast timing studies, though, used presentation times in tens of milliseconds, not whole seconds (Hari & Renvall, 2001). Therefore, all these arguments for higher load in item tasks can only be placed in comparison between tasks, which demand a different kind of processing by definition. But they emphasize the hypothesized impairment of order memory in dyslexic individuals by requiring a higher load of a number of abilities in the item tasks that otherwise might be confounded with the expected findings in order tasks.

This design hence should be able to clarify to what extent the order processing approach is independent of task difficulty, of perceptual processing times, of attentional shifting and of stimulus set size.

The settings list length and presentation time were evaluated in a pilot experiment with 15 normal reading school children. Due to temporal constraints, the results reported here include a group of 11 diagnosed dyslexic children and several non-matched pilot participants, depending on the settings of their participation and on the kind of data analysis. Accordingly, the results have to remain very preliminary, but the study will be continued to include matched control groups for reading and chronological age within the next months.

1. Method

1.1 Participants

Twelve formally tested children aged between 7 and 10 years (M=8;3, SD=;11, 8 males) participated in the study. Their reading, writing, intelligence measures and specific language skills had been assessed by professional speech therapists at the public service institution A.P.S.P. Beato de Tschiderer. Eleven of the children fulfilled criteria for dyslexia showing reading performance below the 10th percentile of their age norms and an average range of IQ (all within 1.5 SD) at the time of their diagnosis. Data of the memory tasks were collected at various seats of the institution in different cities and villages in the Italian region of Trentino. None of the children had diagnosed comorbidities with other learning or sensory impairments and all of them had already received therapeutic intervention for varying time periods since the time of diagnosis. For piloting, 15 children of the same age range (M=8;7, SD=1;0), 11 of whom were males, had participated, being presented with various versions of list lengths to factor out the settings stabilized for the actual study.

All children were native monolingual Italian speakers and lived in the autonomous Italian region Trentino, which is a dialect region, so some had been exposed to dialect.

1.2 Material and Procedure

Parents had given written informed consent and each child was tested individually in a quiet room. The order of the four memory tasks was counterbalanced across participants. All reading and IQ test results were attained from the therapy centre without repeated testing.

1.2.1 Short-term memory tasks

For all four tasks, 24 items were chosen from the original set of materials used in study 2, 48 nonsense drawings for the two nonverbal tasks and 48 pictures with the corresponding sound files containing the respective object name for the two verbal tasks. Those object names were all comprised of 2-syllable words with a mean log frequency of 2.05 (SD=.65, range .6-3.9), a naming agreement of 96% (SD=4%, range 85%-100%) and an age of acquisition of 3 years and 4 months (SD=1 year, range 1;8-5;3, see Nisi, Longoni, & Snodgrass, 2000).

Within conditions materials were randomised so that each item appeared equally often in every list position. Further, each item was used once as a target in every one of two target positions and all items were counterbalanced across trial lists. The sets of material were counterbalanced between tasks, so that one set of pictures and words for example was used once as an item task and next time as an order task, and the same held for the sets of nonsense drawings. Single items were not randomized across sets to maintain the same balance of animate and inanimate objects as well as their balance of category membership (clothes, food, animals, man-made objects, body-parts) within sets. Accordingly, also the nonverbal sets were kept unmitigated.

The constant number of 24 items per set formed 18 trials in each condition, so that each item appeared three times in order tasks and four to five times in item tasks. If anchoring is affected by interference between repeating instances of the same item, also the higher number of repetitions in item tasks should contribute to make these tasks more demanding for anchoring. Presentation times differed between tasks, such that for item tasks, each item was presented for 1 second as in the studies before, whereas for order tasks, presentation time was extended to 1.5 seconds. Equally in all conditions, a blank screen followed the encoding list for one second, after which the consecutive retrieval phase of two target items appeared (see Figure 11). The only crucial difference between all four conditions concerned list length, that was set to 4 items for order tasks but to 6 for item tasks. This setting was chosen to assure that item tasks became slightly more difficult than order tasks. Memory for serial order could influence item task performance as well, in the way that it might be easier to remember which item had been there, if it is mapped onto a list position additionally to its identity information. To control for the influence of order memory on item task performance, the order of those targets in item tasks that constituted a *yes*-trial (all trials in which both target items had been present in the encoding list), was balanced between chronologically ordered target presentation and presentation in opposite order with respect to list presentation, and chronological order per trial was tracked for analysis.

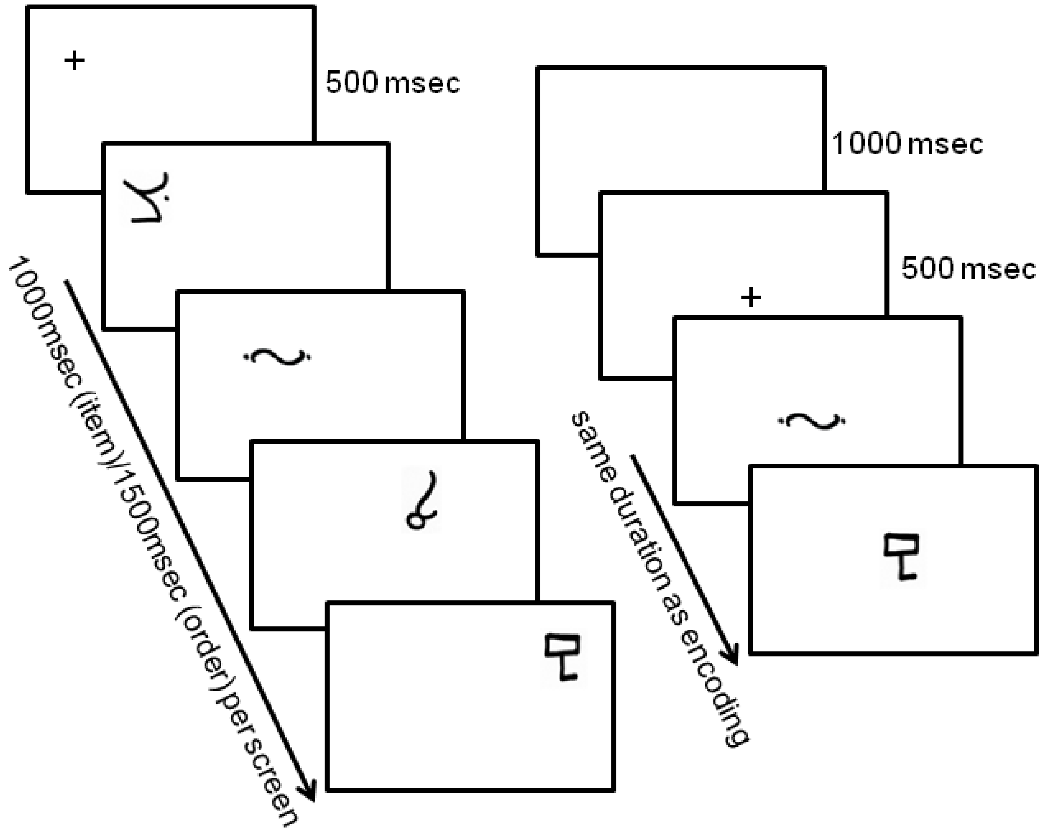


Figure 11: presentation scheme, example of a nonverbal order task. The response would be *yes*, because the first target item had appeared before the second.

For order tasks, participants were instructed to decide whether the two target items had been in the same canonical order and it was assured that children understood that targets did not need to be adjacent, so that a probe of positions 1 and 4 would mean a *yes*-response, whereas 3-1 for example would mean a *no*-response. In item tasks, participants were asked to decide whether both target items had been in the list before or not, and it was made clear that even if one item had not been there, the correct answer would be a *no*-response. Responses were registered from the onset of the second target until maximally 10 sec after it´s offset. A probe-phase of 6 trials using the same stimulus material and providing feedback for each response preceded the experiment proper. Accuracy and reaction times were stored as dependent measure.

1.2.2 Reading and Intelligence tests

Participant data that originated from the time of diagnostic testing of each individual were provided by the collaborating therapy institution, which included the full reading and writing assessment with the DDE-2 (Evaluation battery for developmental dyslexia and dysorthography, Sartori, Job & Tressoldi, 2007) and a full IQ measure of the WISC-III (Wechsler Intelligence Scale for Children, third edition in Italian). The time at which every child had been diagnosed varied, so that at the time of participation some had undergone much more therapeutic intervention than others.

1.2.3 Questionnaire about action scripts and abstract order learning

General problems with serial order are reported frequently as characteristic symptoms for dyslexia in descriptions on how to recognize a possible dyslexic in early diagnosis and therapeutic contexts.[8] These symptoms include but are not limited to: problems to tie shoelaces or learning other action and planning scripts like preparing the schoolbag, brushing teeth or dressing, mixing up left-right and before-after and having problems to learn the sequence of days of the week and months of the year or to learn facts that need rote memorization like multiplication tables or history facts. These symptoms go beyond a mere problem to remember letters or symbols in serial order, but describe a more general impairment with order in everyday life. The descriptions all refer to facts, actions or serially ordered concepts that are arbitrarily set as a common agreement (days/months), that could be ordered in different serial steps (action scripts) and that have little semantic support (multiplication tables, temporal and directional dimensions). To assess these everyday problems and evaluate them as potentially relevant factors, a questionnaire about a number of these facts was included in the present study. The questions were given to the parents of each participating dyslexic child and included 1. a description of serial action scripts and the question whether the child had shown any particularity during learning these scripts (called *scripts* from now on), 2. whether the child has had problems to learn the order of days and months, math tables, temporal and directional order (called *abstract order* further on) and 3. whether there were any recurring errors or problems concerning these or other everyday actions.

2. Results

Data of one participant whose diagnosis for dyslexia was uncertain was excluded from analysis. The other eleven datasets originated from children with a mean age of 8;4 (SD= ;12), 7 of whom were males. The two preliminary analyses presented here are first an evaluation of overall task difficulty by experimental conditions and second, a look at possible facilitation of chronological order information in match-trials of item conditions. For the first analysis by conditions, only those

[8] See for example the symptom descriptions of Bright Solutions for Dyslexia Inc. by Susan Barton, member of honor of the International Dyslexia Association http://www.dys-add.com/dyslexia.html and the Italian Dyslexia Association: http://www.aiditalia.org/it/cosa_e_la_dislessia.html (November 12th 2012 for both links).

participants of both groups were included who had received the exact same settings as described above (9 dyslexics and 2 pilot participants). For analysis of order facilitation in item tasks, a within-subject measure was calculated for every condition separately, so that also those pilot participants were included who had received item tasks of list length 4 (4 children) or list length 8 (2 children), which were 10 children (6 males) with a mean age of 8;7 (SD=1;2) in the pilot group and all 11 dyslexic children in the experimental group.

2.1 *Dyslexia group characteristics*

Table 5 shows characteristics of the 11 dyslexic participants. For the reading measure, scores of word and nonword reading from DDE-2 were collapsed.

Table 5: characteristics of dyslexic participants

	age (y;m)	m / f	reading	total IQ	verbal IQ	performance IQ	scripts	abstract order
M	8;36	7	< PR 10	96.45	93.55	101.18	4 / 11	7 / 11
SD	0;12	4	PR 9	12.22	13.12	9.86		

The parents of 4 children had reported problems with both the learning of action scripts and with abstract order. Three more children were reported to have problems learning abstract order. The third point of the questionnaire, recurring errors, were exclusively answered either with a repetition and emphasis of one of the previous report of everyday-life serial order problems, or with reference to reading and writing, inverting the order of letters or mispronouncing speech sounds. Four of the eleven children had problems to pronounce the correct Italian rolling “r”.

2.2 *Performance by condition*

Data was extracted from the presentation software E-Prime and analysed in R as in the previous studies. For the 9 dyslexic and 2 pilot participants who had been presented with exactly the final settings described above, data was averaged over condition and participant. The two pilot participants were included for illustration, but further statistical analysis by groups is not appropriate with a sample of 2 members in one of two unmatched groups, so this analysis will be carried out with the proper control groups later.

2.2.1 Accuracy

Figure 12 shows mean accuracies averaged over group and condition. Between conditions, dyslexic participants showed highest performance in verbal tasks. The performance drop in the nonverbal item task amounted to 8% compared to the other three conditions.

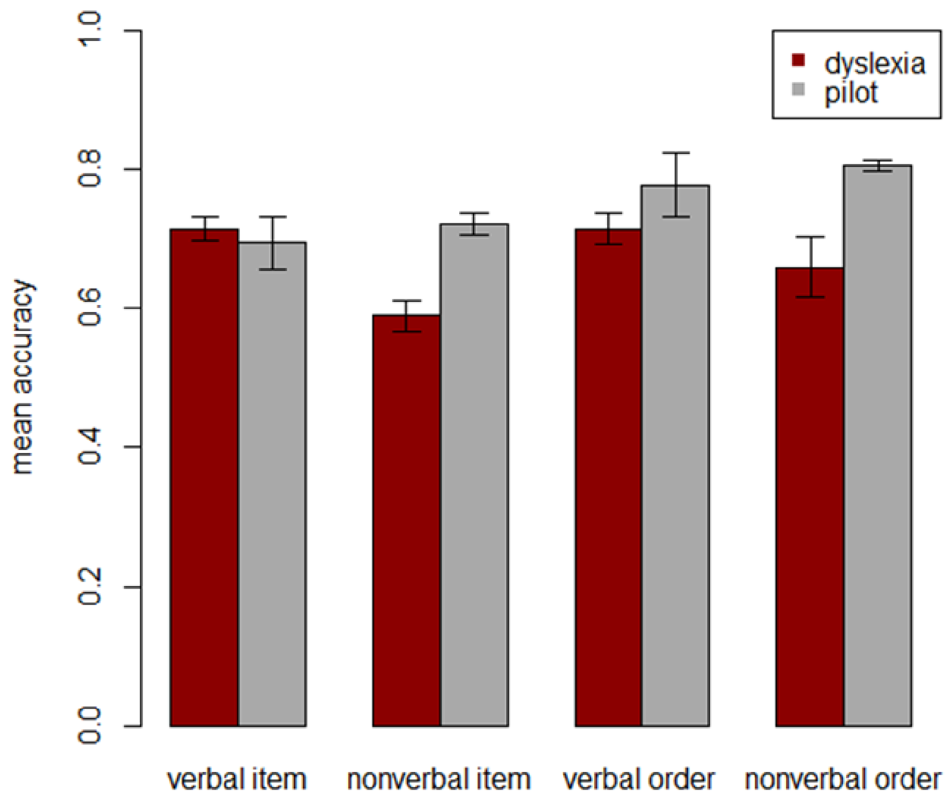


Figure 12: bar plot of mean accuracy by condition and group, averaged over 9 dyslexic and 2 pilot participants respectively. Error bars denote 1.96 SD from mean.

To analyse performance within the dyslexic group, raw accuracy data were subjected to a generalised linear mixed model for binomial distributions, using task and domain as fixed factors and participant and trial material as random factors. There was a main effect of domain (E=.567, SE=.252, z=2.249 p<.05) confirming that verbal tasks were carried out with higher accuracy than nonverbal tasks and no further significant effects or interactions.

2.2.2 Response times

Mean response times by condition and participants were averaged over dyslexic and pilot groups and are shown in Figure 13. Response times were calculated from onset of the second target item even if they had been given after onset of the question mark that followed target presentation. This measure obscures the fact that some children consistently reacted only after they saw the question mark, but it equalizes measures over all participants and across conditions. Some children reacted fast in one condition but in another condition they waited until the question mark appeared.

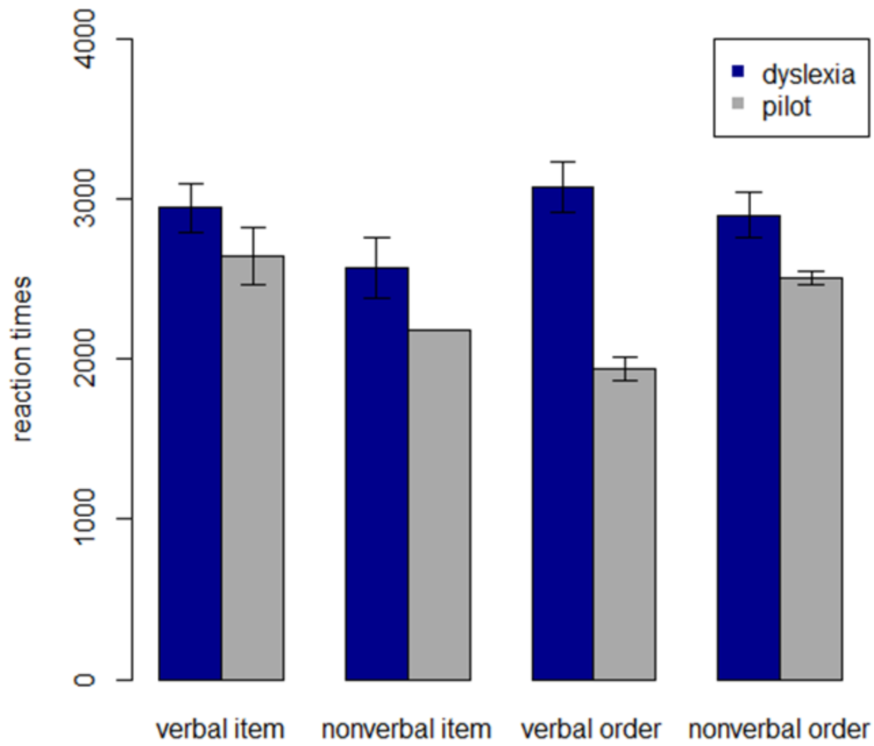


Figure 13: bar plot of reaction times by condition and group. Error bars depict 1.96 SD from mean, which in this case of only 2 participants in the pilot group can lead to very low deviations (see nonverbal item task, SD=1.964msec).

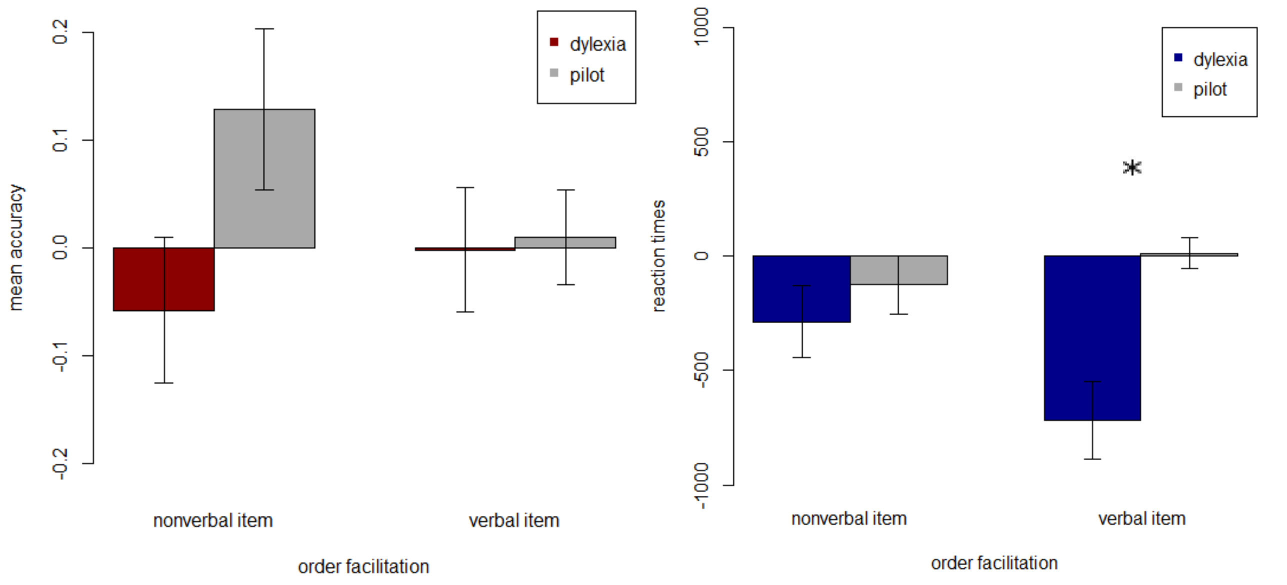
In all 10 cases in which response time lay below 350msec, the answer had been given to a trial in which a decision could be made already after presentation of the first target item (for example: trials presenting the very first or the very last list item as the first target in order tasks, or presenting a mismatch as the first target in item tasks), so also these short responses were kept.

Between conditions, the nonverbal item task shows fastest response times for dyslexics, while pilot participants yielded the fastest responses in the verbal order task. A mixed effects ANOVA on task and domain with the random factor participant revealed a marginal main effect of domain ($F=3.56$, $p=.06$), suggesting that dyslexics responded slower to verbal material than to nonverbal one.

2.3 *Contribution of serial order information to item task performance*

To evaluate whether children had used additional order information in the item tasks to facilitate memorization, for each item condition accuracy was averaged over all trials in which targets had been presented in the order of list presentation (*forward* trials) versus those trials, in which targets were presented in opposite order (*backward* trials). Note that these trials always represent matches (*yes*-trials), because both target items had to be in the list previously presented. Errors in this case mark *false alarms* and not *misses* to reject the mismatching items. For each of 11 dyslexic and 10 pilot participants, mean performance in *backward* trials was subtracted from that of *forward* trials, assuming that if chronological order facilitates memorization and retrieval and leads to higher accuracy, this procedure should result in a positive facilitation measure. The mean facilitation measures per group and item condition are shown in Figure 14A. The same procedure was applied to reaction times, yielding a measure of response latencies to *backward* minus *forward* trials, assuming that in this case facilitation should be reflected in shorter response times. Facilitation should therefore again be depicted as positive values in Figure 14B, that shows mean response time facilitation for both dyslexic and pilot participants.

The pilot group showed facilitation for correct responses in the nonverbal item task in *forward* trials, whereas dyslexics had a tendency for the opposite pattern, but none of the comparisons yielded a significant result. In verbal item tasks, no group revealed neither facilitation nor more difficulty between *forward* and *backward* trials. For response times on the other hand, dyslexics showed an unexpected significant effect of prolonged reactions in *forward* trials compared to *backward* trials in the verbal item task ($p<.05$), and the same as a tendency in the nonverbal item task. Collapsed over both item tasks, dyslexics showed more response time prolongation than pilot participants ($p=.051$).



A B

Figure 14: facilitation scores of accuracy (A) and response times (B) in verbal and nonverbal item tasks, averaged over groups (dyslexia n=11, pilot n=10). Error bars denote 1.96 SD from mean. Positive values in either bar plot indicate facilitation, better performance (A) or faster response times (B) in *forward* trials compared to *backward* trials.

3. Discussion

More than half of the dyslexic participant were reported to having problems with abstract order like days and months, before-after or left-right, most of whom also had shown problems to learn serial action scripts like tying shoelaces. These results suggest that serial order is a more general problem in dyslexia than concerning the manipulation of symbols in short-term memory.

The main effect of domain in accuracy data showed that dyslexics performed better with verbal material than with nonsense drawings in both task conditions. This is not in line with a general verbal processing impairment or with slow naming in dyslexia (Swan & Goswami, 1997). At the same time, the effect in accuracy coincided with longer response times for verbal material, which suggests a speed-accuracy trade-off. Response times though have to be interpreted with caution. They have been collapsed over all conditions to amount from onset of the second target item, confounding the processing of words presented auditorily in the verbal conditions with that of visually presented drawings in the nonverbal conditions. It can be assumed that in this case, visual processing for one medium complex item is significantly faster than listening to a two-syllable word at least until it´s point of disambiguation. The effect can therefore stem from the mere processing time needed for the specific kind of material. To clarify whether a verbal advantage in dyslexics represents a trade-off between speed and accuracy, a much larger and well matched control group is needed. If these children show the same behavior, the effects can be attributed to the kind of measure rather than to longer processing times for verbal material in dyslexics.

A hint towards an independent order impairment in dyslexia is represented by the absence of a main effect of task in this dyslexic sample. If longer lists and shorter presentation times in item conditions had presented anchoring or naming speed difficulties for dyslexics, they should have shown both impaired performance and longer responses in item tasks. An effect of anchoring over all four conditions, though, would remain unrevealed with this sample. So crucially, the effect of task can only properly be investigated in a comparison between groups, once data of matched controls are available.

Pilot participants showed a tendency to respond more accurately to trials in which targets represented *forward* order than those that represented *backward* order in the nonverbal item task. This slight facilitation effect was opposed in dyslexic participants, but none of the comparisons was significant. Further evaluation of the contribution of serial order to item task performance in response times showed a similar pattern for dyslexic participants in which these children were found to answer faster to *backward* trials than to *forward* trials, most pronounced in verbal item tasks. Rather than response prolongation, this finding could be interpreted as a backward or inverse facilitation effect for response times that is in line with the 13.8% better performance of dyslexic children in *backward* trials of the nonverbal item task. Taken together with a predominant problem to confound before and after and left and right in this group, and admitting that serial order can in principle be viewed from both directions, dyslexic children might have used serial order information from the end to the start of the list, to remember the respective items. This interpretation would assume that a) they were able to correctly encode the order of the list and b) they redirected attention to the end of the list and swapped perspective, such that order was viewed from there. If orientation of processing direction is sufficiently insecure, the effect of recency might have played a role for swapping. For such a swap to happen, the orientation of before-after, left-right and forward-backward must be impaired, as reported above, or considerably flexible. Forming subgroups of dyslexic children by reported abstract order problem versus no such report from parents, thought, yielded no significant differences in forward or backward facilitation. Also looking at mean accuracies by target position yielded no clear results with regards to recency effects (see Figure A23 and Figure A24 in the appendix). Also the findings of impaired encoding of new information in a verbal serial recall task (Kramer et al., 2000) speak against this interpretation.

When testing the hypothesis of impaired order memory in dyslexia with the matched control groups, the distinction between a swap in perspective and serial order processing in short-term memory need to be addressed by taking into account response mapping, primacy and recency effects and the direction of response facilitation. Moreover, the measure of order facilitation in item tasks needs refinement to avoid a confound of absence of serial order encoding with serial order encoding but confusion due to disorientation for direction.

In further sessions of this study, the short reading subtests should be repeated to control for the time that had elapsed since initial testing. Diagnosis of young school children is instable (see Shaywitz et al., 1992) and some children had been diagnosed years ago and received regular therapy since, while others had been diagnosed only recently. Temporary other delays with written language acquisition as well as appropriate training or compensating strategies might have introduced uncontrolled and avoidable variance to the presented group. At the same time it would be interesting to see whether the hypothesizes order impairments also persist through therapeutic intervention or vanish with training.

In future studies it would be interesting to use an implicit measure for serial order processing to disentangle the phases of encoding and retrieval and to look at order memory that is unaffected by conscious task processing. With such a measure it could be possible to investigate whether serial order is actually encoded but then lost for example due to directional interferences, or whether the hypothesized order problems indeed originate from poor order representations in analogy to an impaired order layer in the computational model of Page and Norris (2009), as introduced in chapter I.5.

V. Chapter: General discussion

This work investigated serial order processing and item functions in short-term memory in dyslexic children and adults. Short-term memory for order has been associated to new word learning in several studies (Majerus et al., 2006; 2008; 2009a/b; Nairne & Kelly, 2004; Saint-Aubin & Poirier, 1999), and the present findings extend the differentiation between these two functions to the acquisition of written language. Developmental dyslexia seems to be characterized by a specific problem to process serial order in short-term memory, but this problem is neither restricted to linguistic material nor does it extend to the processing of the single items involved. The item function that is used to fulfill serial recall tasks was described as a short-term activation of long-term memory entries (Majerus et al., 2008), and was unaffected in the dyslexic populations tested here.

Short-term memory for order though seems to be a crucial ability that is related to success in written language acquisition. This relation might be a little stronger for reading than for writing, as study 1 showed. Even with a very mixed sample of low performing readers in study 1, the order memory tasks provided a measure that could be related to reading, while the factor domain that distinguished material of verbal content from nonsense drawings seemed to have a smaller mediating influence. Low proficient readers showed an overall impairment in order tasks and this impairment was largest in the verbal order task. Although verbal tasks were easier overall, low proficient readers could benefit least from the fact that material was of verbal content. Still, the stronger predictor of reading was the type of task, in which low performing readers had more problems to remember the order among items. This finding was replicated in a tested adult dyslexic sample in study2. Dyslexics as compared to matched controls showed impaired performance on both the verbal and the nonverbal order task, while their ability to remember single items in large lists of different material did not differ from that of controls. This study demonstrated a clear dissociation between item and order functions in short-term list recognition related to dyslexia, and supports the view that dyslexia is characterized by a specific impairment in short-term memory for order. This impairment may result in slower learning of new written word forms as predicted by the computational model of short-term memory by Page & Norris (2009), and investigated in two studies with adult dyslexic participants (Bogaerts, Szmalec, Hachmann, Duyck & Page, submitted; Szmalec et al., 2011). Study 3 finally was designed to replicate these findings in a formally diagnosed population of dyslexic children, at the same time addressing different other hypothesis about alternative explanations for the findings of studies 1 and 2. Preliminary results suggest that naming times, overall task difficulty and selective attention shifting are unlikely to explain the results of study 1 and 2. The inclusion of matched control groups are vital for this study to investigate whether dyslexic children perform significantly worse on tasks that require the processing of stimuli in serial order than on those that require extended lists of items, and to evaluate stimulus set size as a measure for the alternative explanation of a deficit in perceptual anchoring.

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., 2009a), as described in the introduction. Specifically the IPL has very recently been identified as the relevant locus for expert readers to map graphemes and phonemes, as investigated with Transcranial Magnetic Stimulation (TMS) on nonword reading (Costanzo, Menghini, Caltagirone, Oliveri, & Vicari, 2012). According to the data presented here, dyslexics would be expected to show an alteration both in DLPFC and IPL due to impaired short-term memory for order that should be evident for nonword reading but also for nonverbal order tasks tapping short-term memory. But for item memory tasks, the corresponding temporo-parietal regions that respond to single phonemes or visual shapes should remain unaffected in dyslexics.

1. Reading performance and the order-item dissociation

The findings of studies 1 and 2 show that nonword reading - that played an important role in the diagnosis of dyslexia - was specifically related to order memory. Nonword reading has been attributed to both order and item development (Mosse & Jarrold, 2008; Page & Norris, 2009), as discussed in study 2. Mosse and Jarrold (2008) relate nonword learning both to a specific verbal memory component and a general order learning function. Nonword repetition in this case would not only require short-term memory for order but would also address the acquired result in long-term memory. Accordingly, the impairment in nonword repetition of the group of dyslexic children in the study of Martinez Perez et al. (2012) disappeared in comparison with the reading age matched control group. Taken together with the correlations of order task performance with nonword reading in both the here presented studies 1 and 2, I interpret also the finding of Martinez Perez et al. as support for the claim that nonword reading depends on both order and item functions - as do other complex verbal skills like phonological awareness and rapid naming -

and that originally, serial order processing is a function that characterizes dyslexia earlier and probably more deeply than verbal item impairments.

Phonological skills have been well established as the best predictors for later reading development and are often reported to be impaired in dyslexia (Katz & Shankweiler, 1985; Ramus & Szencovits, 2008; Snowling, 2001; Swan & Goswami, 1997; Ziegler & Goswami, 2005), but as introduced in chapter I.2, their developmental origin and causal role in dyslexia are controversial (Boets, Wouters, von Wieringen, & Ghesquière, 2007; Castles & Coltheart, 2004; Hulme, Snowling, Caravolas, & Carroll, 2005; Melby-Lervåg, Lyster, & Hulme, 2012; Morais & Kolinsky, 1994). The most established measures for phonological processing are tests of phonological awareness (omission and reversion of letters/phonemes) and rapid serial naming tasks (naming a repeating sequence of objects, colors or letters as fast as possible, see Di Filippo et al., 2008). However, both these paradigms heavily tap into the processing and learning of sequential order. This may be an important underlying deficit for which the current findings could offer an explanation. It has been demonstrated that phonological awareness and the concept of subdividing speech into phonological elements develop in interaction with reading (Morais, Gary, Alegria, & Bertelson, 1979; Morais & Kolinsky, 1994). Also according to a sequence learning account, verbal skills would in part be a result of order learning (Page & Norris, 2009; Szmalec et al., 2011). 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, alter the acquisition of linguistic skills that usually develop along with reading. In this view, verbal item impairments as measured with tests of phonological awareness, phonological discrimination, rhyming, nonword reading or even latencies in morphosyntactic processing (Cantiani, Lorusso, Perego, Molteni, & Guasti, 2012) may be impaired as a result of a divergent development, if order requirements can be excluded in the respective tasks. As clearly stated by Snowling (2001), individual language skills prior to the onset of the acquisition of alphabetic language should, nevertheless, serve as protectors against diverging development.

Friedmann and Rahamim (2007) described a subgroup of dyslexics who predominantly show letter position errors within words. This error pattern might directly link the problems of order processing reported here to instable orthographic representations due to impaired order encoding and Hebb learning (Szmalec et al., 2011). The assumption that tests of phonological skills are often confounded with order task requirements taken together with this link to a specific subgroup of dyslexics leads to the conclusion that an account of impaired short-term memory may reunite various approaches to dyslexia. But although in this adult sample in study 2, 90% of the dyslexic participants performed below mean of the control group in both order tasks, it remains to be investigated to what extent the impairment of serial order short-term memory is related to all forms of dyslexia, being conscious of the fact that dyslexia can be associated with a wide variety of heterogeneous causes across studies (Pennington, 2006; Zoccolotti & Friedmann, 2010).

2. *Dyslexia as an emergent phenomenon*

Peterson and Pennington (2012) summarize dyslexia as a genetic predisposition that may or may not cause problems in written language acquisition and that is characterized by a multiple deficits, most noticeably by poor performance in phonological awareness tasks and by slow serial picture naming. Even if these measures were confounded with order memory functions as assessed here and the learning thereof (Bogaerts et al., submitted), the question of a unifying causal link cannot be answered until short-term memory for order was assessed in very young children, and shown that this impairment necessarily leads to reading and writing problems.

Considering the findings from structural and genetic studies referred to in Peterson and Pennington (2012), any single cause model is unlikely to account for the fact that some children with strong genetic predisposition develop in a normal way, while others without these predicting variables do. The likelihood of following the genetic predisposition, in addition, decreases with higher parent education level. Moreover, a single cause model would have to capture all the variance in individual differences among dyslexic individuals, even if possible comorbidities were factored out.

Shaywitz et al. (1992) have described dyslexia as the low end of a normal distribution in reading ability of a population. Using a discrepancy criterion to define dyslexia, they showed not only that dyslexic reading performance made part of a normal distribution taking into account the discrepancy scores of 414 children, but also that retesting the same individuals two years later yielded a re-test reliability of 28% from grade 1 to 3, to maximally 50% from grade 3 to 5. Shaywitz et al. stated that “[t]he possible benefits of early diagnosis must now be tempered by the knowledge that as many as two thirds of the children given this diagnosis early (in the first grade) will not meet the criteria for reading disability two years later.” The discrepancy criterion meanwhile has been largely replaced by age-related norms that make the diagnosis more reliable (Bishop & Snowling, 2004; Lyon, Shaywitz, & Shaywitz, 2003). The criterion of persistence as a crucial part of the diagnosis, however, still imposes considerable difficulty on early detection and intervention, and the cut-off point for diagnosis is set arbitrarily (Peterson & Pennington, 2012). Instead of a discrete tractable and biologically coherent disorder, Shaywitz et al. (1992) thus argue that dyslexia represents the lower end of an ability that is normally distributed over a population and therefore stands for something that necessarily occurs in any ability and population.

I herewith speculatively propose that dyslexia emerges as a phenomenon between individual differences and a normative teaching surrounding that focuses on a set of abilities that are disadvantageous from the point of view of these individuals, thereby slowly creating deficits to varying degrees. A dyslexic individual would in this view not be a person who from birth on is impaired in specific skills, but who holds a set of skills that cause problems when faced with written language in a specific learning environment. The genetic preconditions have been linked to various abilities that develop early, but there is no direct link to written language, for most of dyslexic children, genetic factors seem to play a minor role (Shaywitz & Shaywitz, 2005). Instead, genetically mediated preconditions could represent a specific combination of variation in abilities and processing preferences within a normal range that as such is neither a gift nor a deficit, but that can cause problems in the acquisition of specific skills under certain conditions. This complex set of abilities might be characterized by a lower readiness to process information in serial order that can be manifest in poorer auditory discrimination (Boada & Pennington, 2006; Guttorm, Leppänen, Poikkeus, Eklund, Lyytinen & Lyytinen, 2005) and sluggish attention shifting (Facoetti et al., 2009), but also by a preference to process objects holistically, by a stronger readiness for 3-d mental imagery (Von Károlyi, Winner, Gray, & Sherman, 2003) and by longer dwell times on single elements (Hari, Valta & Uutela, 1999) due to hypothesized stronger activation of associated memory traces with each item (Chakravarty, 2009). Let´s hypothesize that this set of cognitive preconditions represents a combination of a normal gradient within each ability; the question then is how they can lead to impaired written language acquisition. Here, order processing and learning might play an important role. Assuming that such a cognitive system meets a learning environment that is based on phonological strategies of single letter decoding and that then is supposed to learn to quickly and automatically recognize recurring instances of the same letters in various but strictly serially ordered contexts by means of repetition learning, that system might run into difficulties with one or the other constraint of this environment. In demanding exactly those abilities that in the example system are weak, a teaching environment would trigger a different trajectory of development right from the start and under certain conditions even emphasize unsuccessful strategies. But even with this large body of evidence to date about written language acquisition, we might not know every route that leads to reading. Indeed, many former poor readers can compensate or overcome their reading problems, thereby showing a different pattern of brain activation with lower activity in left temporo-parietal language regions (Shaywitz et al., 2003). An increase of activation in left language regions was associated with different activation in right hemisphere brain regions in dyslexic individuals after intensive training of auditory processing (for a review see Gabrieli, 2009). As Chakravarty (2009) proposes, these different patterns of brain activation might point towards a way of processing that is yet undiscovered. Following the same direction of arguments, Poole (2003, p.175) states that "while dyslexia friendly techniques can be applied to children who are not dyslexic, this does not work the other way around". She applies a paradigm to the problem of teaching written language that emphasizes a less normative approach with more open teaching methods. If these methods should prove successful, they might need to achieve yet a better understanding of reading development. This may mean to incorporate techniques that have shown to be successful in therapy as for example visual imagery, conceptual understanding of function words instead of phonological decoding and maybe a more embodied perspective on the origins of serial order understanding. To investigate this approach to an emergent phenomenon, besides the discussed deficits in dyslexia it would be worth looking at advantages and strong abilities in the same population to create an overview of pre-reading abilities and investigate their interdependence. Weak encoding and processing of serial order might go along with a minute and detailed memory for single items, as hypothesized by Chakravarty (2009), and with increased creativity in design and symbol use (Corlu, Özcan & Korkmazlar, 2009).

Future work will then also be needed to clarify the role of these impairments and advantages in the development of reading and spelling. Von Károlyi et al. (2003) argue that dyslexics have a preference for holistic processing. It might be worth considering whether there is a preference for whole word or lexical reading as supported by Barca et al. (2006), but that the transition from phonemic reading to lexical recognition is hindered by instable orthographic representations due to impaired order encoding and learning of sequences. This might also explain the slow reading and why dyslexics have to scan every word sequentially instead of recognizing it in confinement from other words.

Conclusion

The present work proposes that the basis of developmental dyslexia is characterized by a specific impairment in short-term memory for sequential order, as demonstrated in three experiments with verbal and nonverbal task that loaded either on item or on order memory. While dyslexic children and adult participants performed worse than controls in the order tasks, this difference was not found in the item tasks, irrespective of using verbal or nonverbal material. The specific impairment to process serially ordered information may lead to the language problems characteristic for dyslexia: assuming that a deficit in order processing and serial order learning causes impairments in the acquisition of orthographic word form representations, the integration of written language, that is typical for normal development and that provides a format to represent linguistic knowledge, is hindered. Instable acquisition and consolidation of long-term language knowledge are under these assumptions interpreted as a result of difficulty to encode ordered material and can themselves subsequently contribute to a delay in reading development, finally leading to individually varying degrees of reading impairments and other problems associated to dyslexia.

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Appendix

1. *Study 1*

1.1 *Position of mismatch in order tasks*

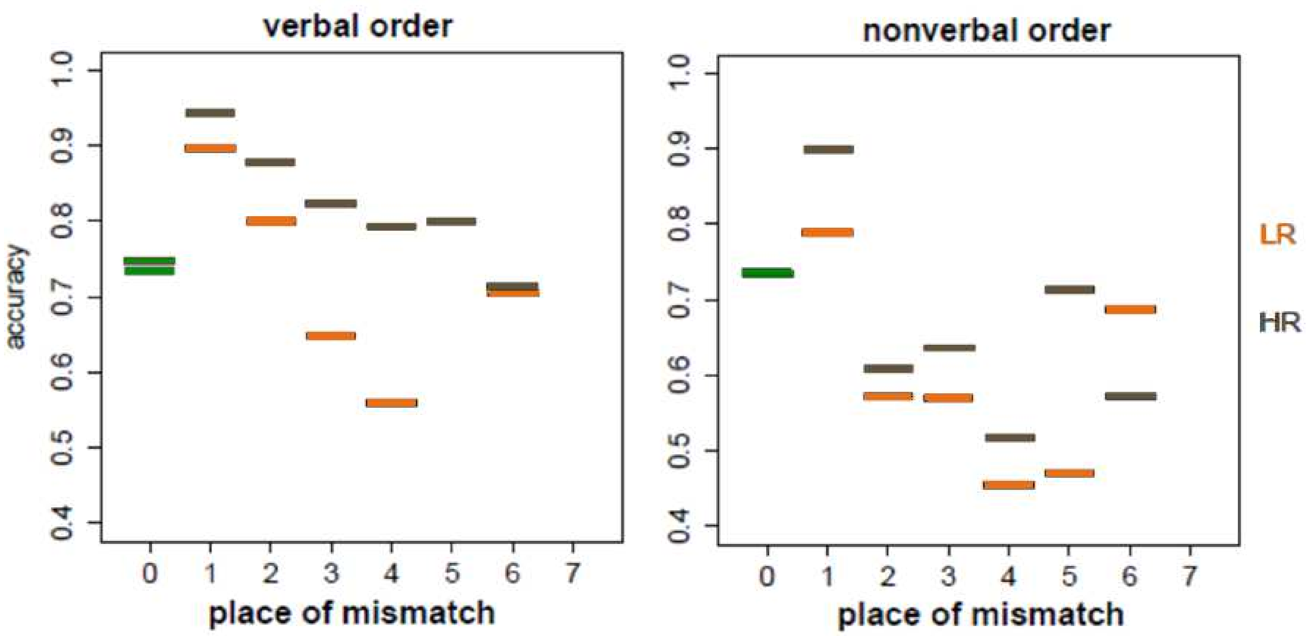

Figure A15: mean accuracy by reading group in order tasks on place of the first mismatching order position during the recognition phase. The green bars denote responses made after target list offset, during presentation of the question mark. Most of these trials were *yes*-trials, for which a late answer was desirable. Note that all other data mostly include trials in which the correct answer would have been *no*, so that the errors here mark *misses*, not taking into account *false alarms*.

1.2 *Position of match in item tasks*

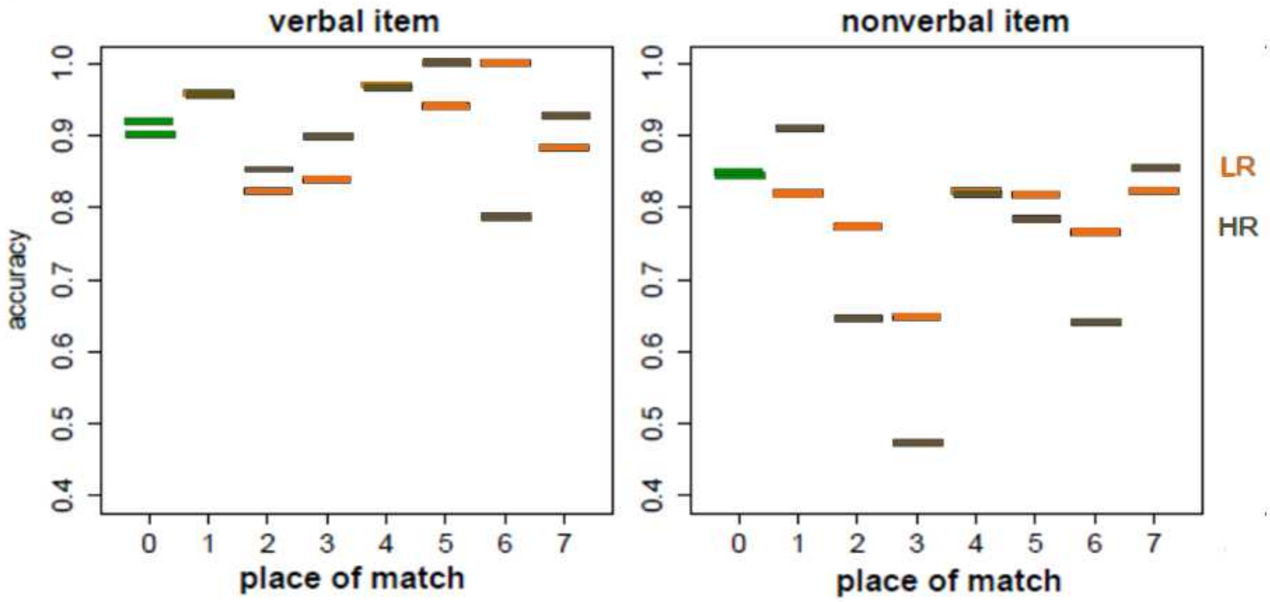

Figure A16: mean accuracy by reading group in item tasks on place of matching order position that the item had held during the list encoding phase. These data contain mean proportion correct of answers to match trials which require a *yes*-answer to the item that had been in the respective list position at encoding. Errors in this position plot therefore mark *false alarms*. The green bars denote answers that were given to mismatch trials that would have required a *no*-response, so here errors mark *misses*. Here as well as in the plot for order tasks on mismatch positions, data become more sparser towards later list positions.

1.3 *Mean accuracy by list length*

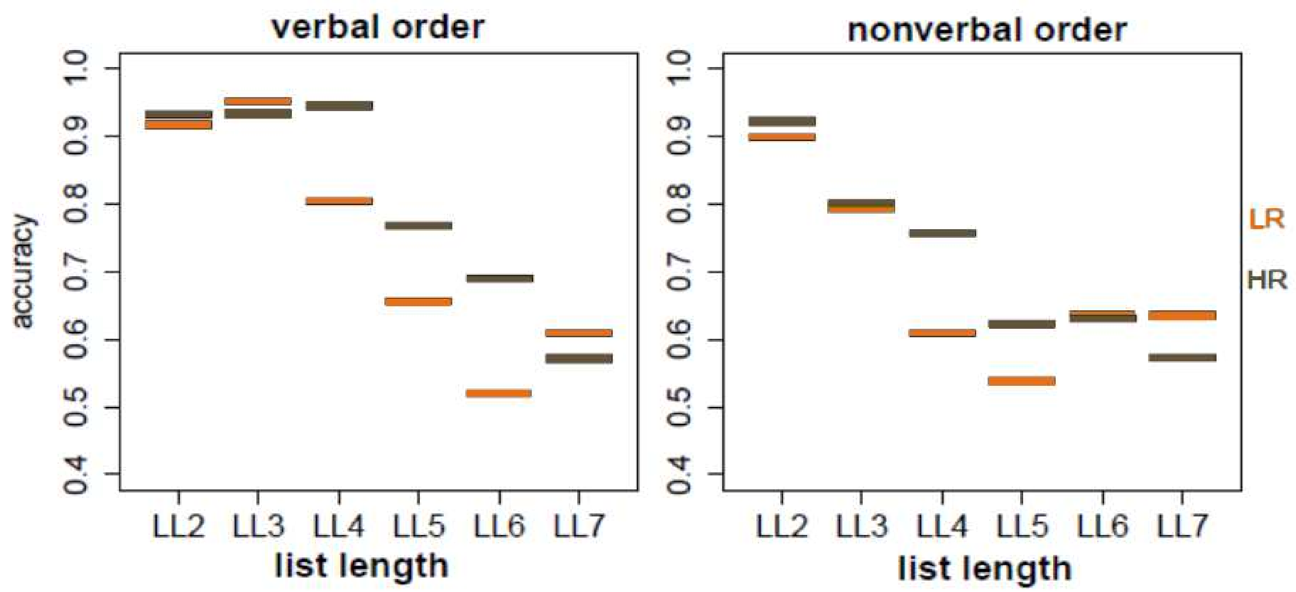

Figure A17: mean accuracy by list length in order tasks for low (LR) and high (HR) proficiency readers. Every participant was presented 6 trials of each list length by increasing length from 2 through 7 items per list. List length therefore is confounded with trial number over the whole task but for every length, there are data for exactly 6 trials per participant. Remember that this experiment was built as a span task.

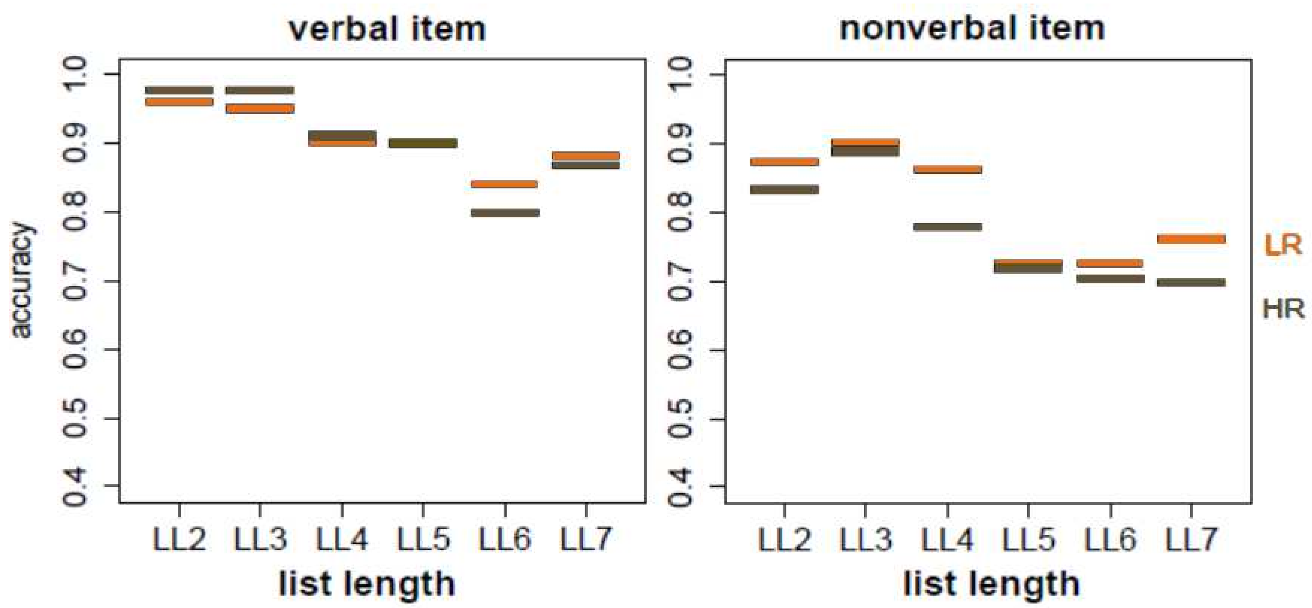

Figure A18: mean accuracy by list length in item tasks for low (LR) and high (HR) proficiency readers.

2. *Study 2*

2.1 *Example stimuli of the nonverbal item task*

Figure A19: example stimuli of a total of 171 drawings for the nonverbal item task.

2.2 *List positions in item tasks*

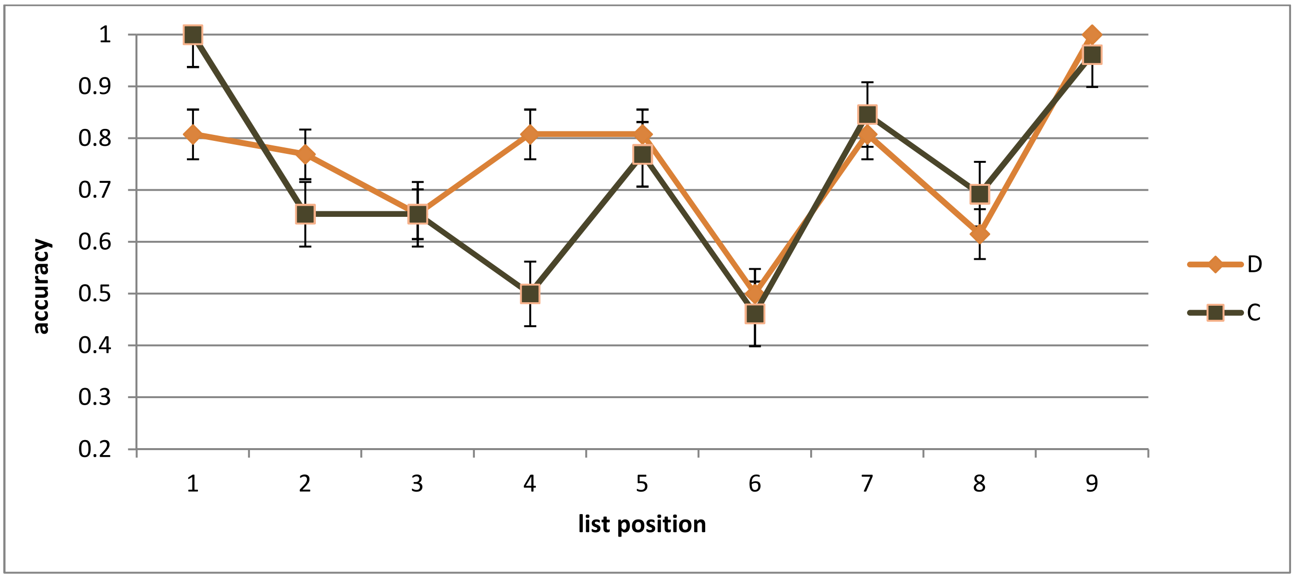

Figure A20: mean accuracy on list positions by group for the verbal item condition with whiskers denoting standard errors. List position is that position in which an item had been displayed that was a correct target in the task (those pictures on *yes*-trials). For every participant there is one data point per match position. This subset thus includes half of the data on item trials, only taking into account *false alarm* errors but not *misses*.

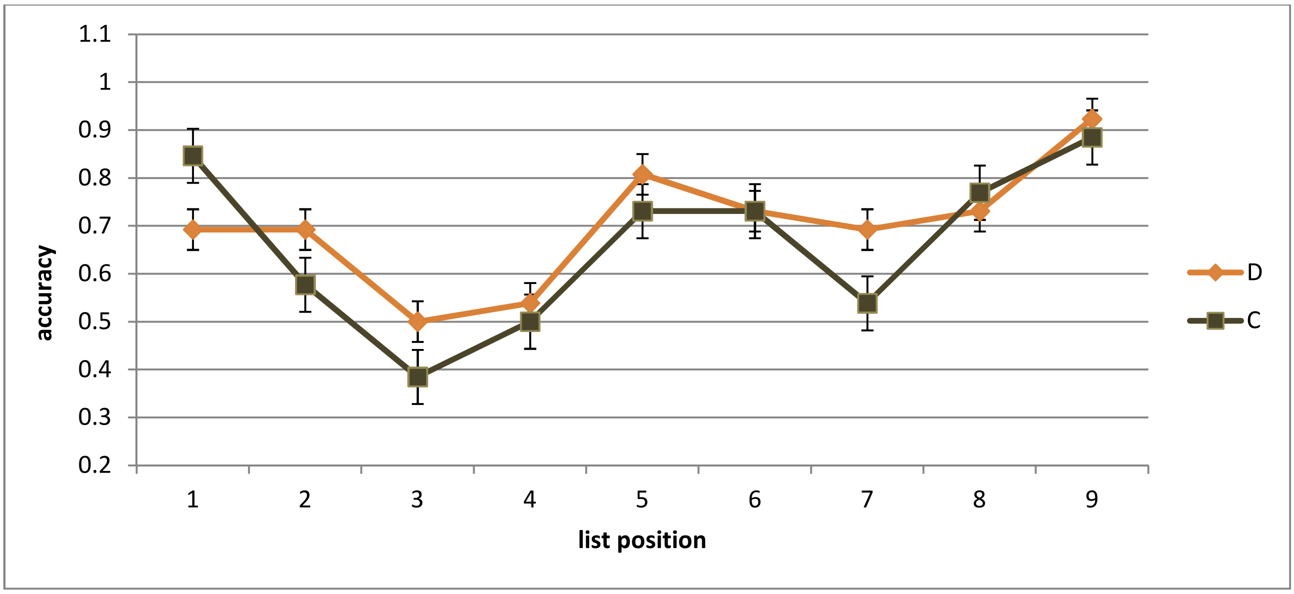

Figure A21: mean accuracy on list positions by group for the nonverbal item condition with whiskers for standard errors, calculated over all *yes*-trials.

2.3 *Regression tree*

To illustrate the contributions of subgroups of factors to performance, I employed a single regression tree model, that is a method of recursive partitioning (see Strobl, Malley, & Tutz, 2009). It split all 180 data points of mean accuracy by the factors group, task, domain and span as in the ANOVA above, and added the variables word reading (EMT), nonword reading (Klepel) and IQ (KAIT). Starting from the whole data set, the model searches for the variable that best reduces the error for that specific data set and partitions it in two subsets, recursively splitting every subset in two again until no variable reduces the error term any further. Reading the tree from the top, the variable name and specification above a node (split) specify the splitting criteria, describing the data subset that is depicted below to the left (left branching). The value of the dependent variable (mean accuracy for this subgroup before splitting) is depicted under the node, including the number of data points of that subset (n=). The other data of the split go to the bottom right of the node.

The tree revealed a first split by task (order to the left, item to the right) as expected from the linear model main effect for task. Within order tasks, nonword reading (Klepel) entered as the second variable, confirmed by the correlation analysis above. It specified that within the order tasks, only for those participants who had nonword reading scores below 68 words per minute domain entered as a discerning variable, but not for very good nonword readers. Moreover, this split illustrates the interaction of task and group in the linear mixed models, in which dyslexics performed worse in order tasks. For the item tasks on the other hand, data were split by domain for all participants, for which IQ was the next predictor differentiating performance within each item task, in line with the correlation of item task performance and IQ.

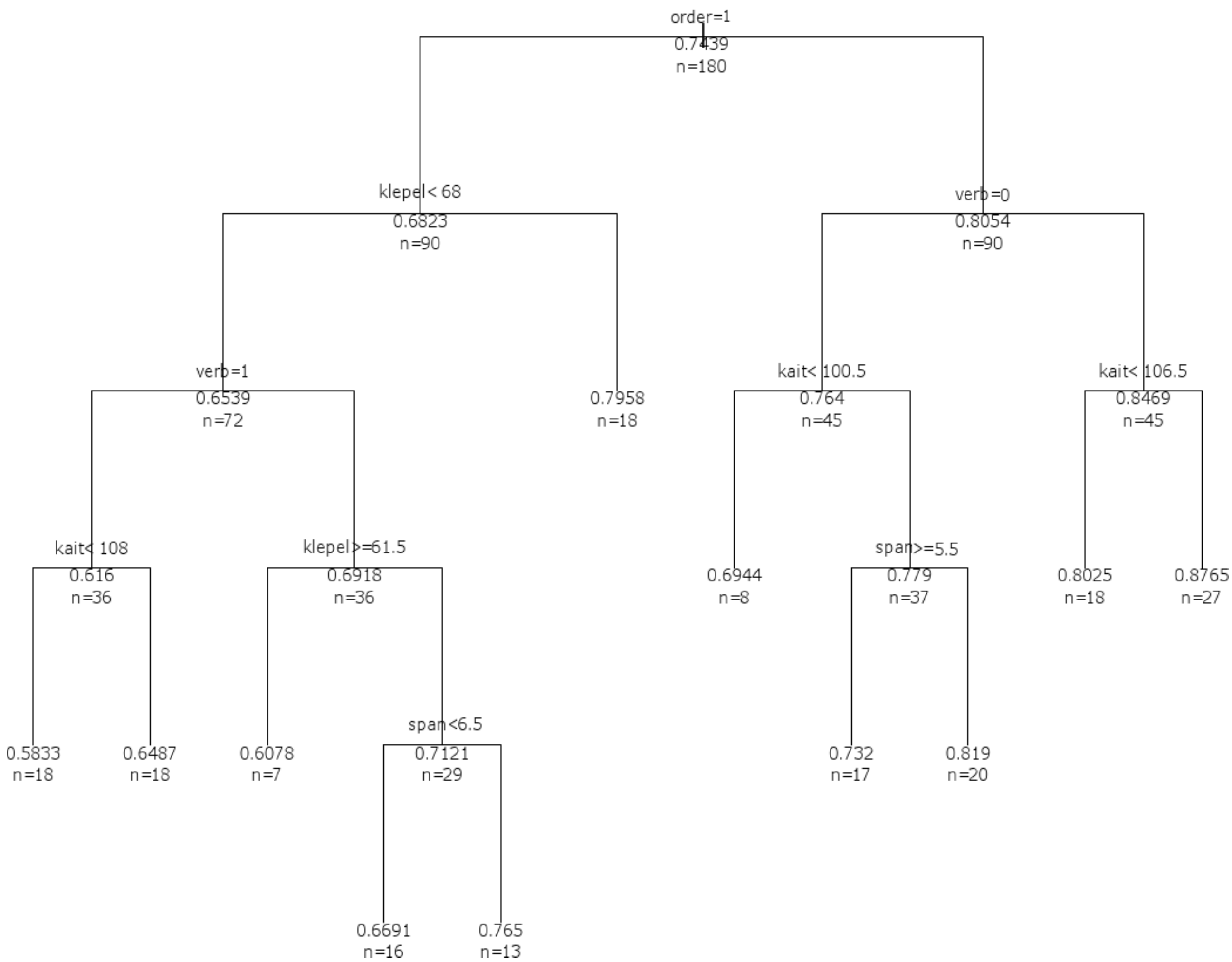

Figure A22: regression tree of mean accuracy by task, domain, span, word (EMT) and nonword reading (Klepel) and IQ (KAIT). The variable that best reduces the error of the respective subset of accuracy data is applied for each split, stepwise from the top. Note that splits can lead to unbalanced sizes of subsets. This analysis is included for illustration and specification but not for predictive purposes.

3. *Study 3*

3.1 *Accuracy by target position in item tasks*

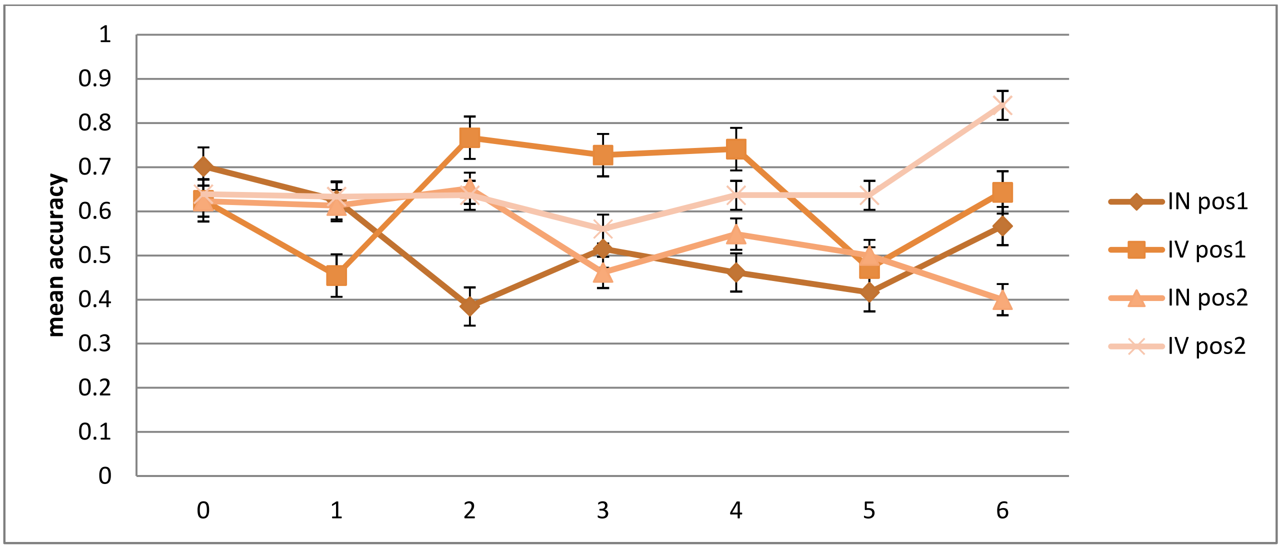

Figure A23: mean accuracy of dyslexic group (n=11) by position of the target item in the previous list. Whiskers depict standard errors. Measures were collapsed over the verbal (IV) and nonverbal (IN) item condition, including all *forward*, *backward* and those *no*-trials, for which one target item had been in the list presented before.

3.2 *Accuracy by target position in order tasks*

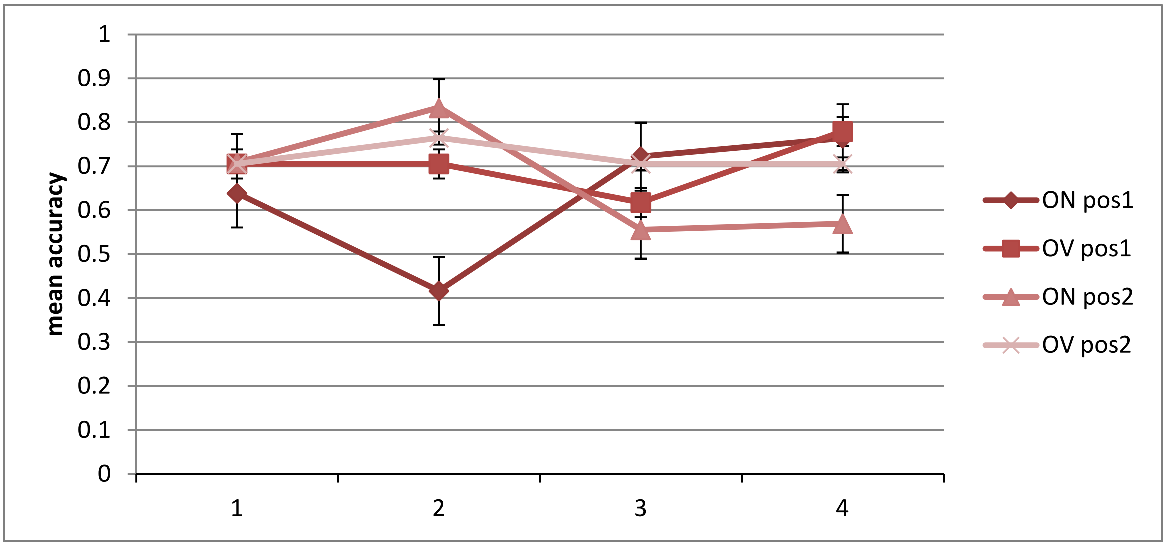

Figure A24: mean accuracy and standard errors (whiskers) of the dyslexic group (n=11) by position in order tasks, e.g. the position that the target item had held in the previously presented list. In order tasks, every target had held a list position before, so this graph includes all data of order trials for the dyslexic group, separately for verbal (OV) and nonverbal (ON) order tasks.