The visual attention span deficit in dyslexia is visual and not verbal

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Article history:
Received 2 February 2011
Reviewed 20 June 2011
Revised 11 July 2011
Accepted 8 September 2011
Action editor Roberto Cubelli
Published online xxx

Keywords:
Reading
Developmental dyslexia
Visual attention
VA span

1. Introduction

Developmental dyslexia is characterized by a severe reading acquisition impairment in children of normal intelligence, free of any neurological or psychiatric condition. It is widely admitted that dyslexia is a consequence of a phonological deficit (Vellutino et al., 2004; Ziegler and Goswami, 2005). Nevertheless, as a significant proportion of dyslexic children exhibit no phonological impairment (Bosse et al., 2007; White et al., 2006), such a deficit cannot account for the full spectrum of the disorder. Concurrently, visual processing performance has been shown to contribute to reading performance in typical readers (Kevan and Pammer, 2008; Kwon et al., 2007; Pammer et al., 2005). Moreover, visuo-spatial attention (Facocetti et al., 2008, 2006) and low level visual processing (Boden and Giaschi, 2007) have been found to be impaired in dyslexic readers. Multifactorial accounts of dyslexia (Menghini et al., 2010) have opened new perspectives such as the existence of a visual rather than phonological system impairment (Vidyasagar and Pammer, 2010).

Several studies have explored multi-element visual processing in dyslexic children using whole and partial report tasks (Bosse et al., 2007; Valdois et al., 2003). Impaired performance on these tasks was interpreted as evidence for a deficit in the number of individual visual elements that can be processed simultaneously, namely a visual attention (VA) span disorder.

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doi:10.1016/j.cortex.2011.09.003

Please cite this article in press as: Lobier M, et al., The visual attention span deficit in dyslexia is visual and not verbal, Cortex (2011), doi:10.1016/j.cortex.2011.09.003
Research has shown that a subset of dyslexic children exhibits such a deficit (Bosse et al., 2007). Within the framework of the Multi Trace Memory (MTM) model of reading (Ans et al., 1998), a VA span deficit can explain impaired reading acquisition by preventing simultaneous processing of the constituent letters of relevant orthographic units. The relevance of the VA span to reading is highlighted behaviourally by the fact that VA span performance is a reliable predictor of reading performance independently of phonological processing in typically developing (Bosse and Valdois, 2009) and dyslexic children (Bosse et al., 2007).

Even though the VA span disorder’s definition encompasses all types of visual elements, behaviourally its hallmark is impaired performance on letter-report tasks. These tasks have two potential caveats: they necessitate a verbal response and use verbal stimuli. Consequently it has been claimed (Hawelka and Wimmer, 2008; Ziegler et al., 2010) that the impairment does not follow from a visual processing deficit but from impaired visual to phonological code mapping in line with the phonological theory of dyslexia. In order to disambiguate from these two interpretations, it is necessary to confront predictions of both hypotheses on available data of tasks requiring verbal report and/or multi-element processing.

String visual processing has been studied extensively in dyslexia, albeit with many different types of paradigms which have led to contrasting results. Because of these numerous paradigms, it is crucial to identify those that do, in fact, investigate multi-element parallel visual processing. Not only do appropriate tasks need to involve processing of several elements, but paradigms also need to ensure that visual processing is parallel. Indeed studies that do not constrain stimulus presentation time (Hawelka and Wimmer, 2008; Pitchford et al., 2009) are not relevant for the VA span hypothesis.

Performance of parallel visual processing can be assessed independently of phonological ability by using tasks that require no verbal report, tasks that use non-verbal stimuli or, ideally, tasks that combine both. Poor performance for dyslexic readers in tasks involving parallel processing of verbal stimuli but no verbal response has previously been reported (Rutkowski et al., 2003; Ziegler et al., 2010). While this data is in line with the hypothesis of a purely visual processing deficit in dyslexia, it is not sufficient to sideline an underlying phonological cause insofar as the use of verbal material might automatically involve phonological recoding and yield a phonologically-constrained performance.

In order to completely disambiguate the role of visual and phonological processing in dyslexia, visual processing has been investigated using change detection tasks with non-verbal material. Not only were dyslexic readers impaired (Jones et al., 2008; Pammer et al., 2004), but task performance predicted reading performance in both children and adults (Pammer et al., 2005, 2004). These results cannot be accounted for by a phonological account of dyslexia, but are in line with predictions of the VA span deficit hypothesis.

However, another symbol processing task has yielded opposite results (Ziegler et al., 2010). Based on data from a partial report identification task, the authors argued against a visual deficit in dyslexia as the task yielded a deficit with letters and digits but not with symbols.

The main goal of this study is to disambiguate which of a parallel visual processing deficit or a phonological coding deficit is the proximal cause of the VA span deficit in dyslexia. We will investigate parallel visual processing in normal and dyslexic children using non-verbal categorization and verbal and non-verbal stimuli. Since we aim to specify the nature of the VA span deficit, all dyslexic participants will exhibit such a deficit. We aim to show (1) that performance on this non-verbal task relates to VA span performance in a large group of typically developing children and (2) that VA span impaired dyslexic children are impaired on this non-verbal task, regardless of character type.

### Table 1: Mean scores (SD) of age (chronological and reading) and reading performance for typically developing (TYP), dyslexic (DYS) and control (CTRL) children.

<table>
<thead>
<tr>
<th></th>
<th>TYP (N = 105)</th>
<th>DYS (N = 14)</th>
<th>CTRL (N = 14)</th>
<th>t or Z</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chronological age</strong></td>
<td>106.4 (14.6)</td>
<td>128.9 (14.6)</td>
<td>128.2 (11.1)</td>
<td>t(26) = .13, n.s.</td>
</tr>
<tr>
<td><strong>Reading age</strong></td>
<td>109.5 (21.5)</td>
<td>86.0 (5.9)</td>
<td>135.9 (18.7)</td>
<td>t(15.6) = 9.54***</td>
</tr>
<tr>
<td><strong>Reading</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Regular word</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy/20</td>
<td>17.0 (2.3)</td>
<td>13.1 (3.8)</td>
<td>19.4 (7.3)</td>
<td>Z = –4.34***</td>
</tr>
<tr>
<td>Speed (wds/min)</td>
<td>51.6 (22.7)</td>
<td>22.3 (8.4)</td>
<td>79.9 (20.7)</td>
<td>t(17.1) = –9.65***</td>
</tr>
<tr>
<td>Exception words</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Accuracy/20</td>
<td>10.9 (4.9)</td>
<td>7.9 (4.7)</td>
<td>16.1 (3.5)</td>
<td>Z = –3.69***</td>
</tr>
<tr>
<td>Speed (wds/min)</td>
<td>44.2 (20.4)</td>
<td>21.0 (10.5)</td>
<td>71.1 (18.9)</td>
<td>t(20.3) = –8.67***</td>
</tr>
<tr>
<td>Pseudo-words</td>
<td></td>
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<tr>
<td>Accuracy/20</td>
<td>15.7 (2.7)</td>
<td>10.6 (4.1)</td>
<td>17.5 (2.0)</td>
<td>Z = –3.90***</td>
</tr>
<tr>
<td>Speed (wds/min)</td>
<td>39.7 (14.3)</td>
<td>19.7 (5.4)</td>
<td>56.8 (14.2)</td>
<td>t(16.6) = –9.14***</td>
</tr>
<tr>
<td><strong>VA span</strong></td>
<td></td>
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<tr>
<td>Global report</td>
<td>80.7 (10.9)</td>
<td>64.0 (7.7)</td>
<td>89.6 (7.0)</td>
<td>t(26) = –9.22***</td>
</tr>
</tbody>
</table>

*** p < .001.
children were native French speakers, had normal or corrected to normal visual acuity and no reported learning disability. All participants and their parents gave informed written consent prior to the experiment. Characteristics are provided in Table 1.

Dyslexic children were recruited via the Dyslexia Unit of the Grenoble University Hospital. Diagnosis of developmental dyslexia was established using both inventories and testing procedures in accordance with the guidelines of the ICD-10 classification of Mental and Behavioural disorders. Dyslexic participants had normal IQ [full IQ superior to 85 on the WISC III or IV, or a score superior to the 25th percentile on Raven’s Progressive Matrices (Raven et al., 1998)]. The Alouette Reading Test (Lefavrais, 1965) was used to estimate children’s reading age. Children were diagnosed as dyslexics if their reading age was at least 18 months below their chronological age. Furthermore, all dyslexic children were screened to ensure that individual performance on the VA span report tasks (see task description in Methods) was at least 1.5 standard deviations (SDs) below age group norms.

An age-matched control group of 14 normal readers was selected amongst the typically developing children. These participants scored above the 15th percentile on all reading measures and had no reported learning disability. None of them exhibited a VA span deficit (Global Report Z-Score > −1). As shown in Table 1, the two groups did not differ significantly in chronological age [t(26) = .13, n.s.], whereas the dyslexic group’s reading age was significantly lower than the control group’s [t(15.6) = −9.54, p < .001].

2.2. Reading assessment

Participants’ reading skills were assessed using tasks of isolated word and pseudo-word reading (Jacquier-Roux et al., 2002). Participants were given three lists of 20 items each (20 regular words, 20 irregular words and 20 pseudo-words). Both accuracy and reading speed were scored.

2.3. VA span assessment

VA span performance was assessed using a five-consonant global report task. Twenty random five letter-strings (e.g., RHSDM; angular size = 5.4°) were built up from 10 consonants (B, P, T, F, L, M, D, S, R, H). Each letter was used 10 times and appeared twice in each position. Strings contained no repeated letters and never matched a real word skeleton (e.g., FLMBR for FLAMBER “burn”). Letters were presented in upper case (Geneva, 24) in black on a white background. Distance between adjacent letters was of .57° in order to minimize crowding. At the beginning of each trial, a central fixation point was presented for 1000 msec followed by a blank screen for 50 msec. A consonant-string was then displayed at the centre of the screen for 200 msec. Children had to report verbally as many letters as possible. Twenty experimental trials were preceded by 10 training trials for which participants received feedback. The dependent measure was the total number of letters accurately reported (identity not location) (maximal score = 100).

2.4. Experimental tasks

The categorization task was carried out using five different character categories: two verbal (letters and digits) and three non-verbal (Hiragana, pseudo-letters, and unfamiliar shapes). Each category was made up of six different characters (see Fig. 1). We calculated each set’s mean perimetric complexity (Majaj et al., 2002) as the best measure of character identification efficiency (Pelli et al., 2006). Our stimuli categories showed no significant difference in visual complexity. Categories were assigned a visual label made up of all the
category’s characters. All five categories and their characters were presented to the participant for 1 min before testing.

A single element categorization task was designed to control that participants had sufficient efficiency in identifying each individual character’s category. Stimuli were the 30 characters previously described, displayed once in each experimental block. Each trial began with a black fixation cross displayed on a white screen for 1000 msec, followed by a 50 msec blank screen. A single character subtending a vertical angle of .7° was then displayed in the centre of the screen during 200 msec, followed by a 500 msec mask. The answer screen (displayed next) required the participant to click on the visual label of the character’s category. Participants carried out 10 training trials with feedback, and two blocks of 30 experimental trials with no feedback. The dependent measure was the success rate across trials.

In the multi-element categorization task, participants had to count the number of elements of a character string belonging to a previously defined target category. Forty character strings were designed. Each string contained characters from two categories, a target category and a distracter category. Ten category/distracter category combinations were chosen so that each category was a target category twice and a distracter category twice. Combinations indifferently coupled verbal or non-verbal target categories with verbal or non-verbal distracter categories. Overall, each category was target for eight trials, with the number of target category characters varying from 1 to 3. Positions of the target category characters were counterbalanced across trials and trials were randomly drawn. Character strings were displayed in black on a white background. Each character subtended 1° vertical angle and the distance between the centres of each character was 1.4° in order to minimize crowding. Each trial began with the target category label which was displayed until the participant clicked on a button. A central fixation cross was then displayed during 1000 msec, immediately followed by a 50 msec blank screen. The character array was next displayed in the screen centre for 200 msec, immediately followed by a 500 msec mask. The answer screen displayed both the target category as a reminder and three buttons (1, 2, and 3) on which the participant was required to click according to the number of target category characters he had identified (see Fig. 1). Participants carried out five training trials with feedback before the 40 experimental trials with no feedback. The dependent measure was the success rate across trials. Scores for verbal (letters and digits) and non-verbal (Hiragana, pseudo-letters and geometrical shapes) target categories were also computed.

3. Results

Group comparisons showed that dyslexic readers performed worse than control readers on all reading and VA span measures, thus showing a mixed reading profile. Data that met normality assumptions were analyzed using Student’s t-tests; those that did not were analyzed using non-parametric Mann–Whitney U tests. Results are detailed in Table 1.

First, correlation analyses between categorization, VA span and reading age and speed were run on the typically developing population. Four children were excluded from further analyses because of poor performance on the single element categorization task. Single word reading speeds were averaged across lists. To normalize distributions, reading age and speed were log transformed. Table 2 provides Pearson’s full and partial correlations when controlling for chronological age between these variables. A Bonferroni correction for multiple correlations was applied (p = .005). Performance in the categorization task was moderately correlated with the five letter-report task (.35) and with both reading measures (.40–.43). Partial correlations controlling for chronological age showed that categorization performance remained significantly correlated with all other measures (from .28 to .35). To ensure that these correlations were not driven by verbal target performance, we computed correlations for non-verbal target performance. It was moderately correlated with global report performance (.33) and with both reading measures (.41 for both). Partial correlations controlling for chronological age showed it remained significantly correlated with all other measures (from .29 to .31).

Second, performance was compared between dyslexic and control groups. Performance on the single element task was at ceiling for both groups [mean DYS = .98, SD = .03; mean CTRL = .99, SD = .01; Z(28) = −1.53, n.s.]. For the multi-element

![Fig. 2 — Categorization performance (% correct) for dyslexic and control participants, error bars represent the SD of the mean.](image-url)
categorization task, accuracy scores for verbal (letters and digits) and non-verbal targets were analyzed in a 2 × 2 analysis of variance with Group (Dyslexics vs. Controls) as a between-subjects factor and Type (Verbal vs. non-verbal) as a within-subject factor (see Fig. 2). The main effect of Group \(F(1, 26) = 10.9, p = .003, \eta^2 = .295\) was significant showing that dyslexic children (mean verbal = .62, SD = .11; mean non-verbal = .64, SD = .15) performed worse than control children (mean verbal = .77, SD = .09; mean non-verbal = .81, SD = .11). More importantly, neither main Type effect \(F(1, 26) = 2.5, p = .12, \eta^2 = .09\) nor Group × Type interaction was significant \(F(1,26) = .41, p = .53, \eta^2 = .02\).

To further disambiguate the effects of the distracter category on performance, we examined scores obtained for the three category combinations that were entirely (i.e., both targets and distracters) non alphanumeric. Results showed that performance for entirely non alphanumeric character strings was significantly lower for the dyslexic group [mean DYS = .72, SD = .17; mean CTRL = .86, SD = .12; Z(28) = 2.18, \(p < .027\)] indicating that the dyslexic deficit endures even when no letters or digits are present in the character string.

4. Discussion

This study explored performance of both normal and VA span impaired dyslexic children on a non-verbal task and both verbal and non-verbal stimuli in order to disambiguate between a verbal or visual account of the VA span deficit. The first goal of our experiment was to show that the VA span global report task has processes in common with the non-verbal multi-element categorization task. Our results show that high global report performance is associated with high categorization performance, regardless of stimulus type, consistent with a visual interpretation of the VA span. Indeed, if verbal performance constrained VA span performance, no links with the categorization task should have been found. This pattern of findings held when age was controlled for. A ceiling effect on the single element task made it impossible to control for categorization performance, which should be investigated in future research.

The second goal of our experiment was to show that the VA span deficit in dyslexia could be extended to non-verbal tasks and non-verbal stimuli. Since no visual to phonological code mapping is involved in the categorization task, impaired mapping will not lead to impaired performance. In contrast, not only were dyslexic children impaired for alphanumeric categories, but their deficit was present and of similar magnitude for non-verbal target categories. This pattern of results cannot be reconciled with a phonological deficit account of developmental dyslexia but is, however, compatible with a visual processing deficit. A reduced number of visually processed elements would impact both the global report and categorization task. Furthermore, not only was this deficit present with both verbal and non-verbal targets, but it also endured when trials with only non-verbal characters were considered, indicating that it is present regardless of stimuli type. Results show that VA span impaired dyslexic children cannot process as many visual elements as their normal reading peers, regardless of element type. Similar impaired processing of verbal and non-verbal character strings is strong evidence for a purely visual account of the VA span deficit.

Visual crowding (Whitney and Levi, 2011) is known to influence character string processing and one could argue that increased crowding in dyslexic children (Martelli et al., 2009) could also account for their lower categorization performance. Although spacing between characters in both categorization and report tasks was set to a large enough value to prevent crowding, further investigation is needed to assess a potential crowding effect on dyslexic performance. In the same way, potential relationships with attentional masking mechanisms (Ruffino et al., 2010) have yet to be explored (but see Lallier et al., 2010).

Furthermore, our results need to be balanced against those of Ziegler et al. (2010) who found no symbol string deficit in dyslexic children. In contrast with our study where performance for verbal and non-verbal stimuli was similar, performance for symbols was lower than for verbal stimuli. This is consistent with previous results (Pelli et al., 2006) showing that memory span constrains performance on tasks requiring identification and recall of non-alphabetical stimuli. In that case, symbol performance for normal reading and dyslexic children would be equally low, as is the case in Ziegler et al.’s (2010) results.

While further research remains necessary to exclude other explanatory visual factors, this study provides strong evidence that poor VA span performance in dyslexia stems from a parallel visual processing deficit.

Acknowledgements

ML was funded by the ANR Blanc VASRA (ANR-07-BLAN-0019-01) grant and the Region Rhône-Alpes Cluster 11.

References


