FAST-TRACK REPORT

Rapid processing of letters, digits and symbols: what purely visual-attentional deficit in developmental dyslexia?

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Abstract

Visual-attentional theories of dyslexia predict deficits for dyslexic children not only for the perception of letter strings but also for non-alphanumeric symbol strings. This prediction was tested in a two-alternative forced-choice paradigm with letters, digits, and symbols. Children with dyslexia showed significant deficits for letter and digit strings but not for symbol strings. This finding is difficult to explain for visual-attentional theories of dyslexia which postulate identical deficits for letters, digits and symbols. Moreover, dyslexics showed normal W-shaped serial position functions for letter and digit strings, which suggests that their deficit is not due to an abnormally small attentional window. Finally, the size of the deficit was identical for letters and digits, which suggests that poor letter perception is not just a consequence of the lack of reading. Together then, our results show that symbols that map onto phonological codes are impaired (i.e. letters and digits), whereas symbols that do not map onto phonological codes are not impaired. This dissociation suggests that impaired symbol-sound mapping rather than impaired visual-attentional processing is the key to understanding dyslexia.

Introduction

Developmental dyslexia is a severe and long-lasting disorder that affects the acquisition of reading and spelling and that occurs in spite of normal intelligence, adequate schooling, and in the absence of other disabling conditions (Snowling, 2000). The causes of developmental dyslexia are probably multifactorial (Pennington, 2006), yet studies comparing different classes of deficits within the same group of dyslexics show that phonological deficits outweigh visual, auditory and motor deficits both in size of the deficit and the percentage of affected children (e.g. Menghini, Finzi, Benassi, Bolzani, Faccetti, Giovagnoli, Ruffini & Vicari, 2010; White, Milne, Rosen, Hansen, Swettenham, Frith & Ramus, 2006; Ziegler, Castel, Pech-Georgel, George, Alario & Perry, 2008). Particularly robust and predictive of dyslexia are deficits in mapping visual and/or orthographic codes onto phonology (Goswami & Bryant, 1990; Share, 1995; Ziegler, Bertrand, Töth, Csepe, Reis, Faisca, Saine, Lyytinen, Vaessen & Blomert, 2010; Ziegler & Goswami, 2006), a deficit in such a fundamental process will hinder orthographic development and fast, automatic visual word recognition. According to this view, visual and/or orthographic impairments in dyslexia would be a consequence of underlying deficits in phonology and/or deficits in mapping visual onto phonological codes.

In recent years, however, the phonological deficit hypothesis has become increasingly unpopular (e.g. Ramus & Szenkovits, 2008). Indeed, a number of authors have suggested that visual or visuo-attentional rather than phonological deficits are at the origin of dyslexia (e.g. Vidyasagar & Pammer, 2010). Among the visual attention theories of dyslexia, one of the most important theories is the visual attention span deficit hypothesis (Bosse, Tainturier & Valdois, 2007; Valdois, Bosse & Tainturier, 2004). In this research, the visual attention span is estimated by flashing five-letter consonant strings (e.g. R H S D M) for 200 ms at the centre of the screen. Participants are asked to orally report either the whole letter string (whole report) or a single cued letter (partial report). In both conditions, dyslexic children obtained significantly lower scores than chronological age controls
although the deficit appeared to be more robust in the whole report condition. Follow-up work suggested that dyslexics exhibited deficits in oral report of simultaneously but not sequentially presented letter strings (Lassus-Sangosse, N’Guyen-Morel & Valdois, 2008), which was taken as additional evidence that the visual-attentional core deficit reflects a limitation in the number of elements that can be processed in parallel from a brief visual display (i.e. reduced attentional window). Although these results are intriguing, two aspects of the design prevent firm conclusions. First, the use of letter strings, as opposed to nonverbal material (e.g. symbol strings), makes it impossible to assess the underlying nature of the deficit, as the lack of reading stemming from dyslexia should naturally result in poorer letter string perception. Second, the use of the oral report task involves rapid naming and phonological short-term memory, which are two components that are known to be deficient in dyslexia (Di Filippo, Zoccolotti & Ziegler, 2008; Rapala & Brady, 1990; Wolf, Bowers & Biddle, 2000). Thus, it is still not clear to what extent the deficits in letter string perception tasks are really visual-attentional in nature.

Hawelka and Wimmer (2005) addressed the first of these problems, the causality problem, by using digit strings rather than letter strings. That is, while it is obvious that lack of reading might cause difficulties with letter strings, lack of reading should not cause specific deficits with digit strings. Hawelka and Wimmer (2005) presented the two-, four-, and six-item digit strings at the centre of the screen, followed by a post mask. Simultaneously with the post mask, one of the positions was cued and participants had to name the cued digit. Presentation time was adaptively varied. The results showed that dyslexic readers exhibited increased recognition thresholds for four- and six-digit strings but not for two-digit strings, which led them to conclude that dyslexics suffer from a visual multi-element processing deficit. In a follow-up study, Hawelka, Huber and Wimmer (2006) established recognition thresholds for five-element letter and digit strings for each position separately, which made it possible to investigate the serial position profiles of the dyslexics. They argued that most visual-attentional theories would predict that dyslexics’ serial position profiles should be deviant (for detailed discussion, see Hawelka et al., 2006). Yet, the dyslexics’ serial position profiles were normal (i.e. M-shaped for RTs and W-shaped for accuracy; see Mason, 1982), which the authors took as evidence against a visual-attentional basis of the multi-element processing deficit. Hawelka and Wimmer’s paradigm, however, inherited two of the shortcomings mentioned earlier, namely the use of oral report and verbal material (i.e. letters and digits map onto phonology). Thus, any theory that posits impairments in the mapping between visual codes and phonology as the core deficit of dyslexia would be able to account for those findings (e.g. Ziegler & Goswami, 2006). That is, deficits in the visual-attentional span task might not reflect a problem with parallel processing of visual elements but a problem with verbal coding and rapid naming. In support of this, some authors failed to find deficits for dyslexics in a visual task without verbal involvement (Hawelka & Wimmer, 2008) or verbal material (Shovman & Ahissar, 2006). However, the issue is far from being settled, as others have reported reliable deficits in visual-attentional tasks without verbal involvement (e.g. Facoetti, Zorzi, Cestnick., Lorusso, Moltenia, Paganoni, Umlita & Mascetti, 2006; Facoetti, Trussardi, Ruffino, Lorusso, Cattaneo, Galli, Molteni & Zorzi, 2009; Pammer, Lavis, Hansen & Cornelissen, 2004).

The goal of the present study was to investigate the nature of the multi-element processing deficit in a task that does not require oral naming and that compared verbal and nonverbal material, namely letters, digits, and symbols. The use of these three stimulus classes within the same psychophysical paradigm makes it possible to compare the relative size of the deficits for the same population. If the core deficit of dyslexia was visual or attentional (Vidyasagar & Pammer, 2010), we would predict similar deficits for letters, digits and symbols because visual/attentional processes are similar for these three classes of items provided they are matched for visual complexity (Pelli, Burns, Farell & Moore-Page, 2006; Shovman & Ahissar, 2006). However, if the core deficit were related to mapping visual codes onto phonology (Blau et al., 2009, 2010), then dyslexics should show deficits only for letters and digits, not for symbols that do not map onto phonology. Finally, if the letter string deficit were simply a consequence of dyslexia due to lack of reading, we would expect dyslexics to show larger deficits for letters than for digits.

The design of our experiment was modelled after a recent study by Tydgat and Grainger (2009) with skilled adult readers. The authors used the classic two-alternative forced-choice (2AFC) Reicher-Wheeler paradigm (Reicher, 1969) with letter, digit, and symbol strings. The basic design of the Tydgat and Grainger study and schematic results are displayed in Figure 1. Interestingly, letter and digit strings produced the typical W-shaped serial position function with best performance in the centre, worst performance at positions 2 and 4, and intermediate performance for the outer positions (see also Mason, 1982). In contrast, symbols produced an inverted V-shaped function, in which letter recognition performance dropped off as a function of eccentricity. As argued in Hawelka et al. (2006), visual-attentional span deficits should disrupt the serial position functions found with dyslexics. In contrast, finding normal serial position functions would be problematic for visual-attentional accounts of dyslexia.

**Methods**

**Participants**

Twenty-eight dyslexic children were recruited from the University Hospital La Timone Marseille, France. They
were aged between 8;3 and 12;4 years with an average of 10;3 years. Prior to the study, all dyslexics received a complete medical, psychological, neuropsychological and cognitive assessment. This assessment was done by an interdisciplinary team of psychologists, neurologists and speech therapists. Dyslexics were included in the study if their reading age was at least 18 months below chronological age. In addition to the standardized reading, phonological awareness and rapid automatized naming tests, all participants completed a standardized single word reading test (Castel, Pecher-Lefavrais, 1965) and if their nonverbal intelligence was above the 25th percentile on the Standardized Progressive Matrices (SPM; Raven, 1976). They were excluded from the study if their oral language skills were in the pathological range (i.e. formal diagnosis of SLI). Twenty-nine normally developing children were selected as controls from nearby schools. None of the controls reported a history of written or oral language impairment. They were matched to the dyslexics on nonverbal IQ and chronological age. In addition to the standardized reading and nonverbal intelligence tests, all participants completed a standardized single word reading test (Chevrie-Muller, Simon, Fournier & Brochet, 1997) that contains 20 nonwords, 10 regular words, and 10 irregular words, a standardized phoneme deletion and phoneme fusion test (Jacquier-Roux, Valdois & Zorman, 2002), and a rapid automatized naming test (Castel, Pech-Georgel, George & Ziegler, 2008). Subject characteristics and test results are presented in Table 1. The study was conducted with the understanding and consent of the participants and their parents.

Stimuli and design

All stimuli consisted of horizontal arrays of five characters. Three different types of stimuli were used: consonant letters presented in uppercase (B, D, F, G, K, N, L, S, and T), digits (1 to 9), and symbols (%, /, ?, @, ), <, £, §, and µ). Note that most of these symbols are not yet familiar to children within our age range, that is, they would not be able to provide a name for the symbol. The visual complexity of the letters, digits, and symbols was calculated using the perimetric complexity measure described by Pelli et al. (2006). Perimetric complexity is the symbol’s squared perimeter divided by its ink area, where ink area is the number of inked pixels times the area of a pixel. As shown by Pelli et al. (2006), perimetric complexity is the best measure for the efficiency of letter and symbol identification. This is also the measure used by Shovman and Ahissar (2006) to match familiar and unfamiliar alphabets for visual complexity. For our stimulus material, no significant differences in perimetric complexity were found between symbols and letters (p > .90) or between symbols and digits (p > .90).

These three categories were assigned to three blocks, so that one block consisted of 60 letter-array stimuli, one of 60 digit-array stimuli, and one of 60 symbol-array stimuli. Although the presentation order of the blocks was counterbalanced among participants, all other factors were manipulated as within-subjects variables. Each array consisted of a quasi-random sequence of characters. For the purposes of the forced-choice task each target character was paired with an alternative character so that a target character was always presented with the same alternative at each of the five positions. Each target character served as the alternative for one other character. The incorrect alternative presented for forced choice was never present in the stimulus array.

Procedure

The experiment was run inside a dimly lit room and was controlled with E-Prime software (Psychology Software Tools, http://www.pstnet.com/eprime). Participants were seated in front of a computer screen at a viewing distance of approximately 60 cm. At that distance, target stimuli in the five different positions were located at −1.2°, −0.6°, 0°, 0.6°, and 1.2° of visual angle from the central fixation point, and each letter, digit, or symbol character subtended on average 0.44° of visual angle. Stimuli were displayed in white on a black background and were presented in 18-point Courier New font. The instructions

Table 1  Subject characteristics and performance on standardized reading, phonological awareness and rapid automatized naming tests. Standard deviations are presented next to means.

<table>
<thead>
<tr>
<th></th>
<th>Dyslexics</th>
<th>Controls</th>
<th>T-test (p values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (months)</td>
<td>123.1 ± 10.8</td>
<td>119.8 ± 12.8</td>
<td>.235</td>
</tr>
<tr>
<td>Reading age (months)</td>
<td>90.8 ± 21.0</td>
<td>124.1 ± 8.8</td>
<td>.000</td>
</tr>
<tr>
<td>Nonword reading /20</td>
<td>15.8 ± 3.4</td>
<td>19.4 ± 1.0</td>
<td>.000</td>
</tr>
<tr>
<td>Regular word reading /10</td>
<td>9.6 ± 0.8</td>
<td>10.0 ± 0.0</td>
<td>.008</td>
</tr>
<tr>
<td>Irregular word Reading /10</td>
<td>7.0 ± 2.6</td>
<td>9.8 ± 0.4</td>
<td>.000</td>
</tr>
<tr>
<td>Phoneme deletion /10</td>
<td>7.8 ± 2.2</td>
<td>8.4 ± 1.8</td>
<td>.220</td>
</tr>
<tr>
<td>Phoneme fusion /10</td>
<td>7.5 ± 1.8</td>
<td>8.0 ± 1.9</td>
<td>.192</td>
</tr>
<tr>
<td>RAN (sec)</td>
<td>62.2 ± 21.1</td>
<td>44.9 ± 9.4</td>
<td>.000</td>
</tr>
<tr>
<td>Raven SPM (percentiles)</td>
<td>42.5 ± 19.3</td>
<td>44.1 ± 15.0</td>
<td>.693</td>
</tr>
</tbody>
</table>

RAN = rapid automatized naming.
were given orally and participants received 12 practice trials. Each trial began with two vertical fixation bars, placed above and below the centre of a forward mask. The forward mask consisted of five hash marks and stayed on the screen for 515 ms. Then the fixation bars and the mask disappeared, and the array of five characters immediately appeared for a duration of 200 ms. This was followed by a backward mask, which was identical to the forward mask. Simultaneously with the presentation of the backward mask, a target cue was displayed in the form of a horizontal bar below the hash mark at the critical target position and the two response alternatives were presented in a central location below the mask. Participants had to decide which one of these two characters was present in the corresponding position of the preceding array. They were asked to respond as accurately as possible by pressing one of two keys on the keyboard. They had to choose either the upward arrow key (for the alternative above) or the downward arrow key (for the alternative below). After the response, the screen was cleared, and the two fixation bars appeared on the screen. The next trial was initiated by pressing the space bar.

Results

The results are presented in two parts. The first compares the deficit for letters and digits, while the second compares the deficit for symbols with that of letters and digits.\(^1\) Accuracy (% correct) in the 2AFC task for letter and digit strings is presented in Figure 2. The data were analyzed in a \(2 \times 2 \times 5\) analysis of variance (ANOVA) with Group (dyslexics versus controls), Stimuli (letters versus digits), and Position (1–5) as factors. Group was treated as a between-subjects factor, while Stimuli and Position were within-subjects factors.

The ANOVA exhibited a significant main effect of Group (\(F(1, 55) = 7.71, p < .01\)) and Position (\(F(4, 55) = 33.61, p < .0001\)). No significant main effect was found for Stimuli (\(F < 1\)). Importantly, there was no significant interaction between the effects of Group and Stimuli (\(F(1, 55) = 0.02, p > .80\)) or Group and Position (\(F(4, 220) = 1.17, p > .10\)). The triple interaction just reached significance (\(F(4, 220) = 2.48, p = .048\)) but was only marginally significant when the Greenhouse-Geisser correction for the violation of sphericity was applied (\(p = .053\)). The triple interaction simply reflects the finding that dyslexics’ letter perception was slightly better than expected at position 4, whereas their digit perception was slightly better than expected at position 5. Visual-attentional theories would have predicted the opposite, namely that dyslexics’ letter perception performance should be particularly impaired at position 4 as this is one of the most ‘crowded’ positions. It is possible that the better performance of the dyslexics at these two positions is simply due to noise in the data. Apart from these two deviations, dyslexics showed a fairly normal W-shaped serial position function.

Figure 3 contrasts the performance for symbols with that of letters and digits. In this figure and the following analyses, the data for letter and digit strings were combined because there were no significant differences between letters and digits in the above analysis. To compare the symbol string deficit with that of letters and digits, we therefore conducted an ANOVA with Group (dyslexics versus controls), Stimuli (symbols versus letters/digits), and Position (1–5) as factors. The results showed a significant main effect of Group (\(F(1, 55) = 5.06, p < .05\)), Stimuli (\(F(1, 55) = 13.1, p < .001\)) and Position (\(F(4, 55) = 46.2, p < .0001\)). More importantly, the main effect of Group was qualified by a significant interaction between Group and Stimuli (\(F(1, 55) = 4.11, p < .05\)). This significant interaction reflects the finding

\(^1\) We refrain from presenting the results of the global ANOVA as we had specific a priori predictions about alphanumeric stimuli (letters/digits) being processed differently from non-alphanumeric stimuli (symbols). This said, the triple interaction of Group (dyslexics, controls), Stimuli (letters, digits, symbols), and Position (1–5) approaches significance (\(F(8, 440) = 1.89, p = .06\)), which largely justifies the breakdown into two separate analyses.
that there was a deficit for letters/digits but not for symbols. Neither the Position by Group, nor the triple interaction reached significance (all $F$s < 1.4). To further test the absence of a deficit for symbols, we conducted an ANOVA with Group and Position as factors for symbols only. This analysis confirmed that neither the main effect of Group nor the Group by Position interaction were significant (both $F$s < 1).

**Discussion**

The results can be summarized as follows. As a group, children with developmental dyslexia showed significant deficits in processing letter and digit strings (verbal material) but not symbol strings (nonverbal material). This is not to say that it would be impossible to find deficits in processing symbol strings in dyslexia as some previous research has reported such deficits (Pammer et al., 2004). However, it is clear from our results that the same experimental conditions that give rise to robust deficits with letter and digit strings do not produce deficits with symbol strings. Thus, this dissociation shows that deficits for verbal material are more important than deficits for nonverbal material even if the task does not involve oral naming. The present finding thus joins the results from Shovman and Ahissar (2006) who investigated symbol processing in Hebrew dyslexics by using a set of Georgian letters that were graphically similar to Hebrew letters but yet unfamiliar to the participants. As in our study, dyslexics performed as well as controls with these unfamiliar letters across a variety of conditions. A similar finding was reported by Hawelka and Wimmer (2008) with pseudoletters. Together then, the absence of a robust deficit for symbols in the presence of robust deficits for letters and digits is difficult to reconcile for purely visual or attentional theories of dyslexia.

The second main finding of our study was that serial position curves were normal in dyslexics, that is, dyslexics showed the classic W-shaped function for letters and digits and the classic inverted V-shaped function for symbols (Mason, 1982; Tydgat & Grainger, 2009). As discussed by Hawelka et al. (2006), if dyslexics suffered from a narrowed attentional window, as suggested by Valdois et al. (2004), they should have shown no deficits for the fixated middle letter and increased deficits for the outer letters. However, this was not the case. Similarly, if deficits were due to increased interference from adjacent letters in the periphery (i.e. crowding), as suggested by Martelli, Di Filippo, Spinelli and Zoccolotti (2009), dyslexics should have shown larger deficits at positions 2 and 4 as these positions should be more affected by crowding. However, there was no evidence for larger deficits at positions 2 and 4. Furthermore, if dyslexics had difficulty in allocating attention to the beginning or the end of a string, they might not have shown the release-from-masking effects for letters and digits in the outer positions. Finally, Tydgat and Grainger (2009) hypothesized that during reading acquisition, children learn to adapt to the unusually crowded conditions imposed by strings of letters, and that it is this adaptation that causes the different serial positions functions for letters and digits compared with stimuli that are typically not processed in such crowded conditions. Therefore, if part of the problem in dyslexia was related to an inability to adapt to the particular visual constraints imposed by strings of letters, then one would have expected a serial position function for letter stimuli that resembles that seen with symbols. The results of the present study clearly showed that this is not the case.

It remains to be explained why dyslexics show impairments for letters and digits but not symbols. The first hypothesis is that letters and digits (but not symbols) might be processed by the visual word form system located in the left hemisphere occipito-temporal cortex. Given the evidence that this region is dysfunctional in dyslexia (e.g. Kronbichler, Hutzler, Staffen, Mair, Ladurner & Wimmer, 2006), this would explain why letters and digits but not symbols are impaired. A problem with this hypothesis, however, is that high-resolution imaging of the visual word form system (Baker, Liu, Wald, Kwong, Benner & Kanwisher, 2007) showed specific sensitivity of that area to letter strings but not digit strings; indeed, digit strings clustered with symbol strings but not letter strings. The second hypothesis is that letters and digits are impaired because only letters and digits map onto phonological codes and it is the mapping between visual and phonological codes that is at stake in dyslexia. This hypothesis receives strong support from recent neuroimaging studies showing fundamental deficits in letter–sound integration in dyslexia (Blau et al., 2009, 2010). Similarly, the fact that dyslexic children show robust deficits when they have to rapidly name objects but not when they have to visually process objects (e.g. Di Filippo, Brizzolara, Chilosi, De Luca, Judica, Pecini, Spinelli & Zoccolotti, 2005) also supports the idea that a deficient mapping between visual and phonological codes is at the heart of dyslexia. As stated by Klein (2002), ‘rapid automatized naming is tapping the efficacy of the pathways connecting the visual pattern recognition module with the auditory language module … and it is likely the pathway upon which print to sound (pronunciation) conversion and hence reading acquisition critically depends’ (p. 228). In conclusion, what initially looks like a visual impairment in processing letters and digits may not in fact be one, given that symbols are not affected in the same way. Instead, if visual impairments are only obtained for verbal material (e.g. letters), everything else being equal, this would certainly put phonology back in the front row.

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