

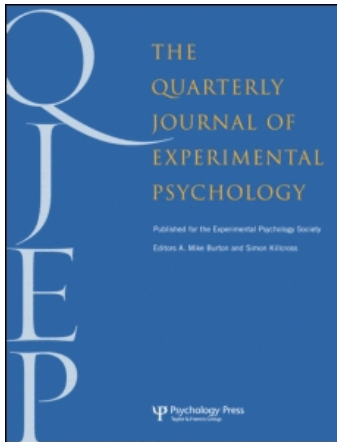
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# Reduced orthographic learning in dyslexic adult readers: Evidence from patterns of letter search

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Visual letter search performance was investigated in a group of dyslexic adult readers using a task that required detection of a cued letter target embedded within a random five-letter string. Compared to a group of skilled readers, dyslexic readers were significantly slower at correctly identifying targets located in the first and second string position, illustrating significantly reduced leftward facilitation than is typically observed. Furthermore, compared to skilled readers, dyslexic readers showed reduced sensitivity to positional letter frequency. They failed to exhibit significantly faster response times to correctly detect target letters appearing in the most, compared to least, frequent letter position within five-letter words, and response times correlated with positional letter frequency only for the initial, and not the final, letter position. These results are compatible with the SERIOL (sequential encoding regulated by inputs to oscillations within letter units) model of orthographic processing proposed by Whitney and Cornelissen (2005). Furthermore, they suggest that dyslexic readers are less efficient than skilled readers at learning to extract statistical regularities from orthographic input.

*Keywords:* Dyslexia; Reading; Orthography; Letter search.

Much of the research that has been conducted on dyslexia over the past 40 years has focused on the difficulties that individuals with dyslexia have in processing phonology (Lieberman, Shankweiler, Fischer, & Carter, 1974; see Castles & Coltheart, 2004, for a review). In contrast, relatively little research has been conducted on the orthographic processing of written words in individuals with dyslexia. Vellutino, Scanlon, and Tanzman (1994) define orthographic processing as “the ability to represent the unique array of

letters that defines a printed word, as well as general aspects of the writing system such as sequential dependencies, structural redundancies, letter position frequencies, and so forth” (p. 314). According to this definition, at least, orthographic learning would emerge from the more general process of statistical learning, in which statistical regularities of the input orthography become encoded within the system dedicated to the processing of written words, through exposure to printed text. A deficiency in

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orthographic learning would thus hinder the development of a rapid, accurate, and efficient system for written-word recognition (Castles & Nation, 2006).

In reviewing the literature supporting causal accounts of dyslexia, Castles and Coltheart (2004) propose that difficulties in establishing mappings between orthography (graphemes) and phonology (phonemes) are more likely to have a causal role in dyslexia than are difficulties with phonological awareness *per se*. Accordingly, Whitney and Cornelissen (2005) propose that any problem in forming the orthographic-to-phonological associations utilized in written-word recognition will have negative consequences for the processes recruited when recognizing and naming written words.

To illustrate how dyslexia may arise from difficulties in establishing orthographic-to-phonological associations, Whitney and Cornelissen (2005) consider the SERIOL (sequential encoding regulated by inputs to oscillations within letter units) model of orthographic processing, originally proposed by Whitney and Berndt (1999) and Whitney (2001). The SERIOL model explicitly focuses on the early processes of visual word recognition and specifies how information represented at the retina becomes encoded in abstract letter units required for lexical retrieval. In particular, it specifies how letter identities and relative position within letter strings are processed, enabling skilled readers to distinguish words that contain the same letters but arranged in a different relative order (e.g., ABLE and BALE).

To show how the SERIOL model may account for the difficulties shown by dyslexic readers Whitney and Cornelissen (2005) extended the model to include a phonological route and reading acquisition (for full details of this model, see Whitney & Cornelissen, 2005). This led to specific predictions regarding how dyslexic readers should process horizontal arrays of letters, some of which we test in this paper. To see how these predictions emerge from the SERIOL model a brief overview of the model is given below.

The SERIOL model of orthographic processing has been developed to account for behavioural data from skilled readers of English and is constrained by the neurobiology of the human visual system. It consists of five layers, these being the edge, feature, letter, bigram, and word layers. At each layer activation of a letter is distributed over nodes, which represent the neural substrate responsible for processing that letter. Different activation gradients are formed at each layer, which serve to transform the retinotopic map into a serial encoding of letter order that is abstract and location invariant. This serial encoding of letter position is used to activate bigram and lexical representations.

Upon fixation of a letter string, information from the retina generates an activation gradient at the edge layer that is based on visual acuity. Activation decreases with increasing eccentricity from fixation; thus letters closest to fixation receive the highest activation. As fixation usually falls near the centre of a letter string (see Brysbaert & Nazir, 2005), letters located in the medial positions benefit from higher activation than letters located at the ends of the array (termed henceforth "medial letter facilitation"). Activation at the edge layer is split across the two hemispheres, including the foveal representation, according to the neuroanatomy of the visual system. Hunter, Brysbaert, and Knecht (2007) provide compelling evidence that this splitting is relevant to reading. This means that letters falling on the retina in the left visual field (LVF) project to the right hemisphere (RH), whereas letters falling on the retina in the right visual field (RVF) project to the left hemisphere (LH). Thus, an acuity gradient is generated in each hemisphere in order to represent the retinotopic information from both visual fields.

This initiates excitation of nodes at the feature layer. Here, the acuity gradient in each hemisphere is transformed into a locational gradient that operates in line with reading habits. Hence, for skilled readers of English the locational gradient operates in the direction of left to right. Accordingly, the initial letter in a string (i.e., the letter in the most leftward position) receives the most

activation, followed by the second letter in the string, and so forth, with the final letter receiving the least activation.

For the “centre-out” acuity gradient, generated at the edge layer, to be converted to a “left-to-right” locational gradient, at the feature layer, two key assumptions are made. First, the acuity gradient of the LVF/RH must be inverted so as to create a directional gradient that benefits activation of letters located to the left of the string (especially the initial letter). This inversion is not necessary for letters processed by the RVF/LH as the acuity gradient generated by the edge layer preserves relative letter order. In order for the inversion of the acuity gradient in the LVF/RH to occur it is assumed that activation of the initial letter in the string receives a boost through a combination of excitation and lateral inhibition in the RH. This results in an activation pattern that decreases towards fixation, in which the initial letter in a string receives the greatest activation (termed henceforth “initial letter facilitation”).

Second, in order to encode relative left-to-right order across a letter string, it is further assumed that excitation is greater overall in the LVF/RH than in the RVF/LH. As a result, letters processed by feature nodes in the LVF/RH inhibit those processed by the feature nodes of the RVF/LH. This results in an overall directional pattern of activation that decreases from the left to right. Accordingly, letters to the left of fixation receive higher activation than letters located to the right of fixation (termed henceforth “leftward facilitation”).

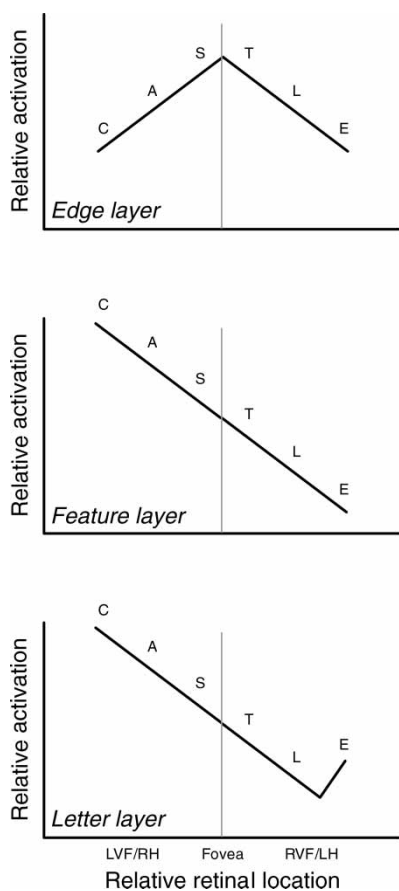
Serial encoding of relative position across a letter string in a left-to-right direction is generated at the letter level from graded input from the locational gradient. Lateral inhibition operates across the letter nodes. As the node of the initial letter is the first to be activated, it starts to inhibit activation of nodes representing letters located to its right. The second letter in the string only becomes activated when the firing rate of the initial letter node slows, and lateral inhibition reduces, thus enabling the next letter node to start firing. This results in a decreasing activation

gradient at the letter layer in which serial order of letters is encoded. In addition, the final letter in the string (i.e., the most rightward letter) benefits from greater activation at the letter layer because it is not inhibited from letters to the right. Consequently, even though the final letter receives the lowest input from the locational gradient, once activated it can fire for longer, until the end of the oscillatory cycle. Thus, a processing advantage for the final letter relative to internal letters in a string emerges at the letter layer (termed henceforth “final letter facilitation”). The relative activation patterns generated at the edge, feature, and letter layers of the SERIOL model are illustrated in Figure 1.

Activation of letter nodes in a left-to-right serial order induces firing of the corresponding bigram nodes, which then initiates firing of word nodes at the word layer. Written-word recognition is finally achieved through weighted connections between bigram and word nodes.

Whitney and Cornelissen (2005) propose that the edge, letter, bigram, and word layers are innately specified and represent general mechanisms used in visual discrimination and learning. The only mechanism in the SERIOL model that is learned, as a consequence of reading acquisition, is the establishment of a locational gradient at the feature layer. Furthermore, establishing a locational gradient is only necessary when horizontal strings of symbols (such as letters or numerals) require relative position to be encoded for precise referential meaning to be extracted (e.g., enabling the difference between ABLE and BALE, and 192, 921, 291 to be determined). Horizontal arrays of other, nonalphanumeric, symbols (such as  $\blacklozenge$   $\blacktriangleright$   $\square$   $\bullet$   $\Omega$ ) would not require direction-specific encoding and would thus be processed by a centre-out acuity gradient, generated at the edge layer.

Whitney and Cornelissen (2005) propose that dyslexic readers may fail to learn this string-specific visual processing. They consider different reasons why dyslexics may have difficulties learning to establish a locational gradient and how this may be intrinsically related to establishing orthographic (grapheme)-to-phonological (phoneme) mappings (see Whitney &



**Figure 1.** Schematic illustration of the relative activation patterns generated at the edge, feature, and letter layers of the SERIOL model demonstrating locational gradient formation (based on Whitney, 2001). The individual letters of the string CASTLE serve to demonstrate the relative activation that those letters would receive at each layer.

Cornelissen, 2005, for further details). Specifically, they propose that if dyslexic readers experience difficulties in learning to encode the serial letter order that is necessary for string-specific visual processing, this would result in different patterns of letter perceptibility (i.e., identification) than those typically observed in skilled readers.

In this paper we test the hypothesis that dyslexic readers will show different patterns of letter identification from those of skilled readers, by comparing the performance of a group of adults

diagnosed with dyslexia to that of a group of adults matched for academic ability, using a visual letter search task. The task requires participants to detect whether or not a previously cued target stimulus (e.g., T) is present within a random five-letter string (e.g., XQLTM). Time to detect targets present is plotted according to string position, and the resulting function shows a characteristic upward sloping M-shape when participants are skilled readers of English. The shape of the function is consistent with the proposed characteristics of edge, feature, and letter layer processing in the SERIOL model, as we outline next.

Previous studies using the search task report qualitative differences in the functions produced when skilled readers of English search for letters compared to nonletter shapes (e.g., Hammond & Green, 1982; Mason, 1975, 1982; Mason & Katz, 1976). When searching for nonletter shapes adults produce a U-shaped function characterized by a significant quadratic component (Hammond & Green, 1982). Nonletter shapes in the centre of the five-item array are detected faster than those at the ends of the array, illustrating a centre-out scanning process, in which there is a bias towards processing items in the fovea that decreases with increasing eccentricity (Mason, 1982). Within the framework of the SERIOL model this pattern of performance is entirely consistent with the mechanisms of the edge layer and reflects the generation of an acuity gradient.

In contrast, the function derived when searching for letters is characterized by significant linear and quartic components that result in an upward sloping M-shaped function (e.g., Hammond & Green, 1982; Krueger, 1970; Mason, 1982). Target letters positioned at the far left of the array, in the initial position, are detected fastest, but the medial and final letters are also detected faster than letters occurring in the second and fourth positions. In addition, letters located to the left of the array (in Positions 1 and 2) are detected faster than those located to the right of the array (in Positions 4 and 5). This pattern is also consistent with the mechanisms proposed in the SERIOL model. As in the case of nonletter

shapes, facilitation of the medial letter would emerge at the edge layer, as this letter position would benefit from greater acuity at central fixation. Facilitation of letters presented to the LVF/RH (especially the initial letter) would arise at the feature layer, due to locational gradient formation. Facilitation of the final letter would emerge from processing at the letter layer, due to a lack of rightward lateral inhibition.

If, as Whitney and Cornelissen (2005) propose, dyslexic readers fail to learn string-specific visual processing, their patterns of letter search should reflect a failure to utilize the mechanisms that operate at the feature layer. If these mechanisms are compromised to some extent this would result in reduced facilitation of the first compared to the second letter of the string and letters to the left of fixation. Total failure to acquire both of these mechanisms would produce a U-shaped letter search function, similar to that observed for nonletter shapes, and would principally reflect acuity-based processing at the edge layer. We test each of these possibilities in the present study.

A further feature of orthographic learning that we explore is the abstraction of information about the frequency with which letters appear in particular positions within words of a specified length (i.e., positional letter frequency). For example, in five-letter words, the occurrence of the letter "A" in Positions 1 (e.g., ADULT), 2 (e.g., CAMEL), 3 (e.g., BLANK), 4 (e.g., PECAN), and 5 (e.g., EXTRA) differs (the positional frequencies are 255, 349, 383, 165, and 12, respectively, according to the counts of Mayzner & Tresselt, 1965).

Recent research has shown that skilled readers encode information about positional letter frequency within the system dedicated to the processing of written words. For example, Grainger and Jacobs (1993) showed sensitivity to positional letter frequency in a series of primed lexical decision experiments with skilled readers of French. In addition, Lupker, Perea, and Davis (2008) showed that lexical priming was modulated by letter frequency in skilled readers of English.

Positional letter frequency has also been shown to influence performance in visual letter search. Pitchford, Ledgeaway, and Masterson (in press; Pitchford, Masterson, & Ledgeaway, 2004) presented skilled readers with each of the letters of the alphabet (excluding letter O) as a cued letter target on four occasions in each of the five positions of the stimulus string. This enabled target detection times to be determined for each of the 25 English letters, in each of the five positions across the string. Results showed that search times were significantly faster to detect letter targets that appeared in the most than the least frequent positions within written English words. Furthermore, significant negative correlations were found between search times and positional letter frequency for the exterior (initial and final) letter positions. The authors suggested that these effects might arise from a process of statistical learning, in which information regarding orthographic regularities is extracted from the input, through exposure to print. These effects might be particularly relevant for exterior letters because speeded processing of letters in these positions may rapidly constrain lexical selection. It is interesting to note, however, that an open-bigram encoding scheme that includes explicit edge bigrams (as in the current SERIOL model) could also account for this finding, as edge bigrams are the only open bigrams explicitly encoding a single letter at a specific string position. Consequently, edge bigrams could become sensitive to positional frequencies of individual letters, whereas other open bigrams could not (Whitney, in press).

Pitchford et al. (in press) proposed that sensitivity to positional letter frequency would emerge, due to implicit learning, within a system of written-word recognition where there is heterogeneity in the input. It follows that if the process of statistical learning (e.g., Bates & Elman, 1996) is deficient in some way, reduced sensitivity to orthographic regularities may be apparent, even on relatively low-level tasks such as visual search. Preliminary evidence supports this prediction. For example, Mason (1975) conducted a study with "good" and "poor" sixth-grade readers in

which positional letter frequency, or what Mason termed “spatial frequency redundancy”, was manipulated across six-letter strings comprising words and random nonwords. Results showed no difference between “good” and “poor” readers in overall reaction times to detect the presence of a prespecified target letter in nonwords, indicating that the ability to utilize distinctive feature information (i.e., curves, angles, lines of letters) was similar across both groups. In contrast, “good” readers were significantly faster than “poor” readers at detecting target letters in words in which positional frequency information was incorporated, indicating a relative impairment in the ability of “poor” readers to utilize this orthographic information.

In a further study, Mason and Katz (1976) investigated whether “good” and “poor” readers would differ in performance on a search task using nonletter shapes, in which positional frequency was equated experimentally in one condition and manipulated experimentally in another condition, such that some nonletter shapes appeared more often than others in certain positions of the array. Results showed that “good” and “poor” readers did not differ in times to search for targets in arrays in which positional frequency was equated. However, when positional frequency was manipulated, the search times of the “good” readers were faster than those of the “poor” readers, indicating that the latter group failed to abstract the positional frequency information. These results suggest that extraction of statistical regularities is a pervasive property of sensory learning that may occur for any input in which irregularities are present.

Based on previous research, we might expect to find reduced sensitivity to the effects of positional letter frequency (as determined by participants’ prior exposure to written words acquired over a lifetime of reading, rather than an experimentally imposed regime) in dyslexic adult readers compared to skilled readers in the visual letter search task. This would imply that the process of statistical learning in dyslexic readers might be less efficient than that in skilled readers. We

tested this hypothesis and the hypotheses outlined above concerning the predictions from the SERIOL model, in a group of dyslexic adult readers.

## Method

### *Participants*

A group of 29 dyslexic readers were recruited to participate in this study via the Student Support Services at the University of Nottingham. The mean age of the participants was 22 years 6 months (range 18–51 years). All had normal or corrected-to-normal visual acuity and presented at university with a history of reading difficulties.

To assess intellectual and reading skills, each participant was given a standardized task of nonverbal reasoning and reading ability. Nonverbal reasoning was assessed using the Standard Progressive Matrices (Raven, Raven, & Court, 2000). The mean percentage correct score was 49.7 ( $SD = 28.47$ ), which indicates average performance on this test. Reading ability was assessed using the National Adult Reading Test (NART; Nelson, 1991), which comprises a set of 50 words of increasing complexity. The mean number of words read correctly was 29.0 ( $SD = 5.92$ ). This was found to be significantly lower than the mean correct score (41.2,  $SD = 2.2$ ) of a group of 18 undergraduate students with no history of dyslexia also attending the University of Nottingham,  $t(40) = 8.55$ ,  $p < .0001$ , two-tailed. Thus, as a group, the dyslexic participants had impaired word reading relative to their peers, despite being of average nonverbal intellectual ability.

### *Apparatus and stimuli*

Stimuli were presented on a CRT Mitsubishi monitor (resolution of  $1024 \times 768$  pixels, with a refresh rate of 85 Hz) under the control of an Apple Macintosh G4 computer using custom software developed in our laboratory written in the C programming language. Stimuli consisted of all 25 letters of the English alphabet (except for O), following Green, Liow, Tng, and

Zielinski (1996). All stimuli were presented in white, upper case, Geneva, 36-point font against a uniform black background and were thus high contrast ( $\sim 95\%$  Michelson contrast). At a viewing distance of 57 cm, on average each letter subtended a visual angle of  $\sim 1^\circ \times 1^\circ$ . Fixation was not artificially constrained (no fixation point was used), enabling participants to view the stimulus strings in line with natural viewing habits.

In total, 1,000 experimental forced-choice trials were given to each participant. Each trial consisted of a letter cue appearing in the centre of the screen for 1,000 ms, followed by an inter-target-letter-string interval lasting 500 ms, during which the screen went blank. A stimulus string comprising five letters was then presented in the centre of the screen. For 50% of the trials (500 trials) the cued letter appeared in one of the five positions of the stimulus string as a target to be detected. For the remaining 50% of trials (500 trials) the letter cue was absent from the stimulus string. The stimulus string remained on the screen until the participant made their response by pressing one of two response keys. At the end of each trial auditory feedback was given, for incorrect responses only, by means of a brief tone. After an intertrial interval of 1,000 ms the next trial was then presented. The order of trials was randomized across participants.

Each of the 25 letters was presented as a cue on 40 trials. For 20 of these trials the cued letter appeared as a target to be detected in the stimulus string, appearing in each of the five string positions for 4 trials. Thus the frequency with which each letter appeared as a cue was equated across the experimental trials in which the target was either present or absent. Stimulus strings were comprised of 5 different letters. When the target letter was present in the stimulus string the remaining 4 letters were selected at random without replacement. When the target letter was absent from the stimulus array all 5 letters were chosen at random. There was a constraint on successive presentation of target letters, such that the same target letter could not be presented in the same string position on consecutive trials. No other constraints

were imposed on the composition of the stimulus strings.

### *Procedure*

Each participant was tested individually in a quiet laboratory. The experiment started with a standard set of instructions presented on the computer screen. Participants were asked to press the “/” key on the computer keyboard with their right hand when they thought the target letter was present in the stimulus string and to press the “Z” key with their left hand when they thought the target letter was absent from the five-letter array. Participants were encouraged to respond as quickly, yet as accurately, as possible.

To familiarize participants with the task, 10 practice trials were given following the instructions, after which the experimental trials were given. To reduce fatigue during the experiment, after every 50 trials participants were asked, by means of a written message on the computer screen, whether they wanted to pause. Furthermore, participants could pause the experimental trials at any time, by pressing the space bar.

Valid response times (RTs) were recorded by the computer for both correct and incorrect responses in ms. The maximum valid response time was 2,000 ms, and any values exceeding this upper limit were excluded from the data analyses.

### *Data analysis*

The experimental design enables five data points to be plotted, which correspond to each of the five letter positions in which the target can appear. The resulting letter search function can then be characterized by four simple components: a linear component (straight line); a quadratic component (U-shape); a cubic component (S- or Z-shape); or a quartic component (M- or W-shape), as used by previous researchers (e.g., Green et al., 1996). Analysis of variance, combined with planned orthogonal contrasts, was used to determine the characteristics of the letter search functions.

## Results

The proportion of errors was low and was consistent across each of the five string positions (Position 1 = .09; Position 2 = .1; Position 3 = .06; Position 4 = .06; Position 5 = .05) so no further analysis of errors was conducted. For each of the participants, mean response times (ms) were determined for correctly identifying letter targets present in each of the five positions of the stimulus string. The performance of the group on the visual search task was then compared to that of the 28 skilled adult readers reported previously by Pitchford et al. (2004, in press) in a 2 (reader group)  $\times$  5 (letter position) mixed analysis of variance (ANOVA). Results are shown in Figure 2.

As can be seen in Figure 2, at each of the five letter positions, the group of dyslexic readers showed elevated response times for correctly identifying letter targets compared to the skilled readers. When collapsed across letter positions the mean response time of the dyslexic readers (734 ms,  $SD = 24.7$  ms) was 60 ms slower than that of the skilled readers (674 ms,  $SD = 25.1$  ms); however, this difference did not reach

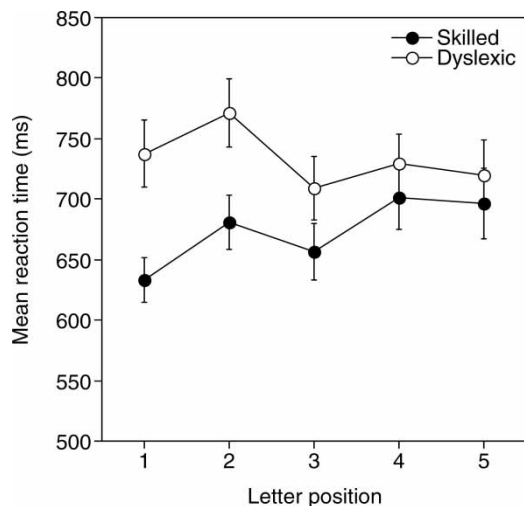


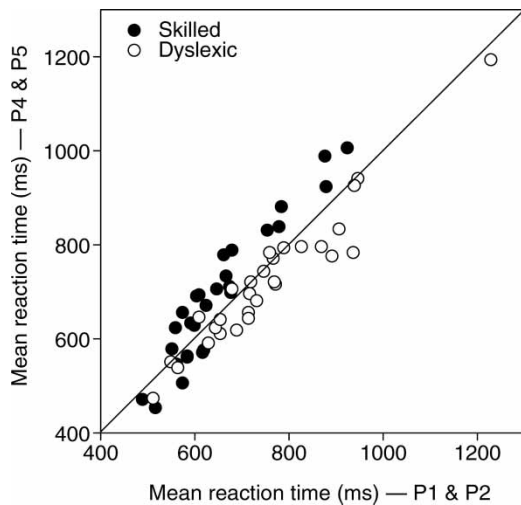
Figure 2. Letter search functions produced by the group of dyslexic ( $N = 29$ ) and skilled ( $N = 28$ ) adult readers on the visual letter search task. Error bars represent  $\pm 1$  SEM.

significance,  $F(1, 55) = 2.9, p = .094$ . When collapsed across reader group a significant main effect of letter position was found,  $F(4, 220) = 14.15, p < .0001$ . Importantly, letter position interacted significantly with reader group,  $F(4, 220) = 14.16, p < .0001$ , suggesting there are differences in the way in which dyslexic and skilled adult readers encode letter position information.

Planned comparisons were performed to examine the nature of the letter search function produced by each reader group. The letter search function of the skilled readers was characterized by significant linear,  $F(1, 27) = 18.9, p < .0001$ , and quartic,  $F(1, 27) = 59.25, p < .0001$ , components, which accounted for 66% and 29% of the variance, respectively. Furthermore, a significant positive correlation was found between mean response time and letter position,  $r = .813$  ( $N = 5$ ),  $p < .05$ , one-tailed, reflecting a general increase for detecting letter targets from Position 1 through to Position 5.

The letter search function produced by dyslexic readers was also characterized by significant linear,  $F(1, 28) = 11.3, p = .002$ , and quartic,  $F(1, 28) = 33.8, p < .0001$ , components that accounted for 30% and 50% of the variance, respectively. However, a significant cubic component,  $F(1, 28) = 18.1, p < .0001$ , was also revealed, which accounted for 21% of the variance. In addition, mean response time did not correlate positively with letter position across the string for the dyslexic readers,  $r = -.545$  ( $N = 5$ ),  $p = .194$ , one-tailed.

Additional unrelated  $t$  tests were conducted to explore differences in target detection time across reader groups for each of the five string positions. Results showed that the dyslexic readers were significantly slower at correctly identifying letter targets appearing in the initial,  $t(55) = -3.104, p = .003$ , two-tailed, and second,  $t(55) = -2.5, p = .015$ , two-tailed, positions of the stimulus string, than were the skilled readers. In contrast, the time taken to identify letter targets appearing in the medial, fourth, and final positions of the stimulus array did not differ significantly across reader groups. This



**Figure 3.** Scatterplots illustrating the relationship between mean reaction time, collapsed across letters, in Positions 1 and 2 (P1 and P2) and Positions 4 and 5 (P4 and P5) for dyslexic ( $N = 29$ ) and skilled ( $N = 28$ ) readers. Each circle represents data for 1 participant. The diagonal line (slope of unity) represents equivalent performance in each visual field, assuming central fixation.

shows that the dyslexic readers were selectively slower than skilled readers at detecting letters to the left of the array only.

A further analysis was conducted to investigate differences in search times to identify letter targets presented to the left and right of the array. Assuming central fixation, the SERIOL model predicts facilitation of letters presented to the left of centre (LVF/RH) for skilled readers, but not for dyslexic readers if they have difficulties forming a locational gradient. Figure 3 shows a scatterplot of the mean reaction time for identifying letter targets in Positions 1 and 2 (i.e., letters to the left of the array) against Positions 4 and 5 (i.e., letters to the right of the array) for each of the dyslexic and skilled readers. As can be seen, most of the skilled

readers (71.4%) showed a relative processing advantage for Positions 1 and 2, whereas only 24.1% of the dyslexic readers showed a leftward processing advantage.<sup>1</sup>

#### *Positional frequency analyses*

To explore whether or not the letter search performance of the group of dyslexic adult readers was influenced by positional letter frequency two analyses were carried out. In both, the positional letter frequency counts of Mayzner and Tresselt (1965) were used, following Pitchford et al. (2004, in press). The counts refer to the number of times a particular letter appears in each position of five-letter words, based on a sample of 20,000 words.

First, a paired  $t$  test was conducted to see whether dyslexic readers, like skilled readers, are faster to detect letter targets appearing in their most frequent position than those appearing in their least frequent position. Results showed that the dyslexic readers were only marginally faster at correctly identifying target letters appearing in the most frequent (mean RT = 723 ms,  $SD = 139$  ms) than those appearing in the least frequent (mean RT = 733,  $SD = 145$  ms) letter position, and this difference was not significant,  $t(28) = -1.572$ ,  $p = .127$ , two-tailed.

Second, a series of parametric correlations was conducted between mean response time generated by the group of dyslexic readers and positional letter frequency for each of the five string positions. Results (see Figure 4) showed a significant negative correlation between mean response time and letter frequency for the initial string position only,  $r = -.532$  ( $N = 25$ ),  $p = .005$ , two-tailed. None of the other correlations reached significance: Position 2,  $r = .045$ ,  $p = .832$ ; Position 3,  $r = -.141$ ,  $p = .505$ ; Position 4,  $r = .081$ ,  $p = .704$ ; Position 5,  $r = -.175$ ,  $p = .408$ ; all  $N = 5$ , two-tailed.

<sup>1</sup> For dyslexic readers the degree of asymmetry in identifying letter targets presented to the left and right of the array did not correlate significantly ( $r = .006$ ) with reading performance. A total of 30 irregular words and 30 nonwords (Castles & Coltheart, 1993) were given to each dyslexic reader to quantify the extent to which they relied on lexical (irregular-word reading) and sublexical (nonword reading) processes. Of the 7 dyslexic readers (24.1%) that showed a leftward processing advantage, 2 were better at irregular word than nonword reading, 2 showed the opposite pattern, and 3 showed no difference.

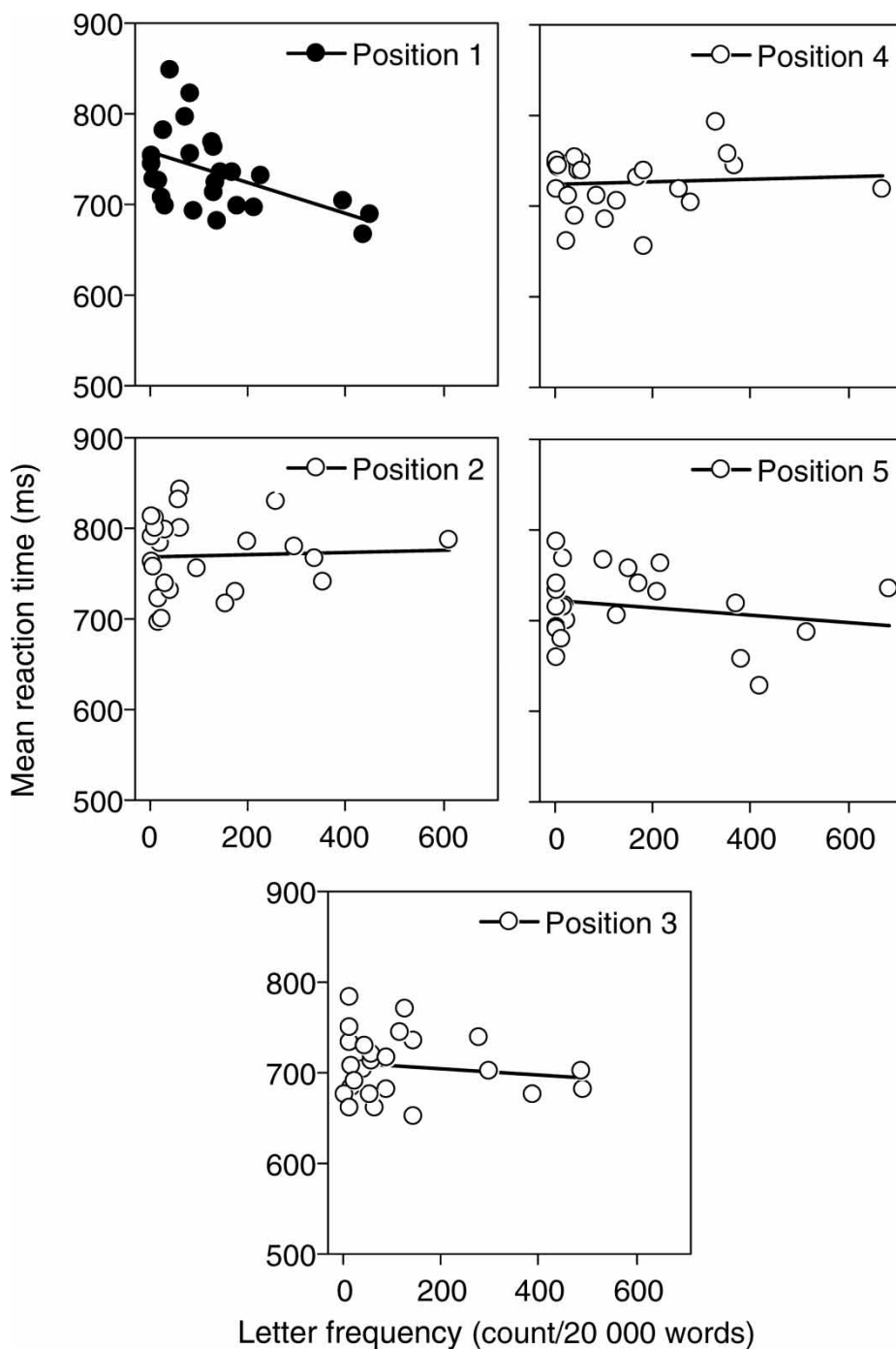


Figure 4. Scatterplots illustrating the relationship between mean reaction time and letter frequency plotted separately for each of the five positions within the stimulus string. For each scatterplot, the 25 circles represent the 25 individual target letters. Filled circles illustrate correlations that are statistically significant (i.e., Position 1).

## Discussion

This study was conducted to examine the performance of dyslexic adult readers in the visual letter search paradigm and to compare this with previously reported results from skilled readers. We used the framework of the SERIOL model (Whitney, 2001) of orthographic processing to interpret patterns of performance in terms of serial encoding of relative letter order within letter strings, which requires learning the directional scanning process required for reading an alphabetic orthography, such as English. Second, we investigated the extraction of positional letter frequency information that is an inherent feature of English words. We addressed these issues by comparing the patterns of letter identification produced by a group of dyslexic adult readers and a group of skilled adult readers, matched for academic ability, using a visual letter search task. We chose to investigate letter search since Whitney and Cornelissen (2005) predicted that dyslexic readers should show different patterns of letter identification from those of skilled readers of English, if dyslexic readers have difficulties in establishing orthographic-to-phonological associations used in written-word recognition.

Our data lend some support to this hypothesis, as results showed both qualitative and quantitative differences in the letter search functions of the groups of skilled and dyslexic adult readers. As reported previously, the group of skilled readers produced an upward sloping M-shaped letter search function, which was characterized by significant linear and quartic components. This pattern is consistent with the results from other studies (e.g., Hammond & Green, 1982; Mason, 1982) and shows evidence of initial, medial, and final letter facilitation relative to neighbouring letters and an overall facilitation for letters located to left, compared to the right, of the array. Thus, performance on this task by skilled readers of English shows the key features of early visual string-specific processing described in the SERIOL model (Whitney, 2001; Whitney & Berndt, 1999).

The group of dyslexic readers produced a search function that showed some similarities but also some key differences to that produced by skilled readers. Results revealed that the main effect of reader group was not significant, suggesting that the group of dyslexic readers identified letter targets at a similar speed to the group of skilled readers. Within the framework of the SERIOL model, this suggests that both dyslexic and skilled readers show similar bottom-up perceptual processing of letters by the edge layer. This result is consistent with previous studies that have compared letter search in “good” and “poor” readers (Mason, 1975; Mason & Katz, 1976).

Also consistent with skilled readers, the letter search function produced by the dyslexic readers was M-shaped and was characterized by a significant quartic component in which the initial, medial, and final letters were facilitated relative to neighbouring letters. In addition, the search function generated by both groups was characterized by a significant linear component, but importantly the direction of slope differed across groups. Skilled readers exhibited a significant upward sloping function, as they responded faster to targets presented on the left than on the right of the array. In contrast, dyslexic readers were no faster at detecting letters in Positions 1 and 2 than those in Positions 4 and 5 of the array. As a result, the search function for dyslexic readers did not slope upwards from left to right (as shown in Figure 2), but was relatively symmetrical.

These results show reduced leftward facilitation for dyslexic readers than is typically observed by skilled readers. This difference was further substantiated by the between-group comparisons conducted at each of the five letter positions of the stimulus string. Target detection times did not differ significantly between groups for the medial and rightward-located letters (i.e., those located in Positions 4 and 5). In contrast, dyslexic readers were significantly slower than skilled readers at detecting letter targets located in the left of the array, in Positions 1 and 2. Additional analyses revealed that a lack of leftward facilitation was characteristic for most of the individual dyslexic readers as only 24.1% showed leftward

facilitation, whereas 71.4% of skilled readers showed a processing advantage for letters appearing to the left of the array.

These results suggest that dyslexic readers may utilize some type of string-specific processing that, within the framework of the SERIOL model, would involve locational gradient formation. However, the lack of leftward facilitation shown by the dyslexic readers suggests qualitative differences in string-specific processing compared to skilled readers, possibly as a result of difficulties in directing attention to the LVF (Facoetti, Cattaneo, Galli, & Lorusso, 2004; Roach & Hogben, 2007) and/or deficiencies in interhemispheric transfer (e.g., Shillcock & McDonald, 2005). Accordingly, we would predict that dyslexic readers should show similar reduced leftward facilitation on other tasks of letter identification in which there is typically a processing advantage for letters located to the left of the array, as has been shown with skilled readers using the Reicher–Wheeler task (Tydgate & Grainger, 2007).

The lack of leftward facilitation shown by the majority of dyslexic readers could have consequences for lexical access, as the SERIOL model proposes that processing at the letter and bigram level is influenced by the graded input activation from the feature level. Our data suggest that dyslexic readers may not benefit from greater activation of letters located to the left than of those to the right of the string. Thus, compared to skilled readers, serial encoding of letter order may be less well represented within the orthographic system of dyslexic readers.

Another aspect of orthographic processing that we investigated in this study was the sensitivity of dyslexic readers to positional letter frequency. Previously, Pitchford et al. (2004, in press) showed that the letter search patterns of skilled readers of English were sensitive to effects of positional letter frequency, suggesting this is a pervasive feature of English orthography that is encoded as a result of reading experience. To see whether

our group of dyslexic adult readers showed evidence of encoding positional letter frequency, we conducted the same analyses as Pitchford et al. performed with skilled readers. In contrast to skilled readers, the group of dyslexic readers did not exhibit a significant advantage for identifying letter targets appearing in the stimulus string in the most, compared to the least, frequent position within written words. Furthermore, dyslexic readers' response times correlated negatively with positional letter frequency only in Position 1, and not Position 5, whereas skilled readers showed significant negative correlations for both the initial and final letter positions.<sup>2</sup>

These results indicate that dyslexic readers exhibited reduced sensitivity to positional letter frequency on the letter search task compared to skilled readers. Our data suggest that, whilst skilled readers encode positional letter frequency for both of the exterior letters, sensitivity to positional letter frequency by dyslexic readers may be restricted to the initial letter of written words. This may seem surprising given that response times to detect the initial (and second) letter in the string were significantly slower for dyslexic than for skilled readers. However, it could be that positional letter frequency modulates letter identification in the initial, and for skilled readers the final, letter position, rather than determining overall detection time. Accordingly, top-down orthographic influences (such as positional letter frequency) may interact with bottom-up visual processes (such as lateral inhibition, as proposed by Whitney, 2001) to advantage processing of exterior letters in strings.

These results are consistent with previous studies that have investigated effects of positional letter frequency in sixth-grade children classified as "poor" readers (Mason, 1975, 1976). Accordingly, we predict that dyslexic readers may also be less influenced than skilled readers by the effects of positional letter frequency in other tasks that involve real words, such as primed

<sup>2</sup> The most frequent letter that occurs in the final position of five-letter English words is the vowel "E". The lack of an effect of positional letter frequency at the final letter (see Figure 4) may have been influenced by the dyslexic readers failing to encode higher frequency letters (e.g., vowels) faster than lower frequency letters.

lexical decision (Grainger & Jacobs, 1993; Lupker et al., 2008). Together with the present study, these results suggest that positional letter frequency becomes encoded within the written-word recognition system due to a process of orthographic learning.

Pitchford et al. (in press) suggested that positional letter frequency could be extracted through statistical learning and encoded explicitly at the letter level. They also proposed that encoding of positional letter frequency could emerge implicitly from the representations stored within the orthographic lexicon, as it is an intrinsic feature of English orthography. Hence, encoding of letter identity at the letter level would be modulated by feed-backward connections from the lexicon. In addition, it is likely that other salient orthographic features, such as bigram frequency, may also be encoded via the same mechanisms (e.g., McClelland & Johnson, 1977; Nuerk, Rey, Graf, & Jacobs, 2000; Rey, Zeigler, & Jacobs, 2000).

It is possible that the reduced sensitivity to positional letter frequency shown by dyslexic adults readers in this study may arise from impoverished orthographic lexicons, due to relatively less exposure to written words than is typical in skilled readers. Accordingly, increasing exposure to print in dyslexic readers could result in a greater sensitivity to positional letter frequency. However, studies have shown that young children have an awareness of orthographic regularities, even after a very limited period of literacy instruction. Even kindergarten children have been shown to exhibit awareness of orthographic frequency and legality (Cassar & Treiman, 1997). Furthermore, after just four months of formal literacy instruction French children showed awareness of the legality and position of double consonants in written words (Pacton, Perruchet, Fayol, & Cleermans, 2001). These studies suggest that orthographic regularities start to be encoded within the developing reading system within the early stages of literacy acquisition. It thus seems unlikely that the lack of sensitivity to positional letter frequency shown by the dyslexic adult readers in this study

arises from impoverished lexical stock, as it is reasonable to assume that our group of dyslexic adult readers, all of whom were attending university, had more established lexical systems than children beginning to acquire a written vocabulary.

Rather, a general deficiency in the process of statistical learning may underlie the reduced sensitivity to the effects of positional letter frequency observed by the dyslexic readers in our study. Pacton et al. (2001) suggested that awareness of the distributional characteristics of orthographic input arises early in childhood from more general learning mechanisms that subserve other forms of statistical learning (e.g., Bates & Elman, 1996). If these general learning mechanisms are responsible for the reduced sensitivity to positional letter frequency shown by dyslexic readers in this study, it follows that dyslexic readers may also show reduced effects of statistical learning in other perceptual domains, such as extracting the frequency with which phonemes appear in certain positions within spoken words.

It is likely that a deficiency in learning to abstract different statistical regularities from visual and/or auditory sensory input (i.e., written and spoken language) could have negative consequences for the formation of orthographic-to-phonological associations, which form the basis of written-word recognition. The data presented in the current study suggest that dyslexic adult readers abstract some statistical regularities from orthographic input, although the extent to which they do this appears to be reduced compared to skilled readers. This may be detrimental to lexical access, as dyslexic readers would not benefit from speeded processing of frequently occurring letters, such as vowels. Reanalysis of our data showed that whilst skilled readers were significantly faster at detecting vowels (658 ms,  $SD = 132$  ms) than consonants (677 ms,  $SD = 123$  ms) collapsed across positions,  $t(28) = -4.08$ ,  $p = .0004$ , two-tailed, dyslexic readers were not (vowels = 728 ms,  $SD = 149$  ms; consonants = 734 ms,  $SD = 157$  ms),  $t(28) = -3.85$ ,  $p = .005$ , two-tailed. Thus, it seems likely that a weakness in statistical learning may hinder a fully proficient reading system from developing

(Pacton et al., 2001). This study has shown that a weakness to encode statistical features of orthographic input is apparent in adults that have experienced persistent difficulties with learning to read, even on low-level tasks of letter identification. Further studies are needed to investigate how pervasive this deficiency may be in dyslexia.

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