Adults with dyslexia exhibit large effects of crowding, increased dependence on cues, and detrimental effects of distractors in visual search tasks

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Abstract

Difficulties in visual attention are increasingly being linked to dyslexia. To date, the majority of studies have inferred functionality of attention from response times to stimuli presented for an indefinite duration. However, in paradigms that use reaction times to investigate the ability to orient attention, a delayed reaction time could also indicate difficulties in signal enhancement or noise exclusion once oriented. Thus, in order to investigate attention modulation and visual crowding effects in dyslexia, this study measured stimulus discrimination accuracy to rapidly presented displays. Adults with dyslexia (AwD) and controls discriminated the orientation of a target in an array of different numbers of - and differently spaced - vertically orientated distractors. Results showed that AwD: were disproportionately impacted by (i) close spacing and (ii) increased numbers of stimuli, (iii) did use pre-cues to modulate attention, but (iv) used cues less successfully to counter effects of increasing numbers of distractors. A greater dependence on pre-cues, larger effects of crowding and the impact of increased numbers of distractors all correlated significantly with measures of literacy. These findings extend previous studies of visual crowding of letters in dyslexia to non-complex stimuli. Overall, AwD do not use cues less, but they do use cues less successfully. We conclude that visual attention is an important factor to consider in the aetiology of dyslexia. The results challenge existing theoretical accounts of visual attention deficits, which alone are unable to comprehensively explain the pattern of findings demonstrated here.

Keywords: developmental dyslexia, attention, crowding, orientation, noise, visual search

1. Introduction

Developmental dyslexia is one of the most common developmental disorders, with a prevalence rate of approximately 4% of the population (Badian, 1994; Jorm, Share, Maclean and Matthews, 1986). Although the most potent and proximal cause of the deficits in reading skills that characterise dyslexia is in the development and use of phonological skills (see e.g. Snowling, 1987; Stanovich, 1988; Vellutino, 1979), an increasing body of research has also highlighted the potential role of non-linguistic processes such as attention to the genesis of reading difficulties. Between group comparisons of samples of participants with and without a history of reading disability have demonstrated that in children with dyslexia compared to controls the distribution of visual attention is more diffuse (e.g. Facoetti, Paganoni and Lorusso, 2000; Facoetti and Molteni, 2001; Facoetti and Turatto, 2000; Sireteanu, Goertz, Bachert and Wandert, 2005) and the control of attention is more asymmetric (Sireteanu *et al.* 2005; Facoetti, Turatto, Lorusso and Mascetti, 2001). Other studies have demonstrated deficits associated with dyslexia in other attentional paradigms such as in serial visual search (e.g. Iles, Walsh and Richardson, 2000), spatial cuing (e.g. Roach and Hogben, 2004; Brannan and Williams, 1987; Facoetti, Paganoni, Turatto, Marzola and Mascetti, 2000), speed of attention engagement and disengagement (Facoetti, Ruffino, Peru, Paganoni and Chelazzi, 2008), filtering of visual information (Sperling, Lu, Manis and Seidenberg, 2005; Roach and Hogben, 2007) ability to adjust the spatial extent of attentional focus (Buchholz and Aimola Davies, 2008; Bednarek, Saldana, Quintero-Gallego, Garcia, Grabowska and Gomez, 2004; Facoetti, Lorusso, Paganoni, Cattaneo, Galli and Mascetti, 2003) and in visual attention span (Bosse, Tainturier and Valdois, 2007).

Importantly, several recent studies have demonstrated robust correlations between attention functions and measures of reading ability, suggesting a direct role of attention deficits in reading difficulties, rather than as secondary symptoms of dyslexia (or indeed another potentially co-morbid disorder such as ADHD) that are not directly related to reading performance. Bosse *et al.* (2007) found that performance on a visual attention span task was associated with reading performance in samples of both French and British children. Sperling, Lu, Manis and Seidenberg (2006) showed that the performance of adults in a high (but not a low) noise version of a motion detection task correlated with general reading ability. Facoetti and colleagues demonstrated correlations between non-word reading ability and both speed of attention shifting (Facoetti, Trussardi, Ruffino, Lorusso, Cattaneo, Galli, Molteni and Zorzi, 2010) and attention engagement and disengagement (Facoetti *et al.*, 2008) in children. Martelli, Di Filippo, Spinelli and Zoccolotti (2009) observed a significant correlation between reading rate and visual crowding (see also Pelli, Tillman, Freeman, Sue, Berger and Majaj, 2007).

Despite such positive findings there have been a number of methodological criticisms levelled at many of the research investigations of the role of visual attention in dyslexia. For example, results obtained from the use of letter stimuli used in such studies potentially limits the inferences that can be made about processing of visual stimuli more generally because deficits in linguistic stimuli might be predicted to be associated with dyslexia, irrespective of their processing demands on visual attention. Alternative explanations of poor performance - such as difficulties in letter recognition – have been postulated to explain these effects. Secondly, visual search paradigms have been criticised for their inability to adequately discriminate between sensory and attentional factors. Hence, differences between groups that arise from sensory deficits might incorrectly be attributed to effects of (in)attention (see e.g. Skottun and Skoyles, 2007a and 2007b). Furthermore, most research has measured reaction times to stimuli that are presented at levels well above the detection threshold, rather than measuring accuracy in conditions where visual information is more limited. In paradigms that use reaction times to investigate the ability to orient attention, delayed reaction times could indicate difficulties in signal enhancement or noise exclusion once oriented rather than an orientation deficit *per se*. Given these methodological issues, three important functions of attention are the subject of the current investigation, namely: the effects of visual crowding; ability to orient attention; and the focussing of attentional resources through filtering of distractor stimuli.

1.1 Effects of Crowding

Crowding occurs when the presence of spatially adjacent stimuli negatively impact upon target discrimination. The effects of crowding have been reported with a variety of visual stimuli including complex stimuli such as letters and more basic orientation-varying gratings (see e.g. Whitney and Levi, 2011 for a review). Bouma and Legein (1977) reported that recognition performance for isolated letters was similar in children with dyslexia and controls, but when letters were flanked by other letters they were recognised less accurately by children with dyslexia, particularly when items were presented in parafoveal vision.

Lorusso, Facoetti, Pesenti, Cattaneo, Molteni and Geiger (2004) reported a "*lack of narrowing*" (p2422) in peripheral vision (or difficulty inhibiting information), particularly in the right visual field for Italian children with dyslexia (see also Geiger, Cattaneo, Galli, Pozzoli, Lorusso, Facoetti and Molteni, 2008). Pelli *et al.* (2007) demonstrated the deleterious effects of crowding on reading rate. Martelli *et al.* (2009) suggested that word analysis in children with dyslexia is slowed because of greater crowding effects. Pernet, Valdois, Celsis and Démonet (2006) reported poorer performance in processing isolated stimuli in people with dyslexia, which was exacerbated by lateral masking (see also Spinelli, DeLuca, Judica and Zoccolotti, 2002). However, to date, all of the studies examining crowding effects in dyslexia have used either letters or complex 'letter-like' stimuli.

1.2 Attention orientation

In an early study, Brannan and Williams (1987) found differences between good and poor readers on a spatial cueing 'Posner' (Posner, 1980) task for the identification of English letters. The Posner task requires participants to respond to a target presented in either the left or right visual field, following a pre-stimulus cue that can either be valid (i.e. a valid indication of target location), invalid (i.e. misleading), or neutral (providing no information) with respect to target location. The standard pattern of results for this task is an effect of cue validity such that valid cues increase - and invalid cues decrease - the speed or accuracy of response to the target. Brannan and Williams' study revealed lower rates of accurate letter detection in poor readers compared to controls when stimuli were presented at Stimulus Onset Asynchronies (SOAs) of 100ms or less. In addition, they reported a lack of a cueing effect in the group of poor readers, indicating that their performance shows neither costs nor benefits from the presence of valid or invalid cues. The use of letter identification as the task in this experiment limits the inferences that can be drawn from these results. However, using the same spatial cueing paradigm, but employing a linguistically neutral dot detection task, Facoetti, Paganoni, Turatto *et al.* (2000) replicated the lack of a cue validity effect on reaction times in dyslexia when cues were presented peripherally with SOAs of less than 300ms. However, as noted in Facoetti *et al.* (2010), critiquing a similar paradigm they used in a later experiment, "*the failure in orienting visual attention reported by Facoetti et al., 2006 might be explained by an abnormal time course rather than by an orienting deficit per se*" (p1013). Furthermore, Buchholz and Aimola Davies (2008) did identify a cueing validity effect in adults with dyslexia (AwD).

1.3 Attention focussing and exclusion of distractors

Some research studies have implicated deficits in dyslexia in attention focussing and the relative inability to exclude distracting stimuli. Buchholz and Aimola Davies (2008) suggested that although AwD can utilise cues to enhance the detection of targets, as a group they are less effective than controls at reducing the width of their attentional focus (see also Bednarek *et al*. 2004). Sperling, Lu, Manis and Seidenberg (2005 and 2006) argued that previous empirical support for visual magnocellular deficits in dyslexia (see e.g. Stein and Walsh, 1997 for a review) might be explained by a deficit in the ability to exclude perceptual noise. In their experiments, performance of adults in a motion detection task correlated with reading ability, but only in conditions of high external noise. Roach and Hogben (2004) measured psychophysical thresholds of AwD and controls to detect a tilted target stimulus amongst vertical distractors in their visual search paradigm. Accuracy levels of both groups showed similar increases in threshold with increasing set size when targets were uncued. However, although the set size effect of the control group was diminished when targets were cued, the AwD did not benefit similarly from the use of cues (see also Roach and Hogben, 2007 and 2008). Roach and Hogben suggested that the benefits of cueing shown by the controls most likely reflected perceptual processing at a (late) decision level, rather than earlier processing involving visual signal enhancement, and that the lack of such beneficial effects of cueing in dyslexia results from ineffective noise exclusion at the decision level.

1.4 Summary and overview

Differences in attention function have been identified in dyslexia, and there is evidence for: (i) a greater impact of visual crowding, (ii) difficulties in attention orientation, and (iii) difficulties in focussing of attention/ exclusion of distractors. In addition, the magnitude of difficulties in all three areas has been shown to correlate with measures of reading ability. However, some of the previous research has suffered from methodological limitations and has therefore failed to exclude alternative explanations of the results. For example, research on crowding has investigated letter detection accuracy rather than detection of less complex, non-linguistic, stimuli. Investigations of attention orientation have mainly measured response times (although see Roach and Hogben, 2004, 2007, 2008; Ruffino, Trussardi, Gori, Finzi, Giovagnoli, Menghini, Benassi, Molteni, Bolzani, Vicari and Facoetti, 2010; Facoetti, Ruffino, Peru, Paganoni and Chelazzi, 2008). Moreover, studies that have investigated one aspect of attention have often not taken into account other potential methodological factors. For example, the displays used by Roach and Hogben (2004, 2007, 2008) did not control for the spacing of stimuli across the various set sizes. Hence, the large set size display they employed was also that in which stimuli were most closely positioned. Therefore, rather than observing an effect attributable only to set size, the crowding of the visual stimuli (Stuart and Burian, 1962) may have also impacted on the pattern of results obtained.

This experiment therefore aimed to simultaneously investigate effects of crowding, attention orientation, and focussing of attention/ distractor exclusion mechanisms. Importantly, to avoid conflating sensory and attention factors in our data, we measured discrimination accuracy rather than reaction time, with overall performance calibrated across conditions for each individual by altering stimulus duration to fix detection performance at a high level of accuracy. Therefore, rather than comparing absolute performance levels across groups, we compared the modulation of attention across the different experimental conditions. A simple orientation discrimination task ensured that any phonological or letter identification difficulties did not confound the interpretation of results.

Motivated by results of previous studies, the current study had four main aims. First, to investigate whether – and how - cues are used by AwD. In particular, we examined whether cues could be used to improve performance and exclude distractors. Second, target stimuli were pre-cued, post-cued or uncued to contrast early signal enhancement with late noise exclusion explanations for any differences found between groups. Whilst pre-cueing targets allows enhancement of the visual signal as well as noise exclusion, post-cueing only enables noise exclusion. Third, we aimed to clarify whether there are differential effects of stimulus spacing between groups with simple stimuli, and whether these putative effects can be modulated by attention. Fourth, we assessed whether the effects of crowding, cue use and distractor exclusion correlate strongly with measures of literacy.

2. Method

2.1 Participants

Fifteen AwD (five males) and sixteen control adults (six males) matched for both age and IQ participated in this study. IQ was estimated using the Wechsler Adult Intelligence Scale – Third UK edition (Wechsler, 1999a) or the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999b - for control participants). The Wechsler Individual Achievement Test-II (Wechsler, 2005) was administered to measure reading and spelling achievement. All the members of the AwD group had both a formal diagnosis of dyslexia (from an appropriately qualified psychologist) and enduring relative literacy difficulties (either WIAT-II reading or WIAT-II spelling performance significantly below their IQ). AwD were therefore impaired in reading relative to their IQ and not necessarily in absolute terms. In order to avoid practice effects, where a WAIS-III IQ estimate was already available (e.g. from a psychological assessment report for dyslexia) this measure was used rather than the tests being re-administered. WIAT-II reading and spelling were administered at the time of testing unless recent (less than 12 months prior to testing) scores were available. Control participants reported no difficulties with reading or spelling either currently or historically[1]. Psychometric details for both groups are shown in Table 1. Independent samples t-tests (with Levene's correction for unequal variances) confirmed that there were no significant differences between the age ($t(28.3)=.02$) or IQ ($t(27.3)=1.59$) of the groups, but significant differences between their spelling ($t(16.7)=5.40$, $p<.001$) and their reading ($t(22.4)=6.09$, $p<.001$) scores.

******INSERT TABLE 1 ABOUT HERE******

Stimuli and apparatus

Five greyscale Gabor sinusoids ($\lambda=10$ pixels per cycle, $\sigma=10$) were created in Matlab and saved as bitmap images for use in E-prime software. Sinusoids could either be vertically oriented or rotated 5 degrees left, 5 degrees right, 2 degrees left or 2 degrees right.

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[1] Some control participants had significantly lower performance on either reading or spelling than would be predicted from their IQ. In these cases this was at least partly due to the WIAT-II test ceiling for their age (e.g. one participant made no mistakes on either reading or spelling but still obtained a score significantly lower than predicted). One control participant was omitted from analyses because they scored significantly lower than predicted on both reading and spelling.

E prime version 2 professional (Schneider, Eschman, & Zuccolotto, 2002) was used to record responses and present stimuli on a CRT *Vision Master Pro510* monitor. A chin rest ensured that participants viewed the monitor from a fixed, central position and at a distance of 57cm from the screen. The experiment was conducted in a dimly lit room.

2.2 Design

The independent variables were group (AwD or control), display type (one stimulus, eight spaced stimuli, eight crowded stimuli or sixteen stimuli), cue type (pre-cued, post-cued or uncued) and difficulty (easy or difficult tilt). The location of the target, distractors and the direction of tilt of the targets were fully randomised. The dependent variable was accuracy for the discrimination of the correct orientation of the target stimulus.

****INSERT FIGURE 1 ABOUT HERE*****

Participants performed a two alternative forced choice task (see Figure 1) in which they indicated whether a single tilted stimulus in an array of vertically oriented distractors was tilted in its orientation to the left or right

(50% probability each). On each trial, the stimulus could either have a tilt of ± two degrees (designated here the ‘difficult’ condition) or± five degrees (the ‘easy’ condition) with equal probability. The array could consist of a single stimulus, eight stimuli or sixteen stimuli, all of which were positioned on the circumference of an imaginary circle appearing five degrees of visual angle peripheral to a central fixation point. Only one target stimulus was presented on any trial. Distractor stimuli were always oriented vertically.

In arrays of eight stimuli, targets and distractors were presented in two conditions that manipulated crowding. They were either distributed equally (3.5 degrees of visual angle between each – spread condition) or positioned around one-half of the imaginary circle (1.6 degrees of visual angle between each –crowded condition). The crowded condition had the same spacing as in the set size sixteen condition. The four possible display configurations were equally probable (25% of trials each). The position of the tilted stimulus in the array was randomised across the sixteen possible locations around the imaginary circle. In the set size eight, crowded condition, the eight stimuli would appear in contiguous locations at a random point around the imaginary circle with the target stimulus presented in any of the eight locations in the contiguous string.

This meant that in 25% of these trials – when the target was in either position one or position eight of the contiguous string – the target would be flanked on only one side.

2.3 Procedure

On each trial, a fixation point was initially presented for 110ms. On one third of the trials, fixation was followed by a pre-cue of 80ms duration; on the remaining trials, the fixation point was presented for an additional 80ms. This interval was followed by the presentation of the variable duration display, titrated to achieve individual accuracy between 60% and 90%[2], and then a 80ms post-cue (one third of trials) or a further 80ms fixation point. Pre- and post-cues indicated the location of the target stimulus with 100% validity. A fixation point (3000ms or until a response was provided) was then presented, and this was followed by a further response reminder if necessary. Responses were entered with either the Z (left tilt) or M (right tilt) keys on a standard computer keyboard. In any block of 48 trials, two trials of each condition (one target tilting right and one left) were conducted and the detection

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[2] The average display durations of the AwD and the control group differed significantly (264ms vs. 246ms, t (29)=4.62, p<.001)

accuracy calculated for that block. If overall accuracy was above 90%, display time was reduced by 10ms; if accuracy was below 60%, display time was increased by 10ms. Prior to commencing the main experimental trials, a practice and calibration session was performed (using shorter blocks of 24 trials) to ensure that each participant's accuracy level was in the required range. Fifteen blocks of 48 trials each were run for the main experiment, requiring approximately 20 minutes in total for each participant.

3. Results

The results consisted of the proportion of correct discriminations in each of the 24 conditions. The results are presented in four subsections concerning: (i) effects of crowding, (ii) attention orientation, (iii) focussing of attention/ exclusion of distractors and (iv) the relationship between literacy and crowding, cueing, and set size effects.

3.1 Effects of Crowding

Descriptive statistics for the two set size eight display types (spread vs. crowded) in two cue conditions (uncued vs. pre-cued), for both difficulties (easy vs. difficult) are summarised in Figure 2. Despite attempts to equate overall performance, a four factor ANOVA revealed a significant main effect of group ($F_{1, 29}$=10.85, p<.01, η^2_p =.27), with higher performance in the control group. There were also significant main effects of display type ($F_{1, 29}$=23.12, p<0.001, η^2_p =.44), difficulty ($F_{1, 29}$=13.91, p<.001, η^2_p =.32) and cue type ($F_{1, 29}$=28.76, p<.001, η^2_p=.50). These main effects were consistent with the expectation of higher performance accuracy in less densely populated displays, where the orientation of stimuli was easier to discriminate and when stimuli were pre-cued. The interaction between display type and group was significant ($F_{1, 29}$=7.46, p<.01, η^2_p =.21), demonstrating that the performance accuracy of the AwD group decreased more than that of the controls in crowded displays. There were also significant interactions of cue and group ($F_{1, 29}$=8.85, p<.01, η^2_p =.23); cue and display type ($F_{1, 29}$=10.36, p<.01, η^2_p =.26); and cue, display type and group ($F_{1, 29}$=5.03, p<.05, η^2_p =.15). These findings suggested that performance of AwD and controls differed more when stimuli were uncued and crowded. The difficulty by cue by group interaction was marginally significant ($F_{1, 29}$=3.44, p=.07, η^2_p =.11), but the four way interaction between cue, group, display type and difficulty was significant ($F_{1, 29}$=8.95, p<.01, η^2_p =.24). Other main effects and interactions were not statistically significant.

****INSERT FIGURE 2 ABOUT HERE*****

Separate post-hoc analyses were conducted on the group data and for the effect of cue using separate two factor ANOVAs to probe the effects of display type and difficulty. Figure 2 shows the corresponding interaction plots. In cued conditions, neither the performance of the AwD ($F_{1, 14}$=.98) nor the controls ($F_{1, 15}$=.35) showed significant effects of display type. The controls ($F_{1, 15}$=7.11, p<.01, η^2_p =.32) but not the AwD ($F_{1, 14}$=.55) demonstrated a significant effect of difficulty, but neither group showed a display type by difficulty interaction (both *F*s<1). Thus, with the exception of the difficulty effect demonstrated for controls, the performance of both groups was similar when the stimuli were cued. In contrast, whereas the controls showed no significant effect of display type in uncued conditions ($F_{1, 15}$=2.25, p=.15, η^2_p =.13), the AwD showed a strong and significant effect ($F_{1, 14}$=34.33, p<.001, η^2_p =.71). The AwD group also showed a significant effect of difficulty ($F_{1, 14}$=5.83, p<.05, η^2_p =.29) and a display type by difficulty interaction ($F_{1, 16}$=11.00, p<.005, η^2_p =.44), suggesting that difficulty impacted on performance levels to a lesser extent when the display was crowded. The control group showed neither of these effects ($F_{1, 15}$=.91 and $F_{1, 15}$=1.15 respectively). Thus, in uncued conditions, the AwD demonstrated statistically robust and strong effects of display type.

3.2 Attention orientation

Figure 3 shows the performance of AwD and controls across three different display set sizes and in three different cue conditions. The effects of cue and set size independently of crowding were tested by comparing performance between the set size eight crowded and set size sixteen conditions. These display types had identical stimulus spacing to equate the effects of crowding across conditions.

****INSERT FIGURE 3 ABOUT HERE*****

A four factor ANOVA, investigating the effects of set size (eight/ sixteen), difficulty (easy/ difficult), cue type (pre-cued/ post-cued/ uncued) and group on performance, revealed multiple interaction effects and a main effect of group. For transparency of interpretation, analyses were partitioned by group and a three factor ANOVA conducted for each group separately, together with pair-wise comparisons for cue type.

The control group showed significant main effects of difficulty ($F_{1, 15}$ =6.36, $p<.05$, η^2_p =.30) and cue ($F_{2, 30}$ =4.31, $p<.05$, η^2_p =.22), and a marginal main effect of set size ($F_{1, 15}$ =3.93, p=.066, η^2_p =.21). Interactions between set size and difficulty ($F<1$), set size and cue type ($F_{2, 30}$ =1.50), difficulty and cue type ($F<1$), and set size, difficulty and cue type ($F<1$), were not statistically significant. Pair-wise comparisons for cue type indicated significant differences between the pre-cued and uncued ($p<.01$) conditions only.

The AwD group showed significant main effects of difficulty ($F_{1, 14}=27.17$, $p<.001$, $\eta^2_p=.66$), cue ($F_{2, 28}=48.88$, $p<.001$, $\eta^2_p=.77$), and set size ($F_{1, 14}=30.69$, $p<.001$, $\eta^2_p=.69$). In addition, there were significant interactions between set size and difficulty ($F_{1, 14}=49.87$, $p<.001$, $\eta^2_p=.78$), set size and cue type ($F_{2, 30}=3.43$, $p<.05$, $\eta^2_p=.20$), difficulty and cue type ($F_{2, 28}=3.41$, $p<.05$, $\eta^2_p=.20$), and a three way interaction between set size, difficulty and cue type ($F_{2, 28}=6.30$, $p<.01$, $\eta^2_p=.31$). Pair-wise comparisons for the cue type measure indicated significant differences between pre-cued and post-cued ($p<.001$) and between pre-cued and uncued ($p<.001$) conditions. The difference between post-cued and uncued conditions was not significant statistically ($p=.076$).

3.3 Attention focussing and exclusion of distractors

To determine whether groups differed on their ability to exclude distractors, the interactions found in section 3.2 were analysed more fully by splitting the analyses by cue type and group. Thus, six separate two factor ANOVAs were conducted to investigate whether the effects of set size differed for each group as a function of cue type (see Figure 4). As in section 3.2, the set size eight crowded conditions were analysed since this display type was equated in terms of stimulus spacing with the set size sixteen condition. These analyses were therefore equivalent to those conducted for the crowding effects in section 3.1, but investigated the effect of increasing the distractor numbers in each cueing condition, whilst stimulus spacing remained constant.

In uncued conditions, both the controls ($F_{1,15}=8.93$, $p<.01$, $\eta^2_p=.37$) and the AwD ($F_{1,14}=10.89$, $p<.005$, $\eta^2_p=.44$) showed significant effects of set size. The AwD also showed a significant effect of difficulty ($F_{1,14}=11.15$, $p<.005$, $\eta^2_p=.44$) and a difficulty by set size interaction ($F_{1,14}=13.81$, $p<.005$, $\eta^2_p=.50$). This pattern of results demonstrated that the effect of set size was greatest when the discrimination was difficult. The controls showed no main effect of difficulty ($F_{1,15}=1.50$) or interaction between set size and difficulty ($F<1$).

In the pre-cued conditions the controls showed an effect of difficulty ($F_{1,15}=5.66$, $p<.05$, $\eta^2_p=.27$), but no effect of set size or difficulty by set size interaction (*Fs*<1). In contrast, the AwD group showed significant effects of both set size ($F_{1,14}$ =17.20, $p<.001$, η^2_p =.55) and difficulty ($F_{1,14}$ =29.95, $p<.001$, η^2_p =.68) and a significant interaction ($F_{1,14}$ =36.15, $p<.001$, η^2_p =.72), suggesting that the set size effect was only apparent when the discrimination was difficult.

In post-cued conditions, the controls showed an effect of difficulty ($F_{1,15}$ =5.60, $p<.05$, η^2_p =.27), but no effect of set size ($F_{1,15}$ =1.04) or interaction ($F<1$). In contrast, the AwD showed a significant effect of set size ($F_{1,14}$ =24.43, $p<.001$, η^2_p =.64). The effect of difficulty narrowly missed reaching statistical significance ($F_{1,14}$ =4.38, $p=0.055$, η^2_p =.24) and there was no significant interaction between set size and difficulty ($F<1$).

*****INSERT FIGURE 4 ABOUT HERE*****

3.4 The relationship between measures of literacy and crowding, cueing and set size effects

The potential predictive relationships for cueing, crowding and set size on reading skills were evaluated by creating four summary variables of participant performance across the task conditions.

Firstly, the difference in performance between spread vs. crowded conditions within the uncued, set size eight, easy conditions was calculated for each participant to create a measure of crowding. The comparison of the two set size eight conditions was used as an operational measure of the effect of crowding, independent of the number of distractors. The easy condition was chosen because the results from the difficult condition appeared to indicate a floor effect of performance.

Second, the mean differences in accuracy across (i) pre-cued vs. uncued, (ii) post-cued vs. uncued conditions were calculated to summarise effects of pre- and post-cues respectively. Set sizes one, eight spread[3] and sixteen were used to calculate these averages.

Finally, the mean difference in accuracy across set size eight crowded and set size sixteen uncued conditions was calculated for the summary measure of set size effects. Data from the set size eight crowded (rather than spread) condition was used so that any effects of crowding were

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[3] It had already been demonstrated that AwD are most affected by visual crowding and therefore might be expected utilise cues more heavily in crowded conditions.

similar, with the main variable of interest being the effect of the number of distractors.

The summary measures of crowding, pre-cueing, post-cueing and set size were evaluated as predictor variables of the psychometric and literacy measures in correlation analyses (*n*=31 in all cases, approximate critical value of *r* for a two-tailed 5% confidence level =0.35). Table 2 shows the values of Pearson's *r.*

*****INSERT TABLE 2 ABOUT HERE*****

As can be seen in Table 2, both spelling and reading ability increased significantly as the influence of crowding decreased. In contrast, the association between crowding and IQ was not statistically significant, suggesting that the effects of crowding impact on reading ability directly rather than through a third variable such as general cognitive ability. Figure 5 shows scatterplots of these relationships and also demonstrates the sensitivity of the effects of display type to discriminate between the participant groups. The increased use of pre-cues and the influence of set size were both significantly associated with decreases in spelling scores, reading scores and IQ. The use of post-cues was not associated with reading, spelling or IQ variables. Partial correlations, to control the effects of IQ in these analyses led to exactly the same pattern of results. Significant relationships were found between both measures of literacy and crowding, both measures of literacy and use of pre-cues, and both measures of literacy and effects of set size. Correlations between both measures of literacy and use of post-cues remained small and were not statistically significant.

In a simultaneous multiple regression analysis, set-size, crowding and pre-cue use were entered as predictor variables of spelling ability. Together, these three factors explained 69.8% of the variance (adjusted R^2= .43). However, only set size (β=-.35, $t(27)$=-2.26, $p<.05$) accounted for statistically significant unique variance in spelling ability, while measures of crowding (β=-.31,$t(27)$=-1.30) and pre-cue use (β=-.31,$t(27)$=1.28) were not significant predictors. The equivalent regression analysis for reading ability revealed that the predictors as a group explained 70.9% of the variance (adjusted R^2= .45). Individually, only pre-cue use accounted for significant unique variance (β=-.57, t (27)= -2.42, $p<.05$), with the set size measure marginally significant statistically (β =-.27, $t(27)$=-1.79, $p=.08$) and the measure of crowding accounting for small and non-significant unique variance (β =-.03, $t(27)$=-.15).

****INSERT FIGURE 5 ABOUT HERE*****

4. Discussion

This study investigated the extent to which the performance of a group of adults with a history of reading disability (AwD) and a control group on a visual discrimination task was modulated by different characteristics of the displays presented, and by various modes of stimulus cueing. Previous studies have investigated cue use, focussing of attention/ distractor exclusion or crowding in dyslexia in isolation, and largely with inconsistent results. To our knowledge, this is the first study to have simultaneously investigated both the independent and combined influences of these factors in a systematic way. In a departure from the methodology employed in previous studies, we calibrated discrimination accuracy for individuals across conditions and then compared AwD and control performance to evaluate the (i) impact of visual crowding, (ii) orientation of attention, and (iii) focussing of attention and exclusion of distracting stimuli. We then assessed the relationships between crowding effects, cue use and set size effects and literacy variables to better understand whether the potential impact of visual attention variables impact upon literacy skills directly or via tertiary variables such as IQ.

4.1 Effects of Crowding

Our results indicate substantial decreases in discrimination performance when stimuli were crowded compared to when they were spread, but only for AwD and not controls (see Figure 2). This demonstration of crowding effects concurs with previous evidence obtained in studies using letters or other complex stimuli (see e.g. Bouma and Legein, 1977; Pelli *et al.*, 2007; Martelli *et al*. 2009; Pernet *et al*. 2006). For example, Pelli *et al.* (2007) showed the relationship between visual crowding and reading rate in normal readers and Martelli *et al*. (2009) further demonstrated this relationship in readers with dyslexia. Furthermore, Spinelli *et al.* (2002) found that children with dyslexia were slower at processing letter and symbol stimuli in the presence of surrounding stimuli compared to when they were presented in isolation. In addition, they demonstrated that small increases in inter-letter spacing led to faster reaction times. Crowding can therefore occur in reading at both a letter and at a word level, with substantial consequences for performance.

The results of our study replicated the observation of increased crowding effects in dyslexia (e.g. Spinelli *et al.* (2002). In addition, we demonstrated an effect of crowding in AwD using simple visual stimuli for the first time. However, despite our attempts to calibrate detection accuracy for each individual to ensure that putative differences in performance were unrelated to individual differences in stimulus discrimination, overall performance of the AwD group was still lower than that of controls. This result held true even in conditions where only a single stimulus was present (provided that the stimulus was not cued) and despite the fact that average display duration for the AwD was significantly longer than that of controls due to the calibration procedure. Our strategy to split analyses by group – to compare relative (rather than absolute) performance across conditions – has addressed some of the potential limitations arising from differences in discrimination performance. For example, in uncued conditions, the groups showed clearly different patterns of results across the crowded and spread conditions (see Figure 2). Moreover, the comparatively larger effect of crowding found in the AwD group when the discrimination task was easier, suggests that discrimination ability is not the most important mediator of the crowding effect observed.

Romani, Tsouknida, di Betta and Olson (2011) suggested that crowding effects in dyslexia are *“a manifestation of the same reduction of visuo-attentional resources which limits the number of characters which can be* *processed at a glance" (p17).* However, our results showed that the performance of the AwD group differed across stimulus displays of equal set size as a function of the spacing between stimuli. Therefore, if elements in the stimulus display are processed independently of their location (see e.g. Bosse *et al.*, 2007), a more likely explanation is that crowding effects operate independently from, and in parallel with, the allocation of visual attention[4]. Alternatively, within spotlight models of attention, more diffusely allocated attentional resources (see also Facoetti *et al.*, 2000, 2001) might be expected to result in patterns of increased crowding effects of a nature analogous to increases in crowding in the visual periphery (see e.g. He, Cavanagh & Intriligator, 1996). It should be noted that pre-cueing eliminated effects of crowding for AwD in the present study. Yeshurun and Rashal (2010) have also recently demonstrated that attention can eliminate the effects of crowding and decrease the critical distance for correct recognition of targets from distractors.

In summary, the crowding effects supported by our data are consistent with both the hypothesis of a more diffuse mode of attention in AwD (Facoetti *et al.* 2000) and the model of reduced visual attention span in

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[4] We thank an anonymous reviewer for bringing this interpretation of our results to our attention.

AwD (Bosse *et al.*, 2007), provided that they are coupled with an independent - yet parallel - factor of crowding.

4.2 Attention orientation

When needed, the AwD used the presence of pre-cues to enhance performance (see Figure 3). The effect of cueing was highly significant: discrimination accuracy in pre-cued conditions was greater than in both post-cued and uncued conditions. These results suggest that pre-cues provide the AwD a mechanism for signal enhancement during early visual processing as well as, or rather than (the benefit of post-cueing over uncued conditions narrowly missed statistical significance) at the decision stage. The beneficial effects of pre-cueing were even evident for the AwD group in conditions where the target stimulus was presented in isolation for which there was no uncertainty about target position. In contrast, in the control group, performance differed significantly between pre-cued and uncued, but not between pre-cued and post-cued or uncued and post-cued conditions. Overall, this suggested involvement of early visual processes following pre-cueing, but the lack of significant differences between either the pre- and post-cued or the uncued and post-cued conditions, makes it difficult to disentangle the relative importance of the early and late processes engaged by tasks of this kind.

Previous studies have yielded inconsistent patterns of results for the effects of cue validity, with some labs demonstrating such effects (e.g. Facoetti et al., 2000) and others showing no beneficial effects (e.g. Buchholz and Aimola Davies,2005;2008). We showed a greater dependence on pre-cues for AwD than controls to maintain good discrimination performance and to minimise the detrimental effects of visual crowding. Our findings contrast with those demonstrated by Buchholz and Aimola Davies (2005 and 2008) - in that they suggest similar ability to use cues in AwD and controls - and from Facoetti and colleagues' studies on children with dyslexia - suggesting decreased use of cues.

There are at least five potentially important differences between our experiment and others in existing literature:

i) Our cues were always valid (also see Roach and Hogben, 2004; 2007). In the majority of cueing paradigms, cue validity is manipulated, requiring participants to reserve attentional resources for monitoring uncued locations. If AwD have reduced attentional resources, then splitting those resources across more than one location is likely to impact on performance, even if they are able to use cues.

ii) We required discrimination rather than just detection of a stimulus. Discrimination demands more attentional resources than detection and therefore may (i) benefit more from cueing and (ii) be expected to produce different results if attentional resources are limited. For example, a more diffuse attentional spotlight may be sufficient to detect stimuli, but not to discriminate between them - therefore reduced attention resources may only be evident when stimulus discrimination is required.

iii) The SOA used in studies of this kind. Facoetti and colleagues (e.g. Facoetti *et al*. 2000; Facoetti *et al*., 2008) claimed that children with dyslexia have ‘sluggish’ attention and therefore that performance may differ systematically with the length of the SOA employed. However, we consider a difference in SOA as an unlikely explanation of our data, because attention orientation in adults occurs within a relatively short time period in our study (<80ms SOA: see Figure 3).

iv) The majority of studies have been conducted on children, rather than adults, and therefore developmental factors could have influenced the results. For example, dorsal stream function has been shown to have a prolonged developmental time course (see e.g. Klaver, Marcer and Martin 2011 for a review),which may make it particularly vulnerable to adverse and genetic environmental influences (Braddick, Atkinson and Wattam-Bell, 2003). Impaired dorsal stream function has been linked with dyslexia (see e.g. Vidyasagar and Pammer 2010 for a review) as well as other neurodevelopmental disorders (Atkinson and Braddick, 2011)

v) Facoetti, Zorzi, Cestnick, Lorusso, Molteni, Paganoni, Umiltà and Mascetti (2006) found decreased cue use only in children with dyslexia who had impaired nonword reading. Nonword reading ability was not investigated in our study. Children with impaired nonword reading, particularly in the Italian language because of its transparent orthography, are likely to have more severely impaired reading skills. In contrast, many of our adult participants performed at average or above average levels on measures of literacy, so may not have been as severely impaired as children in such studies.

4.3 Attention focussing and exclusion of distractors

The performance of the AwD on our task was significantly decreased compared to controls when the number of distractors was increased. In particular, this occurred when the perceptual discrimination was more difficult (see Figure 4), even when the target was pre-cued. While this effect was highly significant and robust for the AwD, it was only marginally significant for the control group across all conditions. For controls, but not for AwD, both pre-cues and post-cues eliminated the effects of set size.

Our results are generally concordant with the conclusions of Roach and Hogben (2004), who argued that AwD *"failed to gain the same effect of cueing that normal readers did"* (*p650).* However*,* Roach and Hogben (2007) suggested that deficits in attentional orienting are unlikely to account for cueing deficits in dyslexia, and instead the difference resides in "*ability to select or prioritise task-relevant sensory information to optimise task performance*" (*p206*). Similarly, our results do not support the suggestion that AwD are unable to use cues to orient attention, because AwD showed increased dependence on cues for accurate performance (as shown in section 4.2).

Effects of set size were found for AwD in uncued, pre-cued and post-cued conditions when the discriminations were difficult. In contrast, when the discrimination condition was easier, set size effects were evident only in post-cued conditions. Below we consider three possible explanations for these results.

Firstly, if visual attention resources are reduced in AwD (e.g. Bosse *et al.*, 2007) this mechanism may explain the dual findings of lower performance in conditions of increased difficulty in discrimination and with large set sizes. Moreover the increased performance of the AwD with the presence of a pre-cue is consistent with this account. However, it is not clear how this a reduction in resources for visual attention can explain the ineffectiveness of pre-cueing in eliminating the effects of set size. A reduced attention span that can be oriented effectively with cue use should not be affected by the presence of uncued items.

The second possibility - a mechanism of increased diffusivity of attention in dyslexia (e.g. Facoetti *et al.,* 2001) - cannot fully explain the comparatively larger effects of set size in uncued conditions. If the overall attentional resources of AwD and control adults are equivalent, but distributed differently, then – at least in uncrowded conditions – performance would be expected to be similar. In our paradigm, effects of crowding were held constant (see section 4.1). However, it is possible that the spread condition was not sufficiently ‘uncrowded’ for the AwD group.

The third potential explanation - a difficulty in excluding distractors (i.e. a noise exclusion hypothesis e.g. Sperling *et al*., 2005) - sufficiently accounts for the observed set size effects in cued conditions. However, this perspective cannot easily explain the performance differences in uncued conditions, because all stimuli are potential targets in these conditions, particularly when the orientation discrimination is difficult. The extent to which AwD demonstrate difficulty excluding distractors, or whether instead the pattern of performance reflects only greater overall difficulty with the perceptual task is an important question for future research. Nevertheless, the difference in performance in AwD between pre-cued easy vs. difficult conditions with set size sixteen displays serves to highlight how individual differences in the ability to discriminate stimuli can influence the pattern of results gleaned from studies of this kind.

Our results therefore challenge existing theoretical accounts of visual attention in dyslexia. Although our data are generally consistent with the presence of attention deficits in dyslexia, it is not clear how any single account to date can explain the pattern of results obtained in this study.

4.4 Relationship between literacy and effects of crowding, cueing and set size

Summary variables associated with a greater dependence on pre-cues, decreased performance in crowded conditions, and decreased performance with increased numbers of distractors (even in the context of similarly spaced stimuli) were all associated with lower reading and spelling scores (see Table 2 and Figure 5). In contrast, the use of post-cues was significantly correlated neither with reading nor with spelling scores. Thus, the correlations found in this study between reading ability and the ability to perform well with larger numbers of distractors or in visually crowded conditions concur with previous research. Martelli e*t al.* (2009) found a similar pattern of correlations between a measure of letter crowding and reading rate in Italian children with dyslexia. Sperling et al (2006) also reported a correlation between reading ability and ability to detect motion stimuli from noise and Bosse *et al.* (2007) identified an association between reading performance and a visual attention span measure. In contrast, the finding that *dependence* on cues correlates strongly with reading and spelling ability is both unexpected and novel.

A deficit in the ability to either orient or focus attention might be expected to be associated with difficulties in reading (see e.g. Morris and Rayner, 1991). However, our data suggest that attention orientation in AwD is not impaired. Instead the successful use of (or dependence on) cues is associated with *poorer* reading and spelling performance. In contrast, Facoetti *et al*. (2006) reported negative correlations between nonword reading accuracy and size of cueing effects in the right visual field in a Posner paradigm. It seems reasonable to speculate that the requirements of our tasks to search for targets and reject distractors - rather than to simply detect a target dot in the absence of distractors (Facoetti *et al.*, 2006) - can account for the difference in the direction of correlations between the studies.

4.5 Summary and conclusions

First, we have shown that, rather than not making use of pre-cues AwD were heavily dependent on pre-cues to make accurate discrimination judgements. However, second, we found that whereas for controls both pre- and post-cueing removed effects of set size, for AwD they did not. Third, we have demonstrated that performance of AwD on visual search tasks with even simple visual stimuli was significantly affected by visual crowding. Fourth, we showed larger effects of set size in AwD compared to controls that are independent of the effects of visual crowding. Fifth, effects of crowding, dependence on pre-cues and effects of set size were all associated with measures of reading and spelling.

In summary, our data suggest that AwD do not use cues less, but use cues less successfully. The interaction between some of our effects with task difficulty highlights the importance of controlling for sensory factors in future research. Although our main findings do not preclude the presence of phonological (or other) deficits in dyslexia, they cannot be accounted for by phonological difficulties alone, because the task was purely visual and had identical cognitive requirements in all conditions. It is not clear how any single theory on its own can fully account for the entirety of findings presented here. Further research should aim to confirm that greater set size effects occur independently of task difficulty and in other paradigms. Visual attention is therefore an important factor in dyslexia.

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Table 1. Psychometric details of participants with dyslexia (AwD) and controls. SS: standard score (μ=100, α=15).

	Control *n*=16 Mean (SD)	AwD *n*=15 Mean (SD)	Significance *p* value
Age (years)	25.9 (6.8)	25.9 (7.4)	n.s.
IQ (SS)	124 (9.3)	119 (11.2)	n.s.
WIAT-II UK Spelling (SS)	119 (3.6)	102 (11.3)	<.001
WIAT-II UK Reading (SS)	112 (4.5)	98 (7.6)	<.001

*Table 2. Correlation matrix of measures of crowding, cueing and set size with measures of spelling, reading and IQ. Values of Pearson's r shown. *p<.05, **p<0.001*

	Spelling	Reading	IQ
Crowding	-0.52*	-0.45*	-0.29
Pre-cueing	-0.62**	-0.66**	-0.41*
Post-cueing	-0.13	-0.03	-0.09
Set size	-0.40*	-0.40*	-0.05

Figure 1. Schematic representation of the time course (left to right) of the procedure.

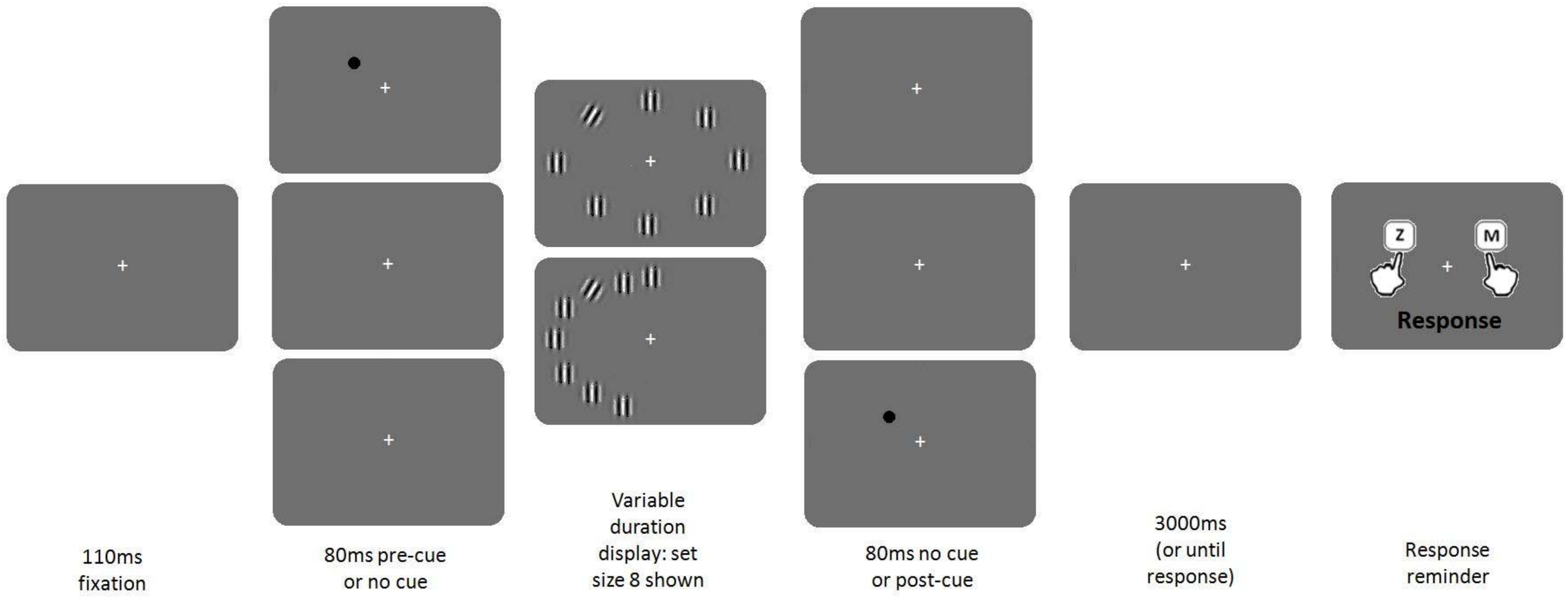


Figure 2. Performance accuracy of AwD (bottom panels) and control (top panels) groups as a function of the density of stimuli (spread vs. crowded) and the ease of orientation discriminability (easy vs. difficult). Solid lines indicate easy conditions, dashed lines indicate difficult conditions. See text for further details.

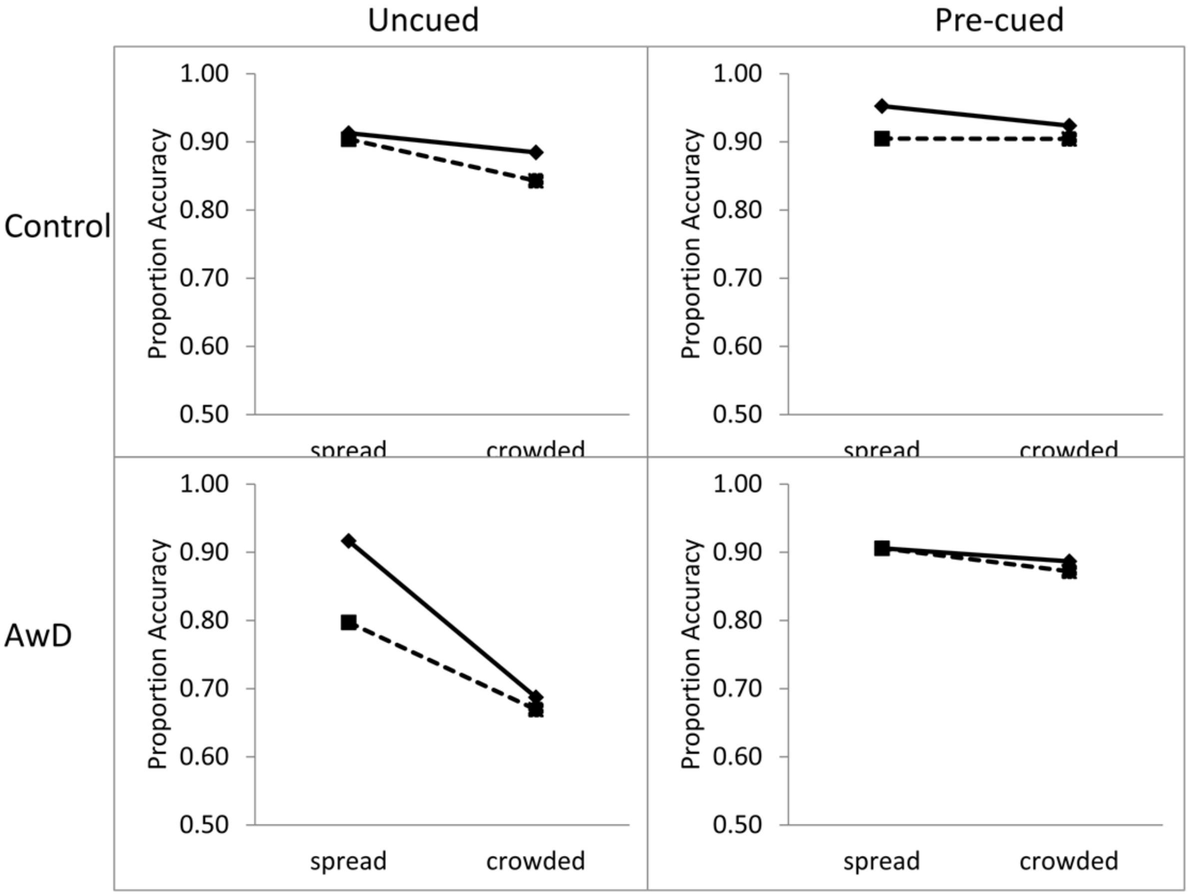


Figure 3. Mean proportion accuracy of (A) controls and (B) adults with dyslexia in uncued, pre-cued and post-cued cue conditions in set sizes one, eight crowded and sixteen. Error bars ± 1 SEM.

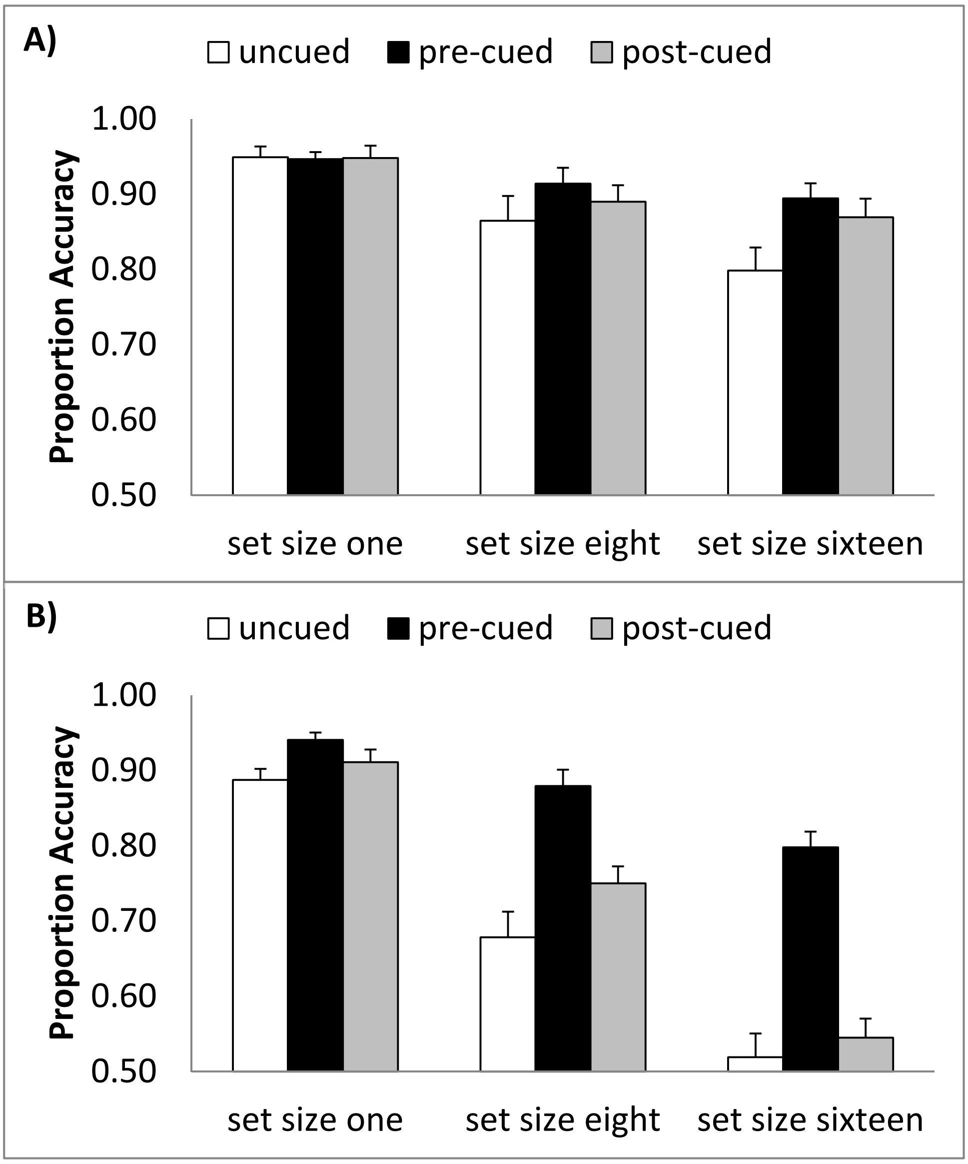
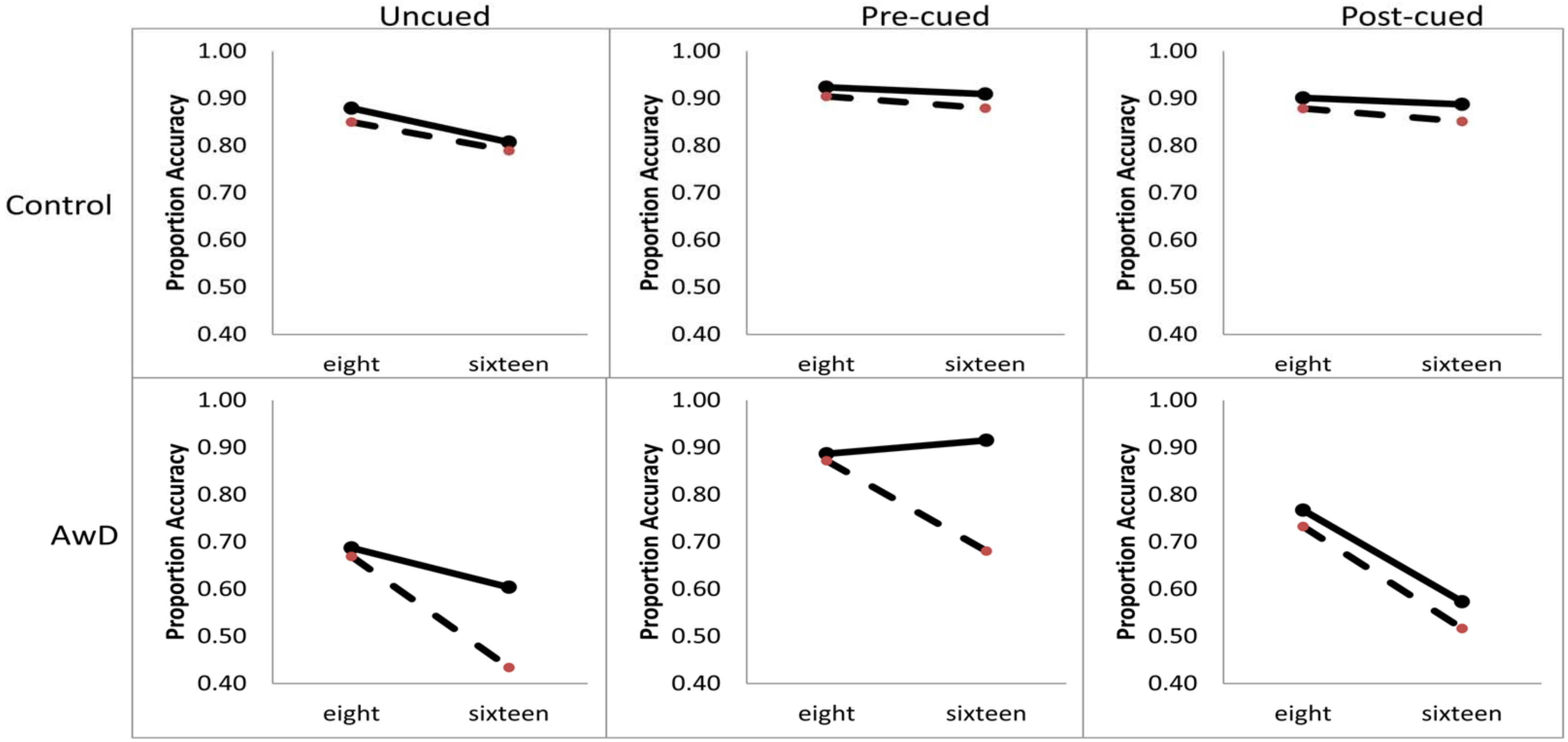


Figure 4.The effect of set size for controls (top panels) and AwD (bottom panels) groups in each of three cueing conditions. Solid lines indicate the easy orientation discrimination condition, and dashed lines the more difficult discrimination blocks.



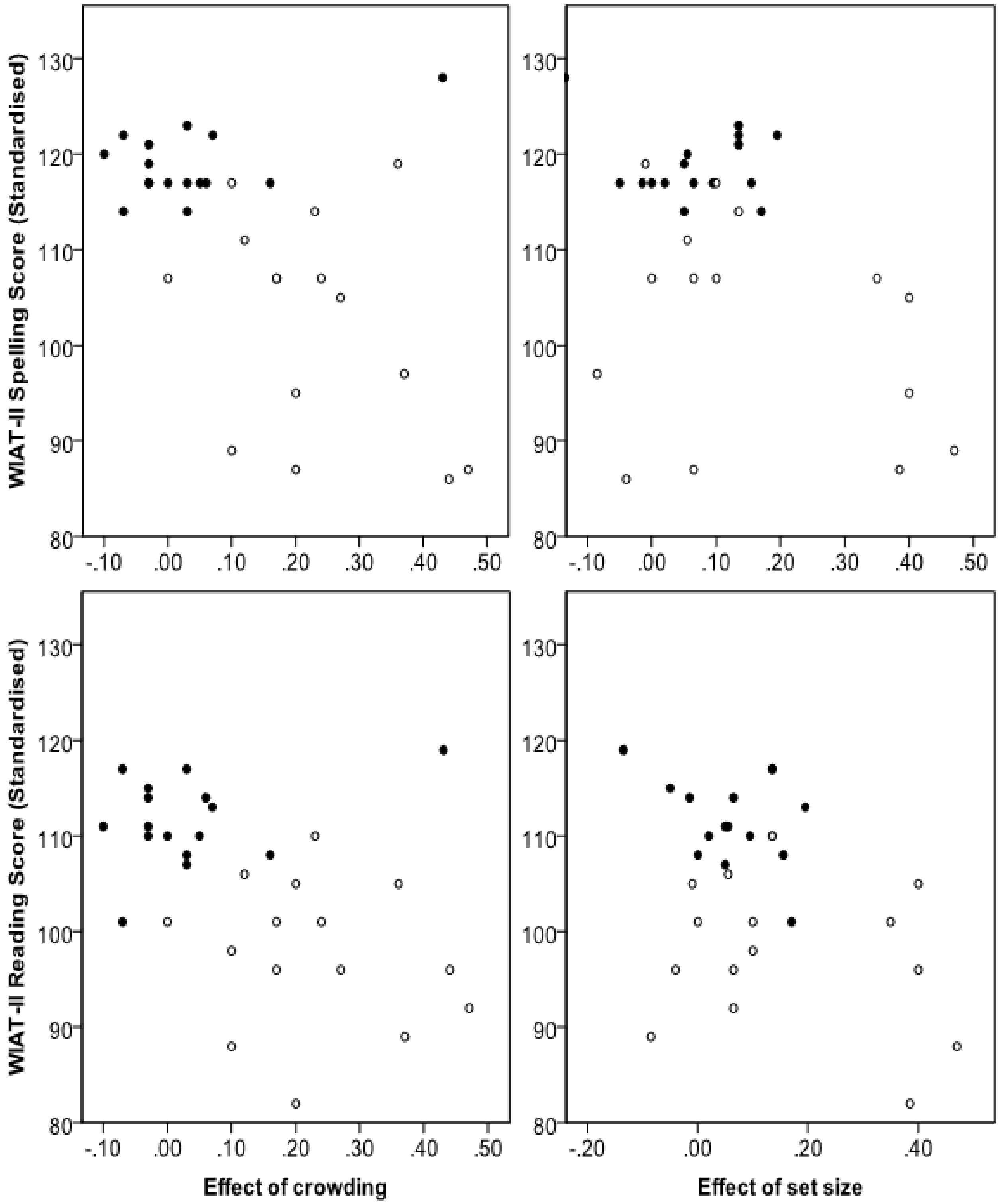


Figure 5. Scatterplots showing the relationship between the effects of crowding and set size on WIAT-II reading and spelling scores for control adults (filled dots) and adults with dyslexia. The effect of crowding reflects the performance difference in crowded vs. spread conditions. The effect of set size reflects the performance difference in set size 8 crowded vs. set size 16 conditions.