

The influence of contrast on coherent motion processing in dyslexia

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ABSTRACT

The aim of the experiments was to investigate how manipulating the contrast of the signal and noise dots in a random dot kinematogram (RDK), influenced on motion coherence thresholds in adults with dyslexia. In the first of two experiments, coherent motion thresholds were measured when the contrasts of the signal and noise dots in an RDK were manipulated. A significantly greater processing benefit was found for the group with dyslexia than a control group when the signal dots were of higher contrast than the noise dots. However, a significant processing disadvantage was found for the group with dyslexia relative to the control group when the signal dots were of lower contrast than the noise dots. These findings were interpreted as supporting evidence for the noise exclusion hypothesis of dyslexia. In Experiment 2, the effect on coherent motion thresholds of presenting a cue that alerted observers to which stimuli, high or low contrast contained the signals dots was investigated. When the cue directed attention to low contrast signal dots presented in high contrast noise, coherent motion thresholds were only enhanced for the group with dyslexia. This manipulation produced equivalent coherent motion thresholds in the reader groups. In other conditions, the group with dyslexia had significantly higher coherent motion thresholds than the control group. It was concluded that adults with dyslexia who show evidence of a coherent motion deficit (37% of the dyslexia group in each experiment), have a specific difficulty in noise exclusion. This appears to occur as consequence of a sensory processing deficit in the magnocellular or dorsal stream.

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Skilled reading involves a combination of linguistic and visual processes. Adults with dyslexia have poor reading fluency, poor spelling, and difficulties with phonological decoding (Bruck, 1990; Conlon & Sanders, 2011; Hatcher, Snowling, & Griffiths, 2002; Shaywitz et al., 2003; Wilson & Lesaux, 2001). Deficits in non-linguistic factors including speed of visual processing (Conlon, Wright, Norris, & Chekaluk, 2011), difficulties shifting attention between sequentially presented stimuli (Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001; Hari & Renvall, 2001), poor spatial attention (Vidyasagar, 1999; Wright, Conlon & Dyck, 2012) and reduced capacity to filter irrelevant visual stimuli (Roach & Hogben, 2007) have also been reported. Although controversial, these disparate difficulties have been explained by the presence of a visual sensory processing deficit in the magnocellular and/or dorsal stream of individuals with dyslexia (e.g., Lovegrove, 1993; Stein & Walsh, 1997).

Evidence supporting a sensory deficit in dyslexia is obtained from findings of reduced sensitivity in these individuals to visual stimuli such as motion that stimulate the magnocellular (M) pathway and extrastriate dorsal stream and normal sensitivity to stimuli that are processed in the parvocellular (P) pathway and

extrastriate ventral stream (e.g., Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Demb, Boynton, & Heeger, 1998; Hansen, Stein, Orde, Winter, & Talcott, 2001; Lovegrove, Martin, & Slaghuys, 1986; Wilmer, Richardson, Chen, & Stein, 2004). However, failures to replicate these effects (White et al., 2006; Williams, Stuart, Castles, & McAnally, 2003) and findings that poorer sensitivity only occurs when using specific stimulus parameters or methodologies (Ben-Yehudah et al., 2001; Hill & Raymond, 2002) have led to alternative explanations.

The noise exclusion hypothesis proposes that individuals with dyslexia have difficulties processing task relevant information that is presented in a noisy visual environment because of a specific difficulty excluding irrelevant noise (Sperling, Lu, Manis, & Seidenberg, 2005; Sperling, Lu, Manis, & Seidenberg, 2006). Supporting evidence has been obtained from a study that has shown reduced contrast sensitivity in a group with dyslexia to stimuli processed in the M and P pathways, when the stimuli contained added Gaussian visual noise. No group differences in sensitivity were found when noise was not added to the stimulus. From these findings it was concluded that difficulties with noise exclusion and not an M-pathway deficit explained the findings of poorer contrast sensitivity in the group with dyslexia (Sperling et al., 2005).

A further study used a coherent motion task to assess the impact of difficulties with noise exclusion in the dorsal visual stream (Sperling et al., 2006). The coherent motion stimulus was generated

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using a random dot kinematogram (RDK), in which a proportion of dots are signal dots which contain the directional motion signal and the remainder are noise dots that contain no information concerning the direction of motion. The global direction of motion is obtained by integrating a proportion of the signal dots (Braddick, 1995; Newsome & Paré, 1988). The coherence threshold is determined by the proportion of signal dots that must be extracted from the RDK to accurately determine the global direction of motion. When the signal and noise dots presented in the RDK were distinguished only by direction of motion, the group with dyslexia were found to have higher coherence thresholds than a control group. This finding is consistent with previous studies (Conlon, Sanders, & Zapart, 2004; Conlon, Sanders, & Wright, 2009; Cornelissen et al., 1995; Raymond & Sorensen, 1998; Talcott, Hansen, Assoku, & Stein, 2000; Talcott et al., 1998). However, no group differences were found when all the signal dots were presented in red and the noise dots in grey, although coherence thresholds improved in both reader groups. In this condition, the colour as well as the direction of motion distinguished the signal from noise dots in the RDK. Sperling et al. (2006) argued that the lack of group differences occurred because the group with dyslexia were able to optimize the perceptual filters tuned to the red signal dots, and in doing so exclude the grey noise dots. This process could not be efficiently conducted when the signal and noise dots were only distinguished by motion.

In the two studies that have provided support for the noise exclusion hypothesis of dyslexia, the tasks used and the manipulations employed were very different. In the first experiment, external noise irrelevant to the task was added to a low contrast stimulus (Sperling et al., 2005). This produced evidence of difficulties with noise exclusion. In the second experiment, the impact of noise dots which form part of the stimulus configuration of an RDK were manipulated by presenting the signal and noise dots in different colours (Sperling et al., 2006). As the group with dyslexia showed evidence of a coherent motion deficit when the signal and noise dots differed only in the direction of motion and showed no evidence of poor performance when the signal and noise dots could be distinguished using colour and motion, it was concluded that noise exclusion represents a difficulty for individuals with dyslexia (Sperling et al., 2006). Methodologically, demonstrating systematic increases and decreases in coherent motion thresholds when the type and amount of noise in the stimulus is systematically manipulated will provide more direct evidence of the proposed effects.

Independently manipulating the contrast of the signal and noise dots in an RDK is one technique that could be used to more systematically investigate problems with noise exclusion in dyslexia. In normal readers, when the signal dots are all presented at a higher contrast than the noise dots, lower coherence thresholds are found, and when the signal dots are all of a lower contrast than the noise dots, higher coherence thresholds are found (Croner & Albright, 1997). These results have been explained using the visual systems response to contrast. As stimulus contrast is increased, the neural response to the stimulus also increases. This has been described as the contrast gain mechanism. In physiological studies this has been shown by a more vigorous excitatory response to the stimulus (Martinez-Trujillo & Treue, 2002; Tootell, Hamilton, & Swites, 1988). Behaviourally, the stronger neural response produces preferential processing of those stimuli (Croner & Albright, 1997). In an RDK, when the higher contrast stimuli are the signal dots, these task relevant signals effectively mask the lower contrast noise dots excluding these stimuli from processing (Braddick, 1995; Croner & Albright, 1997). However, when the signal dots are all presented at a lower contrast than the noise dots, so have a weaker neural response, more signal dots are required to reach coherence threshold because of masking by the higher contrast noise dots (Braddick, 1995; Edwards, Badcock, & Nishida, 1996).

In addition to the increased neural response found with presentation of stimuli of higher contrast in an RDK, there is physiological evidence that using a cue to direct attention to signal dots in an RDK, can also increase the strength of the neural response to the attended stimulus (Martinez-Trujillo & Treue, 2002). Behaviourally, this has been shown in normal readers as noise exclusion when a cue is used to direct attention to a specific feature or location in the visual stimulus (Doshier, Liu, Blair, & Lu, 2004; Lu & Doshier, 1998; Lu & Doshier, 2005; Lu & Doshier, 2008). In groups with dyslexia, when a cue is used to direct attention to a specific feature in a stimulus, improved performance has also been found (Becker, Elliott, & Lackmann, 2005; Hawlka & Wimmer, 2008; Moores, Cassim, & Talcott, 2011). Together these findings suggest that using a cue to direct attention to the signal dots in an RDK, may lower coherence thresholds because of noise exclusion.

The aim of the first experiment conducted in the current study was to determine if coherent motion thresholds could be systematically increased or decreased in groups with or without dyslexia when the contrast of the signal and noise dots presented in an RDK were manipulated. Experiment 2 aimed to determine whether using a cue to direct attention to the signal dots in an RDK could also produce evidence of noise exclusion when the contrast of the signal dots was both higher and lower than the noise dots in the stimulus.

1. Experiment 1

Experiment 1 investigated the influence of contrast on coherent motion thresholds in groups of adults with or without dyslexia. Two baseline conditions used RDKs with signal and noise dots of the same contrast. The contrast was low in one baseline condition and high in the other. Higher coherence thresholds were expected in both conditions for the group with dyslexia than the control group.

Two mixed contrast conditions were used to determine if presenting the signal dots at either a higher or lower contrast than the noise dots in the RDK had a systematic influence on coherence thresholds (see Fig. 1). Independent of reader group, reduced coherence thresholds were expected in the condition where high contrast signal dots were presented in low contrast noise (high contrast signal). Increased coherence thresholds were expected with presentation of low contrast signals in high contrast noise (low contrast signal). Two outcomes were expected if the noise exclusion hypothesis (Sperling et al., 2006) was supported. First, a significantly greater improvement in coherence thresholds would be seen in the group with dyslexia relative to the control group for the high contrast signal condition. Second, significantly higher coherence thresholds were expected in the group with dyslexia relative to the control group in the low contrast signal condition.

2. Method

2.1. Participants

The volunteers were 16 adults with dyslexia and 20 normally reading adult controls. All participants had English as a first language and normal or corrected to normal visual acuity. Individuals with dyslexia were recruited from the University disability office, the laboratory register and from advertising. Normally reading controls were obtained from the student participant pool. All procedures were conducted in accordance with the University human research ethics committee that approved this project.

The criteria used to define adults with dyslexia were based on those we used in previous studies (Conlon & Sanders, 2011; Conlon et al., 2004, 2009, 2011). Individuals with dyslexia reported a history of reading difficulties and had standard word reading scores below 95 on the Wide Range Achievement Test – 3rd edition (WRAT-3; Wilkinson, 1993). This test consists of 42 words of increasing difficulty and has internal consistencies of .90–.95 for the age groups used in this study. Individuals with dyslexia also had scores at least two standard deviations (SD) below the mean of the control group on nonword and exception word reading tests. The nonword and exception word tests each had 25 items matched for word length. The internal consistencies for the nonword and exception word tests are .77 and .84 respectively.

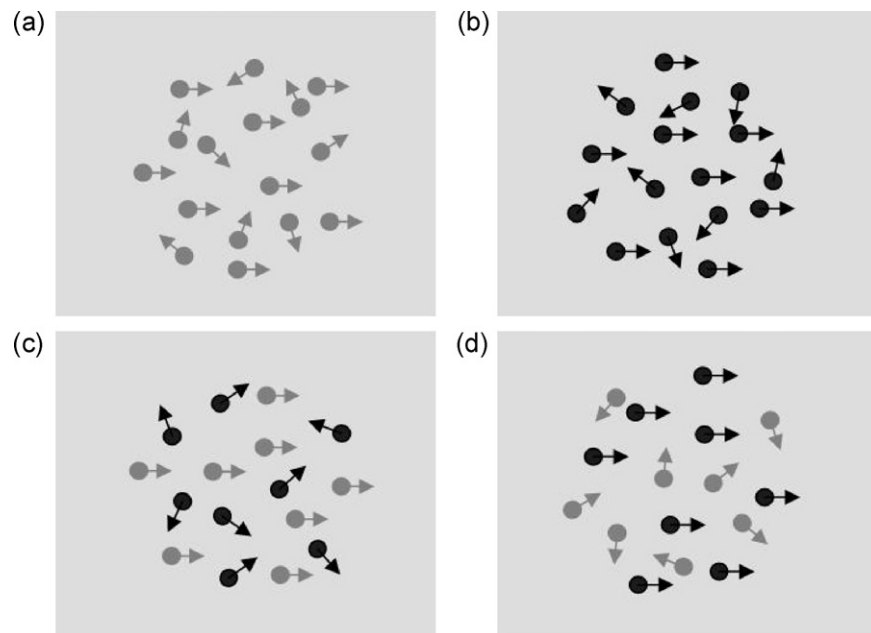


Fig. 1. Representation of the four conditions used in the global motion task in Experiment 1. (a) Signal and noise dots of the same but of low contrast; (b) signal and noise dots of the same high contrast; (c) low contrast signal dots, high contrast noise dots (low contrast signal condition); (d) high contrast signal dots and low contrast noise dots (high contrast signal condition). Please note: contrast, size, and number of dots shown are for illustration and do not match those used experimentally.

A further criterion was that standard scores on the Test of Word Reading Efficiency (TOWRE; Torgeson, Wagner, & Rashotte, 1999) were below a standard score of 90. At least average non-verbal ability as measured using the Block Design subtest from the WAIS-3 (Wechsler, 1998) was the final criterion.

Criteria for inclusion in the control group were a word reading score on the WRAT-3 above a standard score of 105 and nonword and exception word reading test scores of at least 75%. Standard scores on the TOWRE were at least 100. At least average non-verbal ability as measured using the Block Design subtest from the WAIS-3 (Wechsler, 1998) was the final criterion.

Table 1 presents the profile of each of the reader groups. The group with dyslexia was significantly poorer than the control group on word reading, $t(32) = 12.58$, $p < .001$, nonword reading, $t(34) = 10.63$, $p < .001$, exception word reading, $t(34) = 8.29$, $p < .001$, and word reading efficiency, $t(34) = 9.68$, $p < .001$ tests. No significant difference was found between groups on the Block Design subtest from the WAIS-3, $t(34) = .238$, $p = .81$.

2.2. Stimuli

Stimuli for the coherent motion task were generated using the Cambridge Research Systems hardware and visual systems generator, VSG version 2/4. Stimuli were displayed on a 21 in. Hitachi HM-4721-D monitor with a resolution of 800×600 pixels, and a vertical screen refresh rate of 120 Hz. The RDK contained 200 one pixel dark grey (6 cd/m^2) and/or light grey (12 cd/m^2) dots presented on a background with a luminance of 18 cd/m^2 . Michelson contrast of the dots was calculated by obtaining the difference between the dot and background luminance and dividing these by the total of the two luminances. The two contrasts used were .50 (high) and .20 (low). These contrasts were selected to avoid possible floor effects in the low contrast signal in high contrast noise condition (Croner & Albright, 1997). The dots were either signal dots which moved coherently in a single direction or noise dots which moved randomly (see Fig. 1). In two baseline conditions all dots were the same contrast, either high or low. Two mixed contrast conditions provided the high and low signal contrast conditions.

Table 1

Performance of the normal ($n = 20$) and dyslexia ($n = 16$) groups on the reading and ability measures. Experiment 1.

	Normal readers		Readers with dyslexia	
	Mean	SD	Mean	SD
WRAT reading (standard)	110.96	4.2	91.96	4.9
Nonwords %	89%	7.1	56.7%	11.4%
Exception words %	76.5%	7.3	44%	12.7%
TOWRE efficiency standard	114.71	5.9	80	12.1
Non-verbal ability, scaled scores	12.46	2.5	13.31	2.81

The dot density was 7.08 dots/deg^2 and the duration of a single animation frame was 16.67 ms, with dot lifetime of two animation frames, after which the dot would disappear before being regenerated at a randomly selected location in the RDK. A standard wrap around technique was used for the signal dots as they reached the side of the screen. The noise dots randomly changed position at the end of their lifetime. The duration of a single trial was 133 ms and the speed of the stimulus was $10.5^\circ/\text{s}$. For all conditions the starting coherency was 25%.

The psychophysical procedure used to obtain threshold estimates which were the percentage of signal dots needed to discriminate the direction of motion 79% of the time, was a weighted three up, one down adaptive staircase (Kaernbach, 1991). Following three correct responses, the proportion of signal dots was reduced by 1 dB (a factor of 1.122) and following each incorrect response the proportion of signal dots was increased by 3 dB (a factor of 1.412). Participants selected the direction of motion (left or right) at the completion of each trial. For each condition there were two blocks of trials, each using six reversals for leftward and rightward motion. Geometric mean thresholds for each direction of motion were combined across the blocks of trials to obtain an estimate of coherence threshold.

2.3. Procedure

Each participant was first assessed for reading ability. This assessment was followed by a separate session in which measurement of coherence thresholds was undertaken in a darkened laboratory. Viewing was binocular with natural pupils and the viewing distance of 57 cm was controlled with a chin rest. Each trial began with presentation of a fixation cross in the centre of the screen. After 150 ms, this was replaced with the RDK. After 133 ms the RDK was extinguished and replaced with a response prompt. A new trial was automatically triggered when a response was made. Twenty practice trials were given before each experimental condition. The order of presentation of the experimental conditions was counterbalanced between and within groups.

3. Results

One participant from each reader group was excluded from the analysis because they had coherence thresholds more than three SD above their respective group means. A square root transformation was performed to reduce positive skew and meet the assumptions of ANOVA.

Data in the two baseline conditions where the signal and noise dots were of equal contrast was analysed with a 2 (Group: dyslexia or control) $\times$ 2 (Contrast: high or low) mixed ANOVA (see Fig. 2). Statistically significant main effects were found for Group, $F(1, 31) = 6.77$, $p = .014$, $\eta^2 = .18$, and Contrast, $F(1, 31) = 15.99$, $p < .001$, $\eta^2 = .33$. There was no significant interaction between Group and

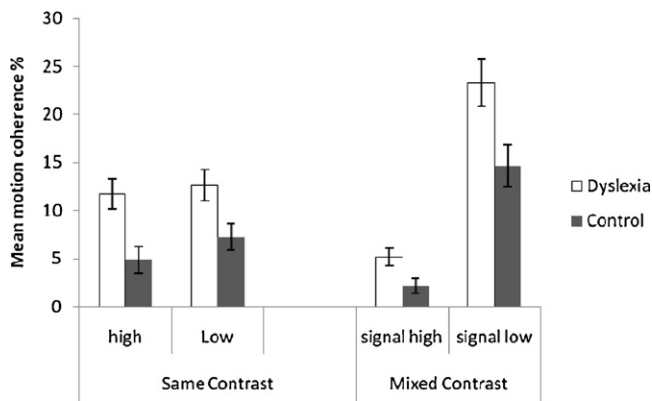


Fig. 2. Experiment 1. Global motion thresholds for the dyslexia ($n = 15$) and control groups ($n = 19$) in the same and mixed contrast conditions. Untransformed scores are reported. Error bars represent ± 1 standard errors.

Contrast, $F(1, 31) = 3.31$, $p = .08$, $p\eta^2 = .10$. Both groups had significantly lower coherence thresholds with presentation of the high compared to the low contrast stimulus. As expected, the group with dyslexia had higher coherence thresholds than the control group regardless of the contrast used.

The mixed contrast conditions were evaluated using a 2 (Group: dyslexia or control) $\times$ 2 (Signal Contrast: high or low) mixed ANOVA. A significant main effect was found for Signal Contrast, $F(1, 31) = 559.1$, $p < .001$, $p\eta^2 = .94$. Consistent with predictions, Fig. 2 shows that both groups had higher coherence thresholds in the low contrast signal condition, in which the signal dots were of lower contrast than the noise dots and lower coherence thresholds in the high contrast signal condition, in which the signal dots were of higher contrast than the noise dots. A significant main effect was found for Group, $F(1, 31) = 5.53$, $p = .025$, $p\eta^2 = .15$, and a significant interaction was found between Signal Contrast and Group, $F(1, 31) = 9.04$, $p = .005$, $p\eta^2 = .23$. The group with dyslexia had significantly higher thresholds than the control group in the low contrast signal condition, $F(1, 31) = 7.82$, $p = .009$, $p\eta^2 = .20$, with no significant group differences found when the signal dots were of highest contrast, $F(1, 31) = 2.03$, $p = .164$, $p\eta^2 = .06$.

Three change scores were generated using the square root coherence threshold scores to determine the extent of the processing benefits and disadvantages produced by the high and low signal contrast conditions. First, the threshold for the high contrast signal condition was subtracted from the threshold for the low contrast signal condition to determine the overall processing benefit of the high contrast signals. A significantly greater processing benefit was found for the group with dyslexia ($M_{\text{change}} = 2.94$, $SD = .67$) than the control group ($M_{\text{change}} = 2.28$, $SD = .61$), $t(31) = 2.92$, $p = .007$, Cohen's $d = 1.04$.

The processing benefit of the high contrast signal relative to the high contrast baseline condition was obtained. The variable of interest was the relative contrast of the noise dots. Therefore, the high contrast signal condition was subtracted from the high contrast baseline condition, as these conditions had the same contrast for the signal dots, but different contrasts for the noise dots across the two conditions. An independent groups t -tests revealed a significantly greater processing benefit in the high contrast signal condition for the group with dyslexia ($M_{\text{dyslexia change}} = 1.27$, $SD = .71$) than the control group ($M_{\text{control change}} = .71$, $SD = .43$), $t(31) = 2.28$, $p = .030$, Cohen's $d = .80$.

The processing disadvantage of the low contrast signal condition was obtained by subtracting coherence thresholds for the low contrast signal condition from the low contrast baseline condition. The low contrast signal condition was compared to the low contrast baseline as these conditions both included low

contrast signal dots, and differed in the contrast of the noise dots only. A significantly greater processing disadvantage for the low contrast signal condition was found for the group with dyslexia ($M_{\text{change}} = -1.55$, $SD = .55$) than the control group ($M_{\text{change}} = -1.10$, $SD = .71$), $t(31) = 2.09$, $p = .045$, Cohen's $d = .72$.

3.1. Who has a motion deficit?

Deviance analysis (Ramus et al., 2003) was used to determine which individuals with dyslexia had a coherent motion deficit in the three conditions where there were between group differences. For each condition, individuals with dyslexia were classified with a coherent motion deficit if their threshold scores were poorer than the one tail 95% confidence limit of the control group, after control group members with threshold estimates beyond this limit were excluded. Consistent with previous research (Conlon et al., 2009; Ramus et al., 2003; Wright & Conlon, 2009), five (36%) participants with dyslexia had a coherent motion deficit in each of the three conditions.

Independent groups t -tests determined whether the sub-group with dyslexia and a motion deficit had a greater processing benefit or disadvantage than the sub-group with dyslexia and typical coherent motion thresholds. The group with a motion deficit ($M_{\text{change}} = 3.20$, $SD = .65$) had a significantly greater processing benefit than the group without a motion deficit ($M_{\text{change}} = 2.60$, $SD = .31$) when the high contrast signal condition was subtracted from the low contrast signal condition, $t(11) = 2.27$, $p = .045$, Cohen's $d = 1.28$. No other significant between groups effects were found.

4. Discussion

The results of Experiment 1 showed that the group with dyslexia had significantly higher coherence thresholds than the control group in the baseline conditions, regardless of the contrast used. Significantly greater improvement in coherence thresholds was seen in the group with dyslexia relative to the control group for the high contrast signal condition. In fact, there was no statistically significant difference in thresholds between the reader groups in this condition. In contrast, significantly higher coherence thresholds were seen in the group with dyslexia relative to the control group in the low contrast signal condition. These data are consistent with the predictions made on the basis of the noise exclusion hypothesis (Sperling et al., 2006).

In both reader groups lower coherence thresholds were found in the baseline conditions for the high relative to the low contrast stimuli. These findings are consistent with the results of a previous study for the control group (Edwards et al., 1996). In that study, the lower coherence thresholds found as the contrast of the stimulus was increased were attributed to the decreasing impact of noise internal to the visual system. As contrast was increased, the effect of internal noise, for example the spontaneous discharge of cells, was overcome because of the stronger neural response to contrast in the stimulated cell groups (Edwards et al., 1996). The finding that the effects were the same for both reader groups might indicate that the level of internal noise in the visual systems of each of the reader groups is the same. This interpretation is consistent with research that has shown that at suprathreshold levels, stimulus contrast has no negative influence on processing in groups with dyslexia (Hayduk, Bruck, & Cavanagh, 1996). This issue will be further discussed in the general discussion.

The results of the mixed contrast conditions indicate that difficulties with noise exclusion represent a greater difficulty for the group with dyslexia than for the control group. This conclusion is supported by the greater processing advantage found in the group with dyslexia with preferential processing of the higher contrast

signal dots (Croner & Albright, 1997; Snowden & Edmunds, 1999). In addition, the greater processing disadvantage found in the group with dyslexia when the signal dots were of lower contrast than the noise dots, and thus masked, provides further evidence of difficulties with noise exclusion. These effects were found in 36% of the individuals in the group with dyslexia.

5. Experiment 2

In a coherent motion task in which the signal dots are uniquely defined from the noise dots by colour or contrast as well as the direction of motion, coherent motion detection is facilitated by the pop-out effect available through segmentation of the groups of signal and noise dots used (Braddick, 1995; Croner & Albright, 1997; Dobkins & Sampath, 2008; Edwards & Badcock, 1996; Snowden & Edmunds, 1999). Groups with dyslexia have normal efficiency when performing these types of search task (Buchholz & McKone, 2004; Hayduk et al., 1996; Iles, Walsh, & Richardson, 2000). One reason that this effect occurs is because the low perceptual difficulty of the task may have required minimal signal integration (Edwards et al., 1996), a process critical when detecting global motion (Cropper, 2001). Poorer capacity to integrate the signal dots to form the global motion percept is one explanation of the motion processing deficit found in dyslexia (Hill & Raymond, 2002; Raymond & Sorensen, 1998; Sperling, Lu, & Manis, 2004). To increase the perceptual difficulty of the global motion task, and to further investigate the effects of contrast, Edwards et al. (1996) added noise dots of either a higher or lower contrast to an RDK containing signal and noise dots of equal contrast. Similar to the findings obtained when all signal and noise dots were defined by contrast, improved coherence thresholds were found when the added noise dots were of lower contrast than the signal and noise dots presented in the RDK. However, a greater percentage of signal dots were needed to reach coherence threshold in this condition. This indicated that the greater perceptual difficulty of the task ensured that a higher proportion of signal dots were integrated to detect global motion (Edwards et al., 1996). Increased coherence thresholds were also found when the added noise dots were of higher contrast than the signal and noise dots presented in the RDK (Edwards et al., 1996).

Using this method, Experiment 2 investigated the influence of contrast and the addition of an attention cue on global motion processing. Our first aim was to determine whether the processing advantages and disadvantages found in Experiment 1 with presentation of either higher or lower contrast signal dots could be replicated when using a task of greater perceptual difficulty. Two outcomes were expected if difficulties with noise exclusion alone explained higher coherence thresholds in the group with dyslexia. First, no reader group differences in coherence thresholds were expected when the added noise dots were of lower contrast than that of the signal and noise dots presented in the RDK. Second, the group with dyslexia were expected to have significantly higher coherence thresholds than the control group when the added noise dots were of a higher contrast than the signal and noise dots presented in the RDK.

The second aim of Experiment 2 was to determine whether a cue which directed attention to the signal dots could enhance coherence thresholds in the reader groups. Based on previous findings, noise exclusion occurs when an attention cue is used to direct observers attention to a specific feature in a noisy visual stimulus (Lu & Doshier, 1998, 2005, 2008). Compared to the no cue conditions, lower coherence thresholds were expected in each of the reader groups with addition of the cue. If the cue overcomes the problem excluding noise in the group with dyslexia, then there will be no group differences found in the cued conditions.

Table 2

Performance of the normal ($n = 19$) and dyslexia ($n = 18$) groups on the reading and ability measures. Experiment 2.

	Normal readers		Readers with dyslexia	
	Mean	SD	Mean	SD
WRAT-3 (standard)	111.71	4.3	92.1	3
Nonwords %	85.5%	8.7	67.5%	7%
Exception words %	77%	10	45%	17%
Non-verbal ability, scaled scores	12.46	2.5	11.23	3

6. Method

6.1. Participants

The volunteers were 18 adults with dyslexia and 19 normally reading controls, none of whom participated in Experiment 1. All participants had English as a first language and normal or corrected to normal visual acuity. The criteria used to define the two reader groups were the same as those used in Experiment 1, with the exception that the TOWRE was not included. University human research ethics committee approval was obtained for this project.

The descriptive statistics for the reader groups on the reading and ability measures are shown in Table 2. The groups differed significantly on WRAT-3 word identification, $t(37) = 13.67$, $p < .001$, and on the nonword, $t(37) = 6.48$, $p < .001$, and exception word, $t(37) = 7.01$, $p < .001$ tests. No group differences were found on nonverbal ability, $t(37) = 1.26$, $p = .214$.

6.2. Stimuli

The equipment used was the same as that used in Experiment 1. The stimulus (see Fig. 3), distinguished the RDK from the added noise dots by presenting the different components of the stimulus in reversed polarity relative to the background luminance. When the signal and noise dots are distinguished by polarity, with for example the signal dots appearing as white stimuli and the noise dots black, this manipulation has no effect on coherence thresholds if the contrast of signal and noise relative to the background luminance is the same (Croner & Albright, 1997). In the RDK there were 300 dots. Half of the dots were of high luminance (24 cd/m^2) appearing white against the grey background of 11 cd/m^2 , and half low luminance (1.56 cd/m^2) appearing black against the grey background. Relative to the background, the white dots had a Michelson contrast of .30, with the black dots a Michelson contrast of .75. These stimuli differed from those used in Experiment 1 because perceptual differences (white versus black) between presentations of the high and low contrast signal dots were essential when investigating the influence of the cue on coherence thresholds. In any condition either the high or low contrast dots contained the motion signals with a proportion of the dots moving coherently. The 150 additional noise dots of either lower or higher contrast added to the RDK produced the high and low signal contrast conditions.

The stimulus was displayed in a borderless area subtending 13.35° horizontally and vertically at a viewing distance of 57 cm. A black fixation cross was presented prior to presentation of each of the test stimuli. The stimulus duration for each trial was 700 ms, with a single animation frame presented for 16.67 ms. Lifetime of the signal dots was three animation frames. This dot lifetime was selected from pilot testing. Noise dots moved randomly with each screen refresh. The velocity of the signal dots was $12^\circ/\text{s}$. A conventional wrap around technique was used for the signal dots that moved out of the display area. When the noise dots disappeared they were regenerated at randomly selected locations within the area of the dot pattern. Catch trials at 60% coherence were randomly presented at least once every 5 trials. Starting coherency in each condition was 35%.

In the conditions where the cue was presented prior to the stimulus, a written message directing attention to either the white dots (low contrast) or the black dots (high contrast) appeared in the centre of the computer screen prior to the beginning of each trial. The message was the word "White" written in white ink when the signal dots were white and the word "Black" in black ink when the signal dots were black.

Coherence thresholds were obtained with the same adaptive procedure used in Experiment 1. There were eight blocks of trials conducted to estimate coherent motion thresholds, four for the no cue conditions and four for the cue conditions. Each block of trials had eight reversals, four for leftward motion and four for rightward motion. The geometric mean coherence threshold for each leftward and rightward motion was combined for each block of trials to obtain a threshold estimate. An overall geometric mean coherence threshold was obtained for each condition by combining scores in each condition conducted.

6.3. Procedure

Reading and ability measures were obtained in the first of two experimental sessions. Coherent motion thresholds were obtained in the second session which took place in a darkened laboratory. Viewing was binocular with natural pupils and the viewing distance of 57 cm was controlled with a chin rest. A grey cardboard

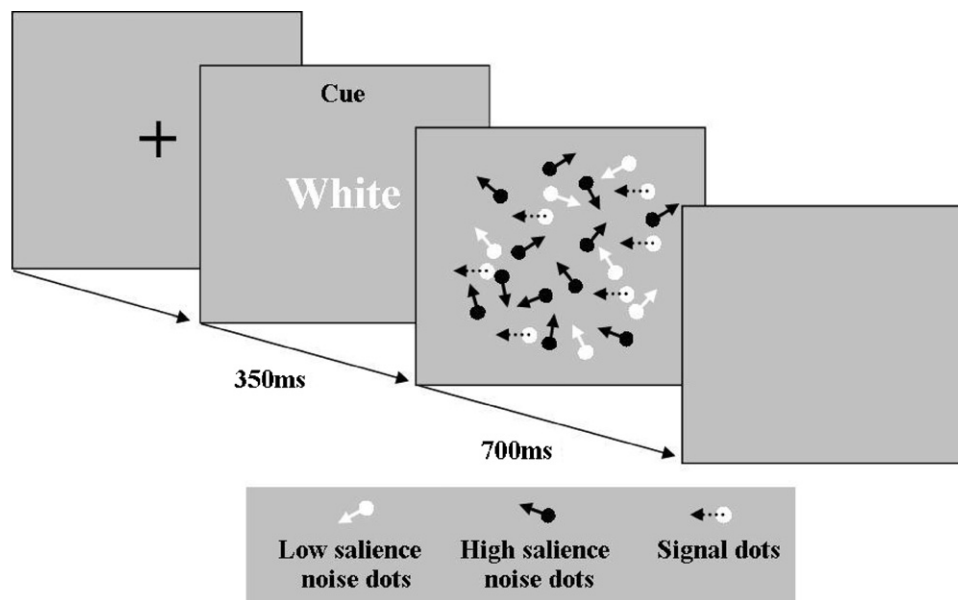


Fig. 3. Global motion task used in Experiment 2.

surround was used to mask the display monitor so only the area containing the RDK only was displayed. In the baseline conditions, the fixation cross appeared in the centre of the computer screen for 350 ms prior to presentation of the RDK, which was presented for 700 ms, after which a response screen that requested observers to provide a response appeared. After a response was made, a new trial automatically began. In each of the cue conditions, the procedure was similar. Following presentation of the fixation cross for 350 ms, the cue directing attention to either the black or white dots was presented, prior to presentation of the stimulus for a further 350 ms. A block of 20 practice trials was undertaken prior to formal testing for each condition. Presentation of the stimulus conditions for the coherent motion tasks was randomised between groups and participants. Errors on the catch trials were negligible on each of the conditions for each of the groups so were not analysed further.

7. Results

The data were analysed using a 2 (Signal Contrast: high or low) $\times$ 2 (Cue: present or absent) $\times$ 2 (Group: dyslexia or control) mixed ANOVA. The assumptions of the analysis were met. A significant three-way interaction was found for Group, Signal Contrast and Cue, $F(1, 35) = 9.69$, $p = .004$; $p\eta^2 = .22$. Fig. 4 shows that coherence thresholds for the reader groups were influenced differently in the cue and no cue conditions. Interaction contrasts were conducted to evaluate these effects.

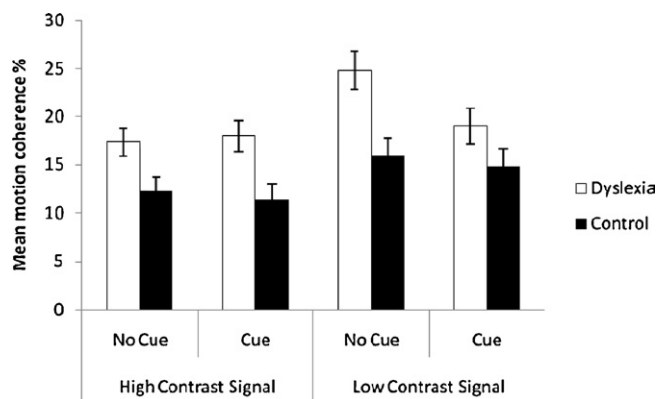


Fig. 4. Experiment 2. Coherent motion thresholds for the dyslexia ($n = 18$) and the control ($n = 19$) groups with or without the attention cue for the high and low contrast signal conditions. Error bars represent ± 1 standard errors.

7.1. High and low contrast signal, no cue conditions

A 2 (Group: dyslexia or control) $\times$ 2 (Signal Contrast: high or low) mixed ANOVA was conducted. Both groups had significantly lower coherence thresholds when the signal dots were of high compared to low contrast, $F(1, 35) = 49.1$, $p < .001$; $p\eta^2 = .58$. Regardless of the condition, the group with dyslexia had significantly higher coherence thresholds than the control group, $F(1, 35) = 9.66$, $p = .004$; $p\eta^2 = .22$. These effects were modified by a significant interaction between Signal Contrast and Group, $F(1, 35) = 6.45$, $p = .016$; $p\eta^2 = .16$. The interaction is explained by a greater increase in coherence thresholds in the group with dyslexia than in controls in the low contrast signal condition (increase: $M_{\text{dyslexia}} = 7.6\%$, $SD = 5.1\%$; $M_{\text{control}} = 3.6\%$, $SD = 4.7\%$, $t(35) = 2.54$, $p = .016$).

7.2. Effects of the cue in the high contrast signal condition

The impact of the cue that directed attention to the higher contrast signal dots on coherence thresholds was evaluated with a 2 (Cue: cue or no cue) $\times$ 2 (Group: dyslexia and control) mixed ANOVA. There was no significant effect of the cue on coherence thresholds for either group, $F(1, 35) = .05$, $p = .82$ (see Fig. 4). Relative to the control group, the group with dyslexia had significantly higher coherence thresholds with, $F(1, 35) = 8.85$, $p = .004$; $p\eta^2 = .20$, and without the addition of the cue, $F(1, 35) = .05$, $p = .82$.

7.3. Effects of the cue in the low contrast signal condition

In the low contrast signal condition, the 2 (Cue: cue or no cue) $\times$ 2 (Group: dyslexia or control) mixed ANOVA produced a significant interaction between Group and Cue, $F(1, 35) = 6.2$, $p = .018$, $p\eta^2 = .15$. The interaction (see Fig. 4) shows that the cue had no influence on coherence thresholds for the control group, $F(1, 35) = .59$, $p = .45$, $p\eta^2 = .02$, but produced significantly lower thresholds in the group with dyslexia, $F(1, 35) = 17.86$, $p < .001$, $p\eta^2 = .34$. No significant group differences in coherence thresholds were found, $F(1, 35) = 2.95$, $p = .09$, $p\eta^2 = .08$.

7.4. Who has a motion deficit?

Deviance analysis was conducted on the coherence thresholds obtained for the no cue and the cue conditions, in which significant

group differences were found. Consistent with the findings of Experiment 1, a coherent motion deficit was found in each of the conditions in 38% (7) of the individuals with dyslexia. The influence of the cue on coherence thresholds in the low contrast signal condition was evaluated in the dyslexia subgroups with ($n = 7$) and without ($n = 11$) a motion deficit. The effect of the cue was obtained by subtracting coherence thresholds in the low contrast signal no cue condition from the low contrast signal with cue condition. A significantly greater change in coherence thresholds were found for the sub group with both dyslexia and a motion deficit ($M_{\text{change}} = 10.99\%$, $SD = 7.1\%$) than the sub group with no motion deficit ($M_{\text{change}} = 2.41\%$, $SD = 5.3$), $t(16) = 2.96$, $p = .009$, Cohen's $d = 1.42$. These results indicate that the cue produced a greater processing benefit for the group with dyslexia and a coherent motion deficit than individuals with dyslexia and no deficit.

8. Discussion

The results of Experiment 2 show that in the no cue conditions, the coherence thresholds found in both reader groups were lower in the high signal contrast condition than in the low signal contrast condition. These results are consistent with the findings of Experiment 1. They indicate that problems with noise exclusion are greater when the signal dots are of lower contrast than noise compared to when the signal dots are of higher contrast than the added noise dots.

The group with dyslexia had significantly higher coherence thresholds than the control group in each of the no cue conditions. These results are consistent with the low signal contrast condition in Experiment 1. These data indicate that the noise dots of higher contrast than the signal dots produced increased difficulties for the group with dyslexia. This conclusion is supported by the significantly greater processing disadvantage found for the group with dyslexia compared to the control group for the low, relative to the high contrast signal condition in both experiments.

No significant differences in coherence threshold were found for good and poor readers when the signal dots were all of a higher contrast than the noise dots in Experiment 1. However, the group with dyslexia continued to have significantly poorer coherence thresholds than the control group when the signal dots were of highest contrast in Experiment 2. In Experiment 1, the reduced perceptual difficulty of the high contrast signal condition produced coherent motion thresholds ranging from 1 to 4%, indicating that minimal integration of the signal dots was needed to accurately detect the global motion. The greater perceptual difficulty of the task used in Experiment 2 required integration of a higher proportion of signal dots to accurately detect the direction of global coherent motion. Using this method, the poorer coherent motion thresholds found in many studies for groups with dyslexia (Raymond & Sorensen, 1998; Talcott et al., 2000) were maintained. These results indicate that the group with dyslexia had little difficulty excluding noise when all or some noise dots were of lower contrast than the motion signals. However, this increased sensitivity did not extend to a stronger response to the attribute of motion that was also present in the higher contrast signal dots.

The cue directing attention to the high contrast signal with added low contrast noise had no influence on coherence thresholds in either group. These findings indicate two things. First, the cue might not have reduced coherence thresholds because its function was to aid the noise exclusion process. As the added noise was of lower contrast than the cued signals, the neural response of the visual system to the higher contrast signals (Edwards et al., 1996; Martinez-Trujillo & Treue, 2002; Tootell et al., 1988) might have made the cue redundant. In addition, the cue directed observers to the higher contrast stimuli, some of which contained the directional

motion signal and some of which were noise. Coherent motion thresholds may not have been influenced in either group because the cue directed attention to the high contrast stimuli (the black dots) rather than the directional motion signals.

A significant processing benefit was found for the group with dyslexia when the cue directed attention to the lower contrast motion signals. This might have occurred because the cue maximised the capacity of the group with dyslexia when excluding the higher contrast added noise. This effect was found specifically in the sub-group with dyslexia and a coherent motion deficit. Unexpectedly, the cue failed to produce a processing benefit in the control group. This may have occurred because stimulus driven factors allowed these readers to maximise sensitivity in all conditions. These issues will be addressed in Section 9.

9. General discussion

The results of these experiments showed that the contrast of the signal dots presented in an RDK can either increase (low contrast signal dots) or decrease (high contrast signal dots) motion coherence thresholds in good and poor readers. These effects were found regardless of whether the signal dots were uniquely defined by contrast and direction of motion (Experiment 1) or when noise of a higher or lower contrast was added to the RDK (Experiment 2). The magnitude of these effects was significantly greater in the group with dyslexia than in the control group when contrast alone was used to manipulate coherence thresholds. These effects were shown by the greater processing advantage found for the group with dyslexia when the signal dots were of a higher contrast than the noise dots and by the greater processing disadvantage found when the signal dots were of a lower contrast than the noise dots. In addition, the group with dyslexia could enhance coherent motion thresholds by using a cue to direct attention to signal dots of lower contrast than the added noise dots in the RDK. Three issues will be discussed. First, how contrast and the attention cue influenced noise exclusion will be described. Second, explanations of the greater effects of noise exclusion found in the group with dyslexia than the control group will be presented. Third, the implications of these findings for reading in the sub-group with dyslexia and a motion processing deficit will be addressed.

9.1. Noise exclusion, contrast and attention

The variable that was manipulated in both experiments conducted was contrast. At a sensory or bottom-up level, physiologically, presentation of higher contrast stimuli produces a stronger neural response than presentation of low contrast stimuli (Martinez-Trujillo & Treue, 2002; Tootell et al., 1988). In the current study, this increased response may explain the preferential processing of the higher contrast stimuli regardless of whether these were the signal or noise dots in the RDK. For the group with dyslexia an increased sensory response to the higher contrast stimuli, when these were the signal dots would aid noise exclusion. When these were the noise dots, the difficulties found with noise exclusion were exacerbated. The systematic effects of contrast found, supports the noise exclusion hypothesis of dyslexia. In the current experiments, the way that the impact of noise was either increased or decreased using contrast only, shows a systematic effect of the manipulations not shown in previous studies (Sperling et al., 2005, 2006).

Further evidence that noise exclusion represents a specific difficulty for the group with dyslexia was found in Experiment 2 when the cue directed attention to the low contrast signal dots, presented in high contrast noise. In this condition, improved coherence thresholds were found in the group with dyslexia, who were able to use cue driven or top-down attention to enhance their response

to the signal dots, aiding exclusion of the higher contrast noise. Supporting evidence for this conclusion is obtained from a physiological study that has shown an increased neural response to low contrast stimuli in an RDK when a cue was used to direct attention to these stimuli (Martinez-Trujillo & Treue, 2002). The use of the cue has been reported to increase the neural response to contrast, in the same way that this occurs when higher contrast stimuli are presented without a cue (Martinez-Trujillo & Treue, 2002). For the group with dyslexia, the increased response demonstrated behaviourally, reduced the impact of masking produced by the higher contrast noise dots. This process aided noise exclusion. In contrast to the findings for the group with dyslexia, the cue had no influence on coherence thresholds in the control group. This result might have occurred because this group had greater efficiency than the group with dyslexia when excluding the higher contrast noise. The 700 ms stimulus duration used may have enabled the control group to exclude the additional high contrast noise dots without the additional aid of the cue.

9.2. *Why did the contrast manipulation produce greater difficulty for the groups with dyslexia than the control groups?*

Greater internal noise in the visual system of some individuals with dyslexia¹ is one explanation of the greater impact found for the contrast manipulations used in the current study. The sensory processing deficit explanation of dyslexia has provided evidence that neurons in the M and dorsal stream are fewer in number, presented more sparsely and in a more disorganised manner than those found in normal readers (Galaburda & Livingstone, 1993; Stein & Walsh, 1997; Talcott et al., 2000). The poorer structural integrity of these components of the visual system in some individuals with dyslexia might produce higher internal noise. If internal noise is high, a stronger response at a neural level is required for the cell to register the presence of the stimulus. This occurs because the excitatory response must be greater, so more vigorous to overcome the higher level of internal noise (Edwards et al., 1996). The results of the mixed contrast conditions presented in Experiment 1 and the findings of Experiment 2 provide some support for this explanation. Specifically, lower coherence thresholds were found in the high signal contrast condition and higher coherence thresholds were found in the low signal contrast condition. However, if increased internal noise in the visual system of the group with dyslexia explained the current results we would have expected that this group would also have shown a processing advantage relative to the control group in the high contrast baseline condition of Experiment 1. The effect of baseline contrast was the same for the reader groups, suggesting that the level of internal noise was similar for good and poor readers. However, the relatively high contrasts used in both baseline conditions may have been sufficient to overcome this difficulty for both groups. Further research which specifically investigates the possible contribution of increased internal noise in individuals with dyslexia is needed to further investigate this explanation.

Reduced sensitivity to motion in the group with dyslexia is a second explanation of the effects found in the current experiments. In the manipulations conducted, it was contrast and not motion that was the major determinant of coherence thresholds. In the high signal contrast conditions, coherence thresholds were enhanced because these higher contrast noise dots had processing precedence, so 'grabbed attention' (Cropper, 2001). This process masked the lower contrast noise dots excluding them from processing. Coherence thresholds could have been obtained with little reference to motion per se. This conclusion is supported from the

findings from the high signal contrast no cue condition used in Experiment 2. Although the lower contrast added noise dots were excluded when the signal dots were of higher contrast, highest coherence thresholds were still found in the group with dyslexia. In this case, the increased perceptual difficulty of the coherent motion task occurred because there were high contrast signal and noise dots used in the RDK. The direction of coherent motion could not be determined predominantly on the basis of their higher contrast. In addition, the greater processing disadvantage found in the group with dyslexia than the control group when the signal dots were of lower contrast than the noise dots, suggests poorer capacity of individuals with dyslexia when processing motion. While these results are consistent with difficulties with noise exclusion (Sperling et al., 2005, 2006), a motion processing deficit was still present in the group with dyslexia.

Evidence from previous studies also supports the conclusion that the difficulties found with noise exclusion in the current study can be explained by reduced sensitivity to motion in the group with dyslexia. First, there is evidence of lower levels of neural activation in groups with dyslexia when performing speed discrimination and global motion tasks (Demb et al., 1998; Eden et al., 1996). These findings are consistent with a weaker neural response in some individuals with dyslexia when processing coherent motion. Second, groups with dyslexia have higher motion coherence thresholds, but not higher coherent form thresholds than control groups (Conlon et al., 2009; Hansen et al., 2001). If difficulties with noise exclusion explained the higher motion coherence thresholds alone, then this deficit would also be apparent when global form was extracted from noise.

When describing the contribution of difficulties that noise exclusion makes to motion coherence thresholds in groups with dyslexia, Sperling et al. (2006) argued that difficulties excluding noise, and problems integrating motion signals across successive frames in the RDK, and not a sensory processing deficit in the M or dorsal stream explained the higher coherence thresholds found. The evidence obtained in the current study together with findings that poorer coherent motion thresholds are found in groups with dyslexia when dot density is low (Slaghuis & Ryan, 1999; Talcott et al., 2000) but not high (Edwards et al., 2004; Hill & Raymond, 2002; Talcott et al., 2000) indicates that for individuals with dyslexia the sensory response to motion signals is poor, a finding consistent with sensory processing deficit explanations of dyslexia.

9.3. *Who has a motion deficit?*

In the current study, and consistent with previous findings (Conlon et al., 2009; Johnson et al., 2008; Ramus et al., 2003; Wright & Conlon, 2009) about 37% of the group with dyslexia were found to have a coherent motion processing deficit. In Experiment 1, a significantly greater processing benefit was found in the sub-group with dyslexia and a coherent motion deficit relative to other individuals with dyslexia. Similarly in Experiment 2, the significantly lower coherence thresholds specifically for the sub-group with dyslexia and a motion deficit when using the attention cue were found. These results add to the evidence that a coherent motion processing deficit found in adults with dyslexia is one component of the heterogeneous profile of these individuals. Previous studies have provided evidence that the group with dyslexia and a coherent motion deficit have poorer verbal short term memory and increased difficulties on more complex language processing tasks, such as spoonerisms and complex exception words than other individuals with dyslexia (Conlon et al., 2009; Johnson et al., 2008). In the current study, all individuals with dyslexia both with and without a coherent motion deficit had poor phonological and orthographic processing skills. These findings indicate that for adults with dyslexia and a coherent motion deficit, it may not be either

¹ The authors would like to acknowledge an anonymous review for the suggestion concerning greater internal noise in the visual system of the group with dyslexia.

phonological processing or orthographic processing alone that distinguishes these individuals from others with dyslexia. A chronic difficulty on all forms of word reading may explain these findings. One consequence of these findings for the sub-group with dyslexia and a motion deficit is that this group might have a specific difficulty when focussing a spotlight of attention on task relevant stimuli like the groupings of letters in individual words (Vidyasagar, 1999; Vidyasagar & Pammer, 2010). This may explain why a specific reader profile is not found for this group. Further research that attempts to focus the spotlight of attention in the sub-group with dyslexia and a coherent motion deficit is needed to determine if this low level sensory difficulty explains the reading difficulties found in this group of adults.

10. Conclusion

The findings of this study add to the body of research in this area, by showing that individuals with dyslexia and a coherent motion deficit, can use both high contrast and a feature based attention cue to aid exclusion of high contrast noise in an RDK. These results indicate that the noise exclusion deficit found in dyslexia may be a consequence of a sensory processing deficit in the M or dorsal streams of individuals with dyslexia. Future research should determine whether the advantages obtained using either a cue or higher contrast can improve the capacity of these individuals when reading words on a page of text.

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