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Visual processing and dyslexia

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Abstract. Magnocellular-pathway deficits have been hypothesised to be responsible for the problems experienced by dyslexic individuals in reading. However, research has yet to provide a detailed account of the consequences of these deficits or to identify the behavioural link between them and reading disabilities. The aim of the present study was to determine the potential consequences of the magnocellular-pathway deficits for dyslexics in a comprehensive range of visual tasks. Dyslexics and nondyslexics were compared on their ability to (i) perform vernier-acuity and orientation-acuity tasks; (ii) perceive motion by using a range of measures common in the psychophysical literature (D_{min}, D_{max}, and global coherence); and (iii) perceive shapes presented in random-dot stereograms at a range of disparity pedestals, thereby dissociating stereopsis from vergence control. The results indicated no significant differences in performance between the dyslexic and nondyslexic subjects in terms of the visual-acuity measures. In general, dyslexics performed relatively poorly on measures of motion perception and stereopsis, although when considered individually some of the dyslexics performed better than some of the controls. The poor performance of the dyslexics in the stereogram tasks was attributable to a subgroup of dyslexics who also appeared to have severe difficulty with the motion-coherence task. These data are consistent with previous evidence that some dyslexics may have deficits within the magnocellular visual pathway.

1 Introduction

The term dyslexia has been used mainly to refer to a constellation of disabilities based around difficulties in learning to read, problems with spelling, and a general slowness in processing symbolic information (see Critchley 1970; Miles 1993; Snowling 1987; Thomson 1990). The disability has often been attributed to problems related to processing sound forms (the phonological-deficit hypothesis; eg Stanovich 1988), although further problems experienced by dyslexics also indicate difficulties in perceptual processes, motor coordination, attention, and memory. These latter deficits can be demonstrated, moreover, in experimental paradigms which do not require phonological processing, and have been used by some theorists (eg Nicolson and Fawcett 1995; see also Willows et al 1993) to argue against the phonological-deficit viewpoint as the sole cause of dyslexia. Consequently, further causal explanations, including visual-based theories, have been sought.

In those visual theories which have received most research attention it has been proposed that dyslexia may be the consequence of an anatomical abnormality in the retinocortical neural pathway of the visual system. This pathway is typically divided into two streams, the parvocellular and magnocellular systems, which in turn have been proposed to be differentially sensitive to different types of visual stimuli. The parvocellular pathway responds best to slowly changing (low-temporal-frequency) information, to more detailed stimuli (ie higher spatial frequencies), and to colour, whereas the magnocellular system is more sensitive to gross (lower-spatial-frequency), moving, or flickering (high-temporal-frequency) information.

Research has documented the dyslexic individual's poor performance on tasks which are considered to assess the functioning of the magnocellular pathway (see recent reviews in Chase 1996; Hogben 1997; Lovegrove 1996), suggesting that dyslexia is related to a deficit (dysfunctioning) in this pathway. Such conclusions have been given added credence by postmortems (Livingstone et al 1991) which have revealed abnormal cell size and organisation in magnocellular layers of the visual system of individuals with documented reading disabilities, and behavioural and fMRI studies of the dyslexic's ability to process moving stimuli (Cornelissen et al 1995; Eden et al 1996). In these latter studies it was suggested that dyslexic individuals have poor motion perception relative to controls, which may be related to reduced activity in cortical areas linked to the processing of retinal motion (see Eden et al 1996). This putative relationship between dyslexia and motion processing was investigated further in the present study by comparing the performance of dyslexic subjects with a group of nondyslexic controls on three aspects of motion processing: $D_{\min}$, $D_{\max}$, and the perception of global (coherent) motion in random-dot kinematograms (RDKs).

Many cells in the dorsal visual pathway (MT and MST) which are involved in the perception of coherent motion are also tuned for binocular disparity (Bradley et al 1995; Maunsell and van Essen 1983; Qian and Andersen 1994). In light of this, the ability of dyslexics to perceive a shape defined by binocular disparity was also determined. The shape was defined by a disparity of 2 min of arc and so was well within typical estimates of Panum's fusional area (see Howard and Rogers 1995) and so should be resolved without difficulty given normal stereopsis and small fixation errors. This stimulus was also presented on a series of disparity pedestals which ranged from 0 to ±64 min of arc, which was well outside fusional limits. To perceive the shape successfully when presented on a large pedestal, a subject is obliged to make vergence movements (of various magnitudes and directions) to bring the pattern of disparities within fusional limits. This manipulation is of interest because a failure to adequately control binocular vergence movements while scanning text may explain the descriptions often given by dyslexics of letters appearing jumbled or moving over each other (Stein 1993). If dyslexics only experience difficulty with stereograms containing large disparity pedestals, then this suggests that stereopsis may be normal although vergence control (in response to disparity) is lacking (Mowforth et al 1981; Saye and Frisby 1975). Interestingly, the control of vergence eye movements has been linked to areas in the posterior parietal cortex which receive projections from the magnocellular pathway via the dorsal stream (Stein and Walsh 1997). This may provide a potential theoretical bridge between the observed deficits in the visual function associated with the magnocellular pathway and dorsal stream and the behavioural consequences of dyslexia (poor reading).

A final purpose of the present study was to combine the data from motion and stereo tests with further tests of visual function to provide a comprehensive account of visual processing and dyslexia. Therefore, in addition to the motion-processing and disparity-processing tasks, dyslexic and control observers completed vernier-acuity and orientation-acuity tasks. This battery of psychophysical tasks (motion perception, stereo processing, and vernier and orientation acuity) allowed us to determine whether the dyslexic subjects (or a subset of these individuals) exhibited specific deficits in their visual perception that might be related to impaired magnocellular functioning as opposed to some generalised visual problem.

2 Method

2.1 *Subjects*

Sixteen dyslexic subjects were recruited for the study from university or local-community populations; they were paid for participation. All had received a recent diagnosis of dyslexia, with student dyslexics receiving exam and study support provisions. Additional assessment of the dyslexic subjects (administered on a separate occasion from the visual tasks reported below) indicated typical problems with reading, spelling, and nonword naming,(1) but average, or greater than average, scores on the similarities and block-design subscales of the Wechler Adult Intelligence Scale (any subject scoring below 8 on either scale was excluded from the study).

Sixteen control subjects were also tested on the same tasks as the dyslexics. Control subjects comprised an opportunity sample, and covered the same age range and sex ratio as the dyslexics (age range: 18 to 36 years for dyslexics, 18 to 30 years for controls; male to female sex ratio: 10 to 6 for dyslexics, 10 to 6 for controls).

Prior to the psychophysical tasks, all subjects were screened for severe visual impairments, by means of the Cambridge low-contrast gratings (Wilkins et al 1988), a Landolt-C acuity task, and the 6-mm plate of the Frisby stereo test. All subjects showed normal visual acuity and contrast sensitivity for each eye, and passed the Frisby test.

2.2 *Apparatus*

Stimuli were presented on two Apple 12-inch monochrome monitors, driven by a Macintosh 7500 computer and arranged in a standard Wheatstone stereoscope configuration. The monitors were viewed through two first-surface mirrors set at ±45° to the median plane. The viewing distance was 114 cm, at which each pixel subtended 1 min of arc. The viewing geometry was such that, when fixated, the vergence angle was appropriate and correct for the viewing distance. The luminance range of the monitor was carefully linearised by taking luminance measurements with a photometer and forming a suitable lookup table. For the vernier-acuity, orientation-acuity, and motion tasks, stimulus elements were positioned with subpixel accuracy by using antialiasing techniques.

2.3 *Tasks*

2.3.1 *Vernier acuity.* Each stimulus comprised two vertical lines, each 33 min of arc in length, with a vertical separation of 2 min of arc. The luminance profile of the lines was a Gaussian with a standard deviation of 2.5 min of arc. Between trials, the lower line was shifted horizontally with respect to the upper reference line. The horizontal displacement of the lower line was varied, with the subjects being required, on an auditory signal, to indicate whether it appeared to the left or right of the reference line. A staircase procedure was used to determine the 79% threshold for subjects to determine the direction of displacement of the lower line.

2.3.2 *Orientation acuity.* Each stimulus consisted of three parallel lines, 2.67 deg in length and separated by 20 min of arc. The lines were presented with an orientation close to, but rotated from, vertical. The subjects' task was to determine whether the lines were shifted clockwise or anticlockwise. Again, an auditory signal indicated when a response was expected, and a staircase procedure was used to determine the 79%-correct threshold for the discrimination of the orientation of the lines.

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(1) The reading comprehension measure was based upon the GAPADOL reading test (McLeod and Anderson 1973), and involved a cloze procedure in which passages were presented with thirty-two words removed and subjects were required to add the missing words. Dyslexics scored on average one standard deviation below controls, though some dyslexic individuals scored within the range of the controls.

In the spelling task, subjects were informed that their spelling would be assessed and were required to write down verbally presented words drawn from the Si. Graded Word Spelling Test of the Schonell Diagnostic and Attainment Test (Schonell and Schonell 1952) and Klein's (1993) advanced spelling list. The average score of the dyslexic subjects was more than two standard deviations below that of the controls.

The nonword naming task comprised four nonwords (WIRT, BLEME, BAKNOW, and GRUSSAR), each repeated six times on a single piece of card. Subjects were required to name as quickly as possible all the letter strings. Dyslexic subjects required, on average, one standard deviation longer than controls to name the complete list. These features (very poor spelling, less able reading, and slower nonword naming, compared with controls) are consistent with other findings in the literature (eg Everatt 1997). During interviews, dyslexic subjects also indicated characteristic problems with acquiring reading/writing skills in childhood.

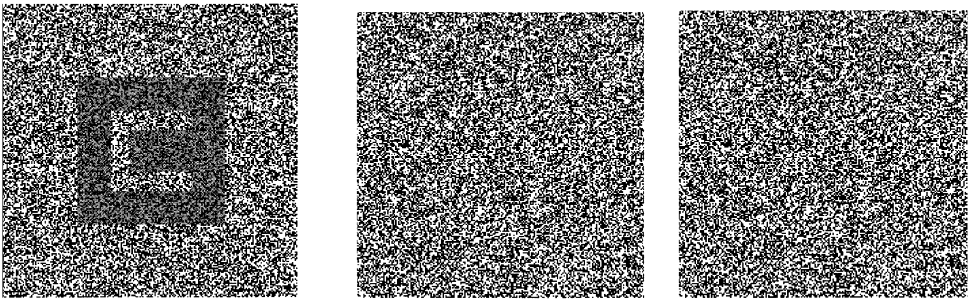
2.3.3 D_{min}. A staircase procedure was used to determine the smallest displacement of a two-frame RDK for which the direction of displacement could be successfully discriminated. Each frame of the RDK contained dots with a density of 12.5 dots deg^{-1}, contained in a 4-deg square window. Frames were presented for 150 ms, with no interframe interval. Dots were formed from Gaussian blobs with a standard deviation of 2.5 min of arc and a maximum luminance of 71.0 cd m^{-2}. Dots which fell outside the square window after displacement between frames were wrapped around to the opposite side of the stimulus.

RDKs were presented in which all dots moved either to the left or to the right between frames. The subjects' task was to determine the direction of motion of the dots. The procedure was started with a displacement of the dots between frames of 8 min of arc, at which the direction of displacement was clearly discernible. The displacement was decreased by 20% after three successive correct responses, and after one incorrect response it was increased. The experiment ended after ten reversals. The mean of the last six reversal points was taken as the 79%-correct point.

2.3.4 D_{max}. A staircase procedure was also used to determine the largest displacement of a two-frame RDK for which the direction of displacement could be successfully discriminated. RDKs were identical to those presented in the assessment of D_{min}, and the procedure was again started with an interframe displacement of the dots of 8 min of arc. The displacement was then increased by 20% after three successive correct responses, and decreased by 20% after one incorrect response. The experiment ended after ten reversals, and the 79%-correct point was taken as the mean of the last six reversal points.

2.3.5 *Motion coherence.* Subjects were presented with RDKs in which a subset of dots (the signal dots) was moved 10 min of arc in the same horizontal direction between frames, while the remaining dots (the noise dots) were randomly replaced between frames. RDKs consisted of eight frames, each presented for 15 ms with no interframe interval. When the number of signal dots relative to the number of noise dots (the coherence of the stimulus) is high, subjects can readily perceive the direction of motion of the signal dots in these stimuli. As the coherence is reduced, subjects are no longer able to determine the direction of motion of the signal dots, and performance therefore falls to chance levels. A staircase procedure similar to the one described above was used to determine the minimum coherence at which the direction of motion could reliably be discriminated. The procedure was started with a coherence of 90%. After three successive correct responses, the coherence was reduced by 20% of its value, and after one incorrect response it was increased by 20%. Again, the procedure terminated after ten reversals, and the mean of the last six reversal points was taken as the 79%-correct point.

2.3.6 *Random-dot stereograms.* Each stereogram consisted of a square (side length 7.3 deg) of random dots presented against a black background. Each dot was formed from a 2×2 square of pixels, with each stereogram being formed from black and white dots with a 50% density. A disparity-defined shape (a rounded square with a gap on its right or left; see figure 1) was presented within a central square region (with sides 3.7 deg). The shape was defined by a disparity of $+2$ min of arc and so stood proud of the central square. The central square was displayed on disparity pedestals of ± 2, ± 4, ± 8, ± 16, ± 32, or ± 64 min of arc, so as to appear either in front of or behind the surrounding dots. Note that the disparity between the shape and its immediate background (the central square) was a constant 2 min of arc throughout the experiment regardless of disparity pedestal. Prior to presentation of each stereogram, a small central cross was presented which the subjects were told to fixate. When the cross was fused, vergence was appropriate for the 114 cm viewing distance.



(a) (b)

Figure 1. Examples of the stimuli presented in the stereogram task. (a) The training stimulus used to explain the task to subjects. The subjects' task was to decide whether the gap in the central shape appeared on the right (as in this example) or on the left. (b) An example stereogram, intended for cross-eyed fusion. Here, the shape appears on a pedestal with crossed disparity, lying in front of the surround. In all the stereograms, the shape appeared 2 min of arc proud of the pedestal, regardless of the disparity of the pedestal.

To ensure that subjects perceived the disparity-defined shape, they were required to make a forced-choice discrimination: whether the gap was to the right or left of centre. A push-button keypad was provided for responses, allowing responses and latencies to be recorded. Although subjects were required to respond as quickly as possible, they were also told not to guess. To allow time for the target to be fully resolved, a time limit of 45 s was set, after which the stereogram disappeared and the trial was recorded as a failure to perceive the shape.

The task was explained to each subject by using the actual experimental apparatus, to allow the subject to be become accustomed to the procedures/equipment, and a series of random-dot images containing a shape with gaps on the right or left (as in the stereogram task) defined by luminance rather than disparity (see Bradshaw et al 1995). An example of the stimuli used in the training phase is given in figure 1a and an experimental stimulus is given in figure 1b; the latter is intended for cross-eyed fusion.

3 Results

The data were initially analysed by task, with later analyses considering relationships between tasks.

3.1 *Vernier and orientation acuity*

Comparisons of the dyslexics' and nondyslexics' performance on the vernier-acuity and orientation-acuity tasks indicated little evidence for acuity deficits within the dyslexics (see table 1, and figures 2 and 3). Note that, although means and standard deviations are presented in table 1, owing to the nonnormal distribution of the data, more conservative nonparametric statistical techniques were utilised to compare the performance of dyslexics and nondyslexics (parametric analyses produced identical results). Mann–Whitney *U*-tests indicated no evidence for a difference in visual acuity between the groups ($p > 0.5$ in both cases).

Table 1. Mean performance (with SDs in parentheses) of the dyslexic and nondyslexic subjects on measures of acuity (vernier acuity and orientation), and motion processing ($D_{\min}$, $D_{\max}$, and coherence).

	Acuity/min of arc	Orientation/°	$D_{\min}$/min of arc	$D_{\max}$/min of arc	Coherence/%
Control	0.55	1.21	3.97	30.99	11.38
	(0.30)	(0.72)	(9.22)	(9.40)	(6.85)
Dyslexic	0.54	1.14	8.46	22.11	26.50
	(0.18)	(0.72)	(9.53)	(11.11)	(18.05)

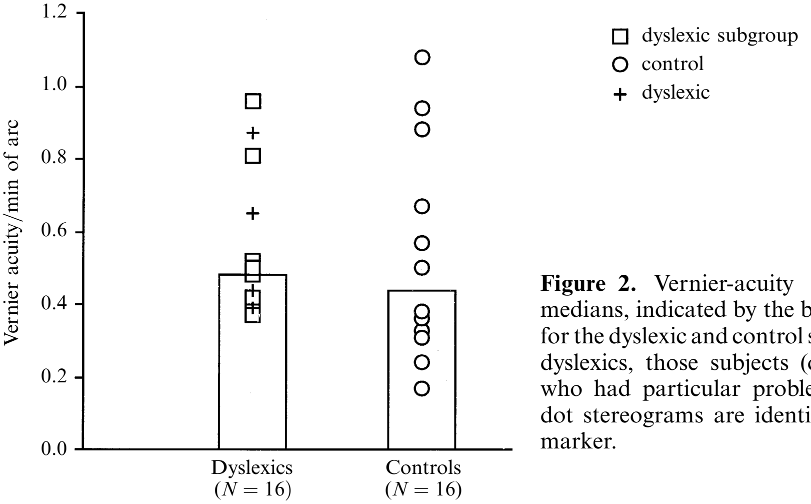


Figure 2. Vernier-acuity scores (including medians, indicated by the block) in min of arc for the dyslexic and control subjects. Within the dyslexics, those subjects (dyslexic subgroup) who had particular problems with random-dot stereograms are identified by a separate marker.

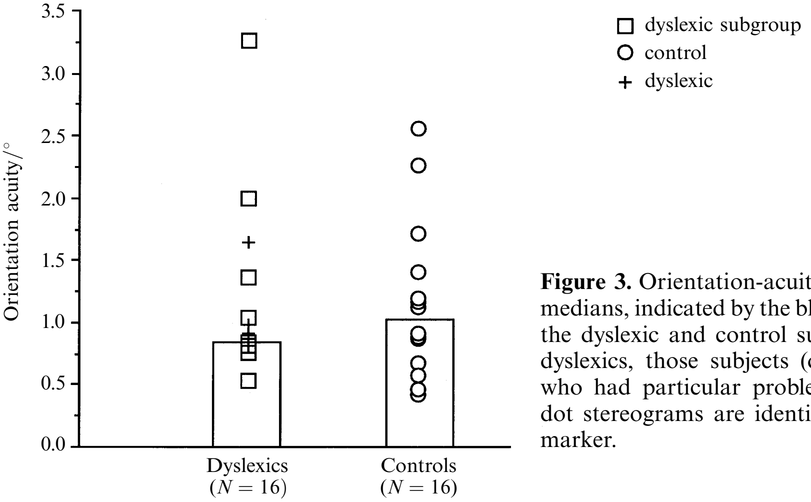


Figure 3. Orientation-acuity scores (including medians, indicated by the block) in degrees for the dyslexic and control subjects. Within the dyslexics, those subjects (dyslexic subgroup) who had particular problems with random-dot stereograms are identified by a separate marker.

3.2 *Motion perception*

Measures of D_{min}, D_{max}, and coherence threshold are also presented in table 1, and in figures 4 to 6. Time constraints meant that we were unable to obtain coherence thresholds for two of the dyslexic subjects. Mann–Whitney U-tests indicated that dyslexics and nondyslexics differed in measures of D_{min} ($U = 51$, $p < 0.01$), D_{max} ($U = 70$, $p < 0.05$), and coherence threshold ($U = 49$, $p < 0.01$). In all cases, the dyslexics' performance was worse than that of the nondyslexics, though inspection of figures 4 to 6 indicates that the distributions overlapped and that not all dyslexics performed worse than the controls.

3.3 *Random-dot stereograms*

Data were inspected to determine whether subjects failed to perceive the cyclopean images at each disparity. Failure to see the images was defined as (i) a nonresponse at a particular disparity before the 45-s time limit, or (ii) if responses were made, correct responses were at no better than chance level. Under these criteria, four dyslexic subjects (referred to as a dyslexic subgroup in subsequent discussions) failed the task at all disparities, whereas none of the nondyslexics showed similar problems (see table 2), though a number of subjects failed at the larger disparities. Response times for each disparity were determined from the remaining data. To avoid the influence of abnormally

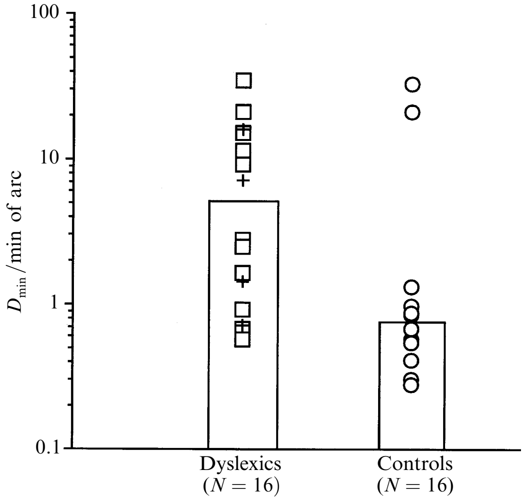


Figure 4. D_{min} scores (including medians, indicated by the block) in min of arc for the dyslexic and control subjects. Within the dyslexics, those subjects (dyslexic subgroup) who had particular problems with random-dot stereograms are identified by a separate marker.

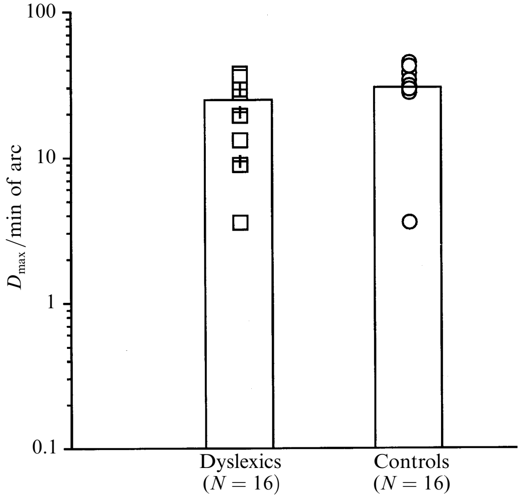


Figure 5. D_{max} scores (including medians, indicated by the block) in min of arc for the dyslexic and control subjects. Within the dyslexics, those subjects (dyslexic subgroup) who had particular problems with random-dot stereograms are identified by a separate marker.

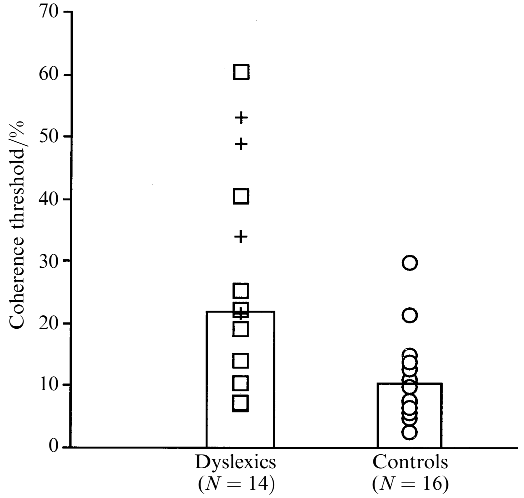


Figure 6. Coherence-threshold scores (including medians, indicated by the block) in percentages for the dyslexic and control subjects. Within the dyslexics, those subjects (dyslexic subgroup) who had particular problems with random-dot stereograms are identified by a separate marker.

Table 2. Mean times (with SDs in parentheses) of the dyslexic and nondyslexic subjects to perceive the random-dot stereograms at the various disparities. Figures in italics indicate the number of subjects (dyslexic and nondyslexic) who failed to perceive the hidden figure at a particular disparity. (Four dyslexic subjects failed at each disparity.)

	Disparity/min of arc					
	2	4	8	16	32	64
Crossed disparity						
Dyslexics	1.38	1.99	2.10	1.66	2.32	7.39
	(1.42)	(2.47)	(2.85)	(1.48)	(2.33)	(9.01)
	4	*4*	*4*	*4*	*4*	*5*
Controls	1.94	1.80	2.22	2.18	2.75	4.99
	(1.27)	(1.13)	(1.72)	(2.06)	(2.11)	(5.21)
	0	*0*	*0*	*0*	*0*	*2*
Uncrossed disparity						
Dyslexics	1.74	1.61	1.57	1.64	3.23	4.40
	(2.39)	(2.04)	(1.44)	(1.15)	(1.99)	(2.26)
	4	*4*	*4*	*4*	*5*	*10*
Controls	3.09	2.30	3.59	2.53	5.59	8.40
	(3.54)	(2.21)	(3.69)	(2.11)	(5.37)	(6.59)
	0	*0*	*0*	*1*	*2*	*4*

long response times, median response times were calculated for each subject at each disparity and used in the subsequent analyses. Table 2 also presents average response times (with standard deviations) of the dyslexic and nondyslexic groups.

3.4 *Comparisons across tasks*

Comparisons were performed to assess whether those individuals who failed the stereogram task also presented evidence of poor motion perception and/or poor acuity. Table 3 presents the data of the dyslexic group divided between the four subjects who failed to see the cyclopean images and the remaining twelve subjects. Although statistical comparisons with only four subjects are inappropriate, the data indicate that those dyslexics experiencing problems within the stereogram task show little evidence of general visual-acuity deficits, but experience particular problems within the coherence measure—their thresholds being, on average, twice as large as the remaining dyslexics and four times as large as the controls.

Table 3. Mean performance (with SDs in parentheses) on measures of acuity (vernier acuity and orientation) and motion processing (D_{min}, D_{max}, and coherence) of the dyslexic subjects who could or could not see the cyclopean images. Dyslexic subjects who consistently failed in the random-dot-stereogram tasks are designated by 'subgroup'. The data from the control subjects are also presented for ease of comparison.

	Acuity/ min of arc	Orientation/°	D_{min} / min of arc	D_{max} / min of arc	Coherence/%
Dyslexic main group	0.52	1.15	9.18	22.04	21.33
($N = 12$)	(0.18)	(0.76)	(10.40)	(11.97)	(17.27)
Dyslexic subgroup	0.59	1.09	6.32	22.31	39.33
($N = 4$)	(0.22)	(0.37)	(7.00)	(9.57)	(14.23)
Controls	0.55	1.21	3.97	30.99	11.38
($N = 16$)	(0.30)	(0.72)	(9.22)	(9.40)	(6.85)

4 Discussion

The series of experiments reported here were designed to compare the ability of dyslexics and controls in acuity, motion, and disparity/vergence tasks. The results indicate (i) little difference between the groups in terms of the acuity measures used, (ii) worse performance by the dyslexics on all measures of motion perception, (iii) some evidence of problems within a subgroup of dyslexics on the stereogram task, regardless of disparity, (iv) little consistent evidence of deficits in the stereogram tasks being confined to large disparities, and (v) that the dyslexic subgroup's difficulties with stereopsis are associated with particular problems on the motion-coherence task. These findings further substantiate the view that within the dyslexic population there are at least some dyslexics whose profile on visual tasks is consistent with a specific deficit within the magnocellular pathway. We will discuss each of these points in the following paragraphs.

The initial factor to note from the data is that the deficits exhibited by the dyslexic subjects were not simply related to poor visual acuity or the psychophysical methodology involved. All subjects were prescreened for severe visual impairment; all participants showing normal performance. Moreover, no differences were found between the dyslexic and control groups in terms of vernier or orientation acuity (thresholds were determined by using similar psychophysical techniques). The differences discussed below are related specifically to performance in the motion and stereopsis tasks.

On all three measures of motion discrimination, the performance of the dyslexic subjects was worse than that of the control group. These results are consistent with those of previous studies (eg Cornelissen et al 1995; Dougherty et al 1997; Eden et al 1996; Felmingham and Jakobson 1995). Felmingham and Jakobson (1995) found that the poor performance of dyslexic boys aged 9 to 12 years when required to detect movement-defined letters was related to poor flicker-contrast sensitivity at high temporal frequencies. In this same study dyslexics and controls were assessed on measures of stereoacuity (random-dot stereograms and the Frisby test), with both measures showing a larger degree of variability within the dyslexic group. Consistent with increased variability in dyslexic groups, the data reported in the present paper present evidence for a subgroup of dyslexics to show poor performance in stereogram tasks. Dougherty et al (1997) also studied motion perception in a group of dyslexic children aged between 10 and 12 years. They found that while the dyslexics showed impaired performance on motion-coherence tasks, they showed better performance than the control group on both $D_{\max}$ and $D_{\min}$. This latter (rather surprising) finding was not replicated with the adult sample used here, though the subgroup of dyslexics showing problems on the stereogram task were particularly poor on the motion-coherence task; the thresholds for this subgroup being double those of the other dyslexics, and four times those of the control group (we will return to this point at the end of the discussion).

The results of the binocular-disparity task suggest that the dyslexics form a heterogeneous group. On the basis of the latency data, the dyslexics did not appear to differ from the controls, whereas the failure rate suggests a subgroup of dyslexics may exist who have difficulty in perceiving stimuli defined by binocular disparity. The reason for this high failure rate has yet to be determined, particularly given that the four dyslexic individuals forming this potential subgroup within the present group of subjects showed normal performance on the Frisby stereo test. Previous researchers have similarly described a subgroup of dyslexic individuals with visual problems. A number of researchers have argued that there are at least two recognisable subgroups of reading-disabled individuals; those who show difficulties when processing phonological information and others who present visuospatial deficits (eg Boder 1971; Satz and Morris 1981; Watson et al 1983). Whether the subgroup identified in the present study is the same as that identified by these other researchers will require further investigation, but the proportion of dyslexics presenting problems in the stereogram task is similar to those showing visuospatial deficits (approx 20%). In a further series of studies in which a visual-based deficit within dyslexics is argued for, it is suggested that an oversensitivity to certain light wavelengths (sometimes referred to as scotopic-sensitivity syndrome; Irlen 1991) is the basis of the dyslexic's problems with reading. Such oversensitivity may also be related to the evidence presented for the benefits of wearing coloured filters or lenses when reading (Wilkins et al 1994). Interestingly, Irlen (1991) argues that not all reading-disabled individuals will present the symptoms of scotopic-sensitivity syndrome, one of which is poor performance in tasks requiring the processing of depth information (Cotton and Evans 1990).

The subgroup identified in the present paper failed at each pedestal disparity, indicating that the deficit was manifest irrespective of vergence demand. However, given that the exact nature of the eye movements involved in perceiving random-dot stereograms remains unknown (but see Mowforth et al 1981; Rogers and Bradshaw 1996) we cannot comment further on their role in this aspect of the present study; although it remains possible that they contributed to the effect. With regard to the claim that dyslexics have poor eye-movement control (Stein 1993), the data were equivocal. Although it appears that the dyslexics had particular difficulty with the condition with 64 min of arc uncrossed disparity, the ten dyslexics who failed here included the four who failed at all disparity pedestals. Moreover, the dyslexics who did perceive the shape at the largest uncrossed disparity took less time than the controls. These data therefore provide no evidence to support the view that dyslexics have *specific* problems with vergence movements—at least those required for this task. Indeed Cornelissen et al (1993) argue that poor vergence control is not responsible for the reading problems experienced by dyslexic subjects, the magnitude of vergence errors made by their dyslexic subjects being no different from those produced by controls. Although it is possible that some reading problems are produced by poor vergence control, the findings of the present study and that of Cornelissen et al (1993) suggest that they are not widespread throughout the dyslexic population.

Associations between performance on the motion and stereogram tasks suggest some common underlying processing problems in the dyslexic group that are not the result of impoverished visual acuity. The differences in motion-coherence thresholds are consistent with the notion that dyslexia is related to deficits in processing in the dorsal pathway. It is likely that the problems faced by the dyslexic subgroup in perceiving depth in random-dot stereograms may be explained in the same manner. Many cells identified in the dorsal stream (MT and MST) which are involved in the perception of motion are also tuned for binocular disparity (eg Bradley et al 1995; Maunsell and van Essen 1983). Interestingly, MT has been particularly associated with the perception of global motion (Hibbard et al 1999; Newsome and Paré 1988), the only motion task where the dyslexic subgroup experienced particular difficulties. MT has also been associated with the perception of depth in global stereopsis (Cumming and Parker 1997; DeAngelis et al 1998). Such views, and the data presented, provide plausible associations between deficits in functions of the dorsal pathway (such as the perception of motion) and binocular processing consistent with a common underlying dysfunction. How this dysfunction leads to reading difficulties is as yet unknown; however, there are several possibilities. Although the present study, and that of Cornelissen et al (1993), suggests that poor vergence control is not the link between visual dysfunction and behavioural outcome, it is still possible that this may interact with unstable ocular control leading to increased confusability between letters. Alternatively, rapidly processed, course-detailed information of the type provided by the magnocellular pathway may be vital for the accurate encoding of a written discourse (Chase 1996), perhaps helping to guide the eyes to salient text locations (Everatt et al 1998). Another alternative is that suppression between magnocellular and parvocellular pathways may be deficient in some way, leading to interference between information across fixations (see Breitmeyer 1993; Burr et al 1994). Further research into the association between deficits in functions of the dorsal pathway and binocular processing may improve our understanding of the underlying visual deficits suffered by dyslexics and identify the behavioural link between these visual deficits and the dyslexic's reading disabilities.

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