

Visual Motion Perception in Children with Dyslexia: Normal Detection but Abnormal Integration

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Studies of the visual system of dyslexics have provided some evidence to suggest that a magno pathway abnormality may be associated with this disorder. Since the magno pathway and its cortical targets are critical for visual motion perception, we investigated motion sensitivity in a group of dyslexic children. We observed significant deficits on a random dot motion coherence test among ten 10-year old dyslexic children compared to age-matched normal readers. Motion sensitivity losses were still evident when measured 1 year later. In a second experiment, we manipulated the number of frames making up the apparent motion stimuli. We observed that whereas children with dyslexia could perform normally with very brief two-frame apparent motion stimuli, indicating motion detection, their rate of improvement with more frames in the stimulus was significantly worse than controls. Our results data suggest that dyslexic children have poor perceptual integration, rather than poor low-level motion detection.

INTRODUCTION

There is considerable evidence to suggest that children with developmental dyslexia, or reading disability, may suffer from a generalised temporal processing deficit; that is, abnormal set of brain mechanisms that operate to link and segment sequentially presented stimuli (see Farmer & Klein, 1995, for a recent review). Within this visual domain, a key consequence of normal temporal

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processing is the perception of motion. In this study, we investigated losses in motion perception among dyslexics to determine whether such deficits reflect low-level sensitivity losses or higher-order problems related to integration of stimulus elements.

Low-level visual processing has been dichotomized as parvo or magno, referring to two functional streams carrying the bulk of information from the retina to the lateral geniculate nucleus (LGN) and on to the primary visual cortex (V1). Recently, studies investigating low-level visual deficits in dyslexia have suggested that the magno pathway may be abnormal, whereas the parvo pathway appears intact. In a neuroanatomical study, Livingstone, Rosen, Drislane and Galaburda (1991) reported pathology of magnocellular, but not parvocellular, layers of the LGN of adults who had had dyslexia. Additional evidence suggesting a magno-specific deficit comes from visual evoked potential (Lehmkuhle, et al., 1993; Livingstone et al., 1991) and psychophysical contrast detection (Lovegrove et al., 1982; Martin & Lovegrove, 1987) studies using grating pattern stimuli manipulated in contrast and spatio-temporal frequency to preferentially activate either the magno or the parvo system. These studies reported normal responses to visual patterns optimal for stimulating the parvo system and abnormal responses for stimuli optimal for the magno system. If, as these studies suggest, specific aspects of early vision are abnormal in dyslexia, then the obvious implication is that processing at the extrastriate cortical sites receiving this information must also be abnormal.

Visual information leaving V1 reaches higher cortical areas via two routes—the dorsal and ventral extrastriate pathways. The ventral pathway projects to the inferior temporal lobe and receives both parvo and magno inputs, whereas the dorsal stream projects to the posterior parietal cortex and receives almost exclusively magno input (Merigan & Maunsell, 1993). The dorsal system is thought to process information about motion, the spatial location of objects, the spatial allocation of attention, and other aspects of visually guided orientation, especially those related to manual and oculomotor responses (Goodale, 1993; Merigan & Maunsell, 1993). The ventral system is thought to function primarily in object recognition and selection. Since the magno pathway provides the primary input to the dorsal extrastriate pathway, abnormal magno function in children with dyslexia implies abnormal functioning of the dorsal extrastriate system. Evidence to support this comes from a recent fMRI study of dyslexic men viewing moving stimuli (Eden, et al., 1996). Whereas brain activity in V1 appeared normal, activity for the motion-sensitive areas of the dorsal pathway (i.e. V5) was reduced or absent in the dyslexics. To probe the perceptual consequences of potential abnormal dorsal function, we investigated visual responses of dyslexic children to complex moving stimuli.

We chose a motion perception task that appears to depend on the integrity of specific areas of the dorsal pathway (Newsome & Paré, 1988; Newsome, Britten, & Movshon, 1989) and seems unaffected by ventral pathway disrup-

tions (Beckers & Homberg, 1992; Zeki, 1991). In this task, observers judge the global direction of motion in a brief "movie" of a dot texture (referred to hereafter as a random dot kinematogram or RDK) in which a variable percentage of (signal) dots move in a single coherent direction, while the remaining (noise) dots are moved in random directions. With repeated trials, a motion coherence threshold can be derived. It is defined here as the percentage of signal dots necessary for correct direction judgement on 71% of trials. Depending on a number of stimulus variables, thresholds range between 5 and 25% coherence in normal naive adults (e.g. Raymond, 1994).

The motion coherence threshold (i.e. the ability to derive a global direction percept with only a small percentage of signal dots) depends not only on the efficient integration of *spatially* distributed local motion events (individual signal dot displacements), but also on *temporal* integration of these events across successive frames, (i.e. the "stills" making up the RDK "movie") (Snowden & Braddick, 1989). In multiple-frame RDKs, as opposed to simple two-frame RDKs, there is an extended opportunity for the perceptual mechanisms to detect and integrate information about local motion. These opportunities are probably actively exploited by cooperative neural networks among direction analysers (Braddick, 1993; Snowden, 1989) producing sequential recruitment effects. Sequential recruitment effects in motion perception are the dramatic improvement in measures of motion perception observed with an increase in the number of frames (independently of total duration) in apparent motion sequences (e.g. McKee & Welch, 1985; Snowden & Braddick, 1989). The neural mechanisms mediating these effects are not understood. However, there is evidence that such effects reflect activation of extrastriate visual motion areas of the brain. In monkeys, visual cells of area MT (the homologue of V5 in humans) are unlike V1 cells in that they are unresponsive to two-frame RDK stimuli, yet show robust directional responses to multiple-frame RDKs (Mikami, Newsome, & Wurtz, 1986). The question addressed here is whether sequential recruitment effects are abnormal in dyslexia.

In our first experiment, we used multiple-frame RDKs and observed elevated motion coherence thresholds in 10-year-old dyslexic children compared to age-matched normal readers.¹ Our findings of a motion perception deficit is consistent with a similar study on dyslexic children by Cornelissen et al. (1995) and with a velocity judgement on dyslexic men by Eden et al. (1996). However, both Cornelissen et al. (1995) and Eden et al. (1996) used long duration stimuli that would have elicited smooth pursuit eye movements. Since such eye movements have been reported to be abnormal in dyslexics (Bogacz, Mendilaharsu, & De Mendilaharsu, 1974), their results may reflect poor oculomotor

¹These results were originally reported at the annual meeting of the Canadian Society for Brain, Behaviour and Cognitive Science, Vancouver, 1994.

control rather than abnormal perception. Although the results of our first study cannot be attributed to abnormal eye movements because our stimuli were only 60 msec in duration, the multiple-frame RDKs we (and the other two studies) used would have allowed cooperative processes in the motion networks to become operative. Thus, deficits could have resulted from abnormal integration of motion events over space and time, or from abnormally low motion sensitivity to local events. In our second experiment, we limited the opportunity for cooperative processes to become engaged (and for eye movement to be elicited) by using brief two-frame RDKs and found that motion sensitivity was comparable to that of normally reading children.

EXPERIMENT 1A

Methods

Participants. Five girls and five boys with dyslexia (mean age = 9.9 years) were recruited from a private school for learning disabilities. These children were reading at least 1.5 years below the expected performance for their age (mean of 2.4 years below), have average intelligence (group mean full scale WISC IQ of 98, SD = 8.9), and an absence of emotional, behavioural, organic and sensory impairments. Reading competency was assessed annually using primarily the Alberta Diagnostic Reading Kit, although other standardised tests, such as the Woodcock Reading Mastery Test and the Jerry Jones Reading Inventory, were also used. All tests were administered by a qualified school psychologist. Psychometric data on these children are presented in Table 1.

TABLE 1
Psychometric Details of Dyslexic Children in Experiment 1

<i>Patient No.</i>	<i>Sex</i>	<i>Age^a</i>	<i>Reading Grade Level</i>		<i>Assessed Grade level^b</i>		<i>Problems with Speech or Language</i>
			<i>Expected</i>	<i>Assessed</i>	<i>Spelling</i>	<i>Maths</i>	
1	M	7, 4	2	PP	PP	3.0	Yes
2	F	9, 8	4	2.4	2.4	4.2	Yes
3	M	9, 8	4	1.5	1.5	1.5	No
4	F	8, 9	3	1.3	—	—	Yes
5	M	10, 9	5	2.5	2.3	4.0	No
6	M	9, 8	4	1.0	—	—	No
7	M	10, 11	5	2.1	2.3	3.2	No
8	F	10, 5	5	3.8	2.7	5.2	No
9	M	10, 2	5	2.9	2.3	3.2	No
10	F	11, 3	6	1.7	—	—	Yes

PP, pre-school level;

^aAge given in years, months. ^ba dash is shown where information was not available.

Nine dyslexic children were right-handed and one was left-handed. None had a concurrent or previous diagnosis of Attention Deficit Hyperactivity Disorder.

Ten age- and sex-matched controls (mean age = 9.9 years) also participated. They were of at least average intelligence and were reading at the expected level for their age. Formal reading assessments of the control children were not done, but all were selected on the basis of teachers' assessments that the children were reading at grade level. Eight were right-handed and two were left-handed. An adult, normally reading control group consisting of nine undergraduate students (6 females, 3 males, mean age of 22.3 years) was included to determine the maturity of motion perception in 10-year-old children. Seven were right-handed and two were left-handed. All participants had normal or corrected-to-normal visual acuity. Informed consent was obtained from all participants and from a parent of each child.

No reading-age matched group was included because there was no *a priori* reason why reading experience would facilitate performance on a novel psychophysical motion test which contained no verbal, phonetic or letter recognition components. (However, see Experiment 2, where a reading-age matched group was used. Here we demonstrate directly that the differences in motion sensitivity between groups cannot be accounted for by reading experience.)

Apparatus. The stimuli were generated by a Macintosh LC computer using custom software written in "C". They were displayed on an Apple 13-inch colour monitor with a temporal resolution of 15 msec.

Stimuli. Motion stimuli consisted of four 15-msec "frames" (total duration of 60 msec), each composed of 100 white dots (each of 2.5 minarc in diameter) randomly plotted within a 3° square area in the centre of the darkened face of a computer monitor. RDK stimuli were generated according to conventional algorithms.² Signal dots were displaced by 10 minarc (effective velocity = 11° per second), whereas noise dots were randomly repositioned within the RDK. The percentage coherence was defined as the percentage of signal dots. There were three stimulus conditions. In one condition, the test RDK appeared alone in the centre of the screen. In the other two conditions, a second, non-directional RDK appeared immediately adjacent to the test RDK, either to the left or to the right. The non-directional RDK had 0% coherence and was otherwise identical to the test RDK. There was no luminance defined border between the two, so

²There was no interval between frames. For successive displacements, signal dots were reselected randomly from the entire array of dots without regard to a dot's prior history. Thus, tracking any individual dot would not lead to an accurate perception of the global direction. A conventional wrap-around scheme was used for dots moving out of the display field.

that the stimulus appeared as a $6^\circ \times 3^\circ$ rectangular field of dots. However, when the global motion in the test RDK was perceptible, a motion defined border was readily apparent. These noise conditions were used to determine if dyslexics could benefit from the motion defined border in the same way that normal readers were observed to do in a pilot experiment.

Task and Procedure. Participants were seated 50 cm in front of the computer monitor in a partially darkened room and viewed the stimuli binocularly. A chin rest and fixation spot were used. Testing consisted of several blocks of RDK presentations, with each RDK within a block varying in coherence according to a conventional psychophysical staircase procedure.³ In each RDK, signal direction was either leftwards or rightwards, and participants chose from these alternatives after each trial. The experimenter entered responses using the keyboard for child participants. Adult participants entered their own responses. Each block of trials produced two estimates of threshold, one for leftward and one for rightward. Testing consisted of a randomized order of four blocks (eight threshold estimates) for each of the three stimulus conditions.

After the motion test, dyslexic children participated in two other simple tests, a single-dot motion test and a line position test. Both tasks consisted of 24 trials, with cartoon pictures presented on the screen between trials to maintain interest. In the motion test, a single dark dot (12 minarc) on a white field moved 2.9° across the screen with a speed of 1.1° per second on each trial. A simple rightwards versus leftwards judgement was required, just as in the more difficult RDK test described earlier. The start position of the dot was randomized so that it could not provide an accurate cue to direction of motion (although direction could be computed by comparing start and end position).

In the relative position task, the stimulus was a thin vertical black 5.2° line presented at various distances (0.6° , 1.3° or 1.9°) to the left or right of the midline of the computer screen. The children were asked to respond "left" or "right" to indicate the perceived position of the line.

³ Each time a participant indicated the correct direction on two successive trials, the percent coherence was halved for the next trial in that direction. If the participant chose the incorrect direction on a trial, the percent coherence was increased by half its current value for the next trial in that direction. This estimates the coherence value needed to produce correct direction identification on 71% of trials. The staircase was terminated after six response reversals and the threshold was defined as the mean of all six reversals. Staircases for leftward and rightward movement were interleaved within a block of trials and the computer randomly chose the direction of the signal dots on successive trials.

Results and Discussion

Figure 1 illustrates two important findings of Experiment 1. First the overall mean motion coherence threshold obtained from the dyslexic children was double that of the age-matched normally reading control group.⁴ Second, mean motion thresholds for normally reading children were very similar to those of normally reading adults, suggesting that children are fully developed in this capacity at 9–10 years of age. The group mean percentage coherence needed for a just correct direction judgement was 23.4% (SD = 3.48%) for normally reading adults and 19.9% (SD = 2.9) for normally reading children. In comparison, the dyslexic children's group mean threshold was 39.8% (SD = 17.2) coherence.

We conducted a four-way, mixed-design analysis of variance on the threshold, with group, direction, condition and block as factors. A significant main effect of stimulus condition, $F(2,44) = 5.44$, $p < .01$, was found. The mean motion threshold for all groups was lower by 3.7% when the motion test

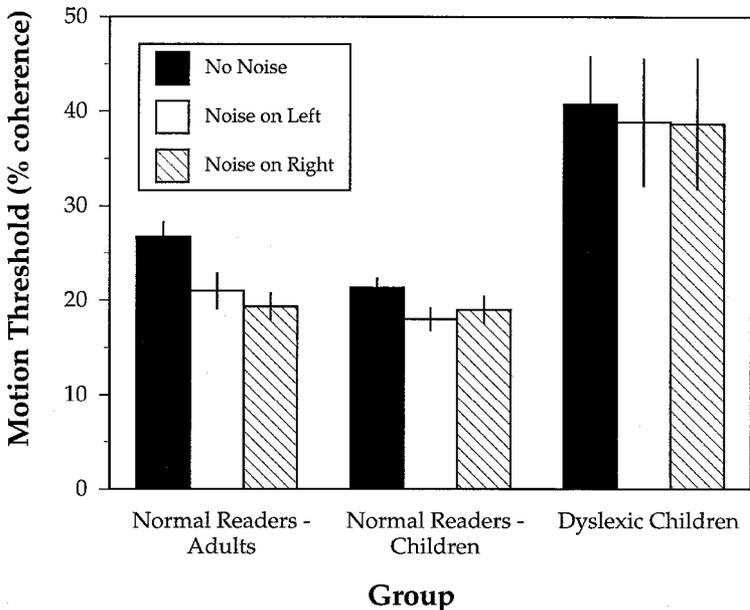


FIG. 1. Group mean motion coherence thresholds for normally reading adults and children, and for dyslexic children, for the three stimulus conditions of the experiment. Vertical bars represent ± 1 SE of the mean

⁴These data are presented on a linear scale rather than a log scale because psychophysical research has shown that humans do not appear to perform a log conversion of percentage coherence (Raymond & Braddick, 1996).

stimulus was viewed with a non-directional RDK simultaneously present, relative to when the test was viewed alone. Although of theoretical interest, there was no significant group \times condition interaction and therefore the results specific to these conditions are not discussed further. A significant main effect of group, $F(2,27) = 9.514, p < .001$, was found but all interaction effects were non-significant. Scheffé tests showed that the mean threshold of the reading-disabled participants was significantly higher ($p < .01$) than the mean threshold of both the control children and the adults and that differences between the control children and adults were non-significant.

Figure 2 shows the mean motion coherence threshold obtained for each of the children in this study. The distribution of thresholds for the control children is tightly clustered around of value of 20% and the upper normal limit (2.82 standard deviations above the mean, $p < .01$) is 27.8% coherence. Individual mean thresholds for 6 of the 10 dyslexic children are above this value. These children, in descending order (i.e. beginning with the most deficit), are numbers 2, 1, 3, 9, 10 and 6. Although the sample size is too small to make any definitive statements, there was no obvious relationship between the presence or absence of speech or language difficulties (as assessed by the school psychologist), or

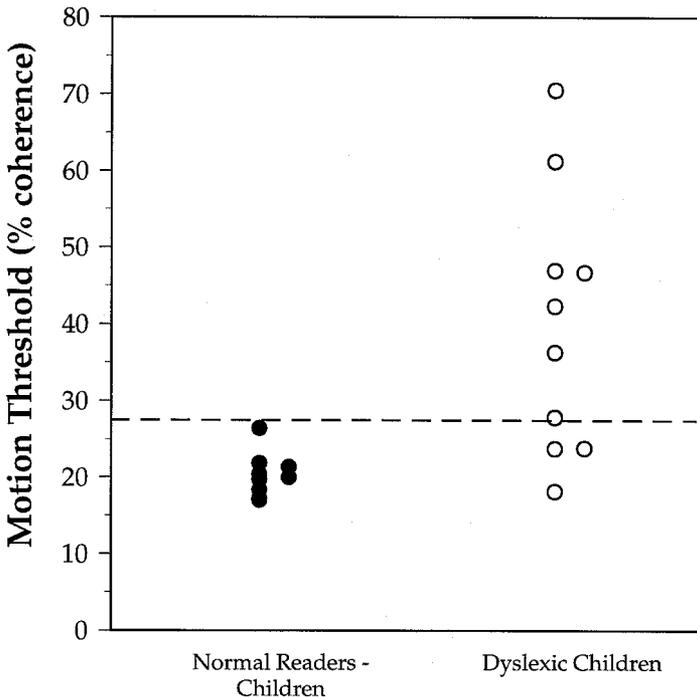


FIG. 2. Individual mean motion thresholds for the normally reading control children (●) and for dyslexic children (○). The dashed line indicates the upper 99% normal limit.

the severity of reading difficulty, with the magnitude of the motion perception deficit.

All dyslexic children performed the single-dot motion task and the line position tasks with greater than 95% accuracy, indicating that they could follow instructions, could discriminate leftward from rightward movement when position and other cues were readily available, and could discriminate left from right position without difficulty.

EXPERIMENT 1B

To test both the reliability of our findings and to determine whether the motion deficit observed in Experiment 1 could be due to a developmental lag, we re-tested as many of the children in the first study as possible on the same RDK test more than 1 year later.

Method

Participants. Nine of the 10 dyslexic children previously tested and 4 of the 10 controls previously tested participated. The group mean age of the dyslexics and controls was 10.2 years and 10.6 years, respectively, in the first experiment; both groups were re-tested 1.3 years after the date of the first experiment, (i.e. when they were 11.5 and 11.9 years of age, respectively). The dyslexic group consisted of four boys and five girls, whereas the control group consisted of two boys and two girls.

Apparatus. The stimuli in this and all subsequent experiments were generated by a Macintosh IIcx computer using custom software written in "C". They were displayed on an Apple 15-inch colour monitor with a temporal resolution of 16 msec.

Task and Procedure. The procedure was similar to that of Experiment 1A except that all testing was done with the test-alone stimulus configuration and was conducted using a different computer display monitor. Within the experimental session, participants were tested in three conditions, which varied in the number of frames in the RDK and the duration of the frames. One condition was identical to the test-alone condition of Experiment 1A. For the sake of clarity, we will treat this as Experiment 1B and treat the remaining two conditions as Experiment 2. In each condition, three thresholds were obtained for each movement direction.

Results and Discussion

The average motion coherence threshold for the test-only condition was lower for both groups of children on the second date of testing by a proportionally

similar amount. Table 2 shows the mean thresholds for both groups measured at both times. Although the actual difference in threshold was greater for the dyslexic group, the mean proportional change (.65 and .66 for the controls and dyslexics, respectively) was highly similar. Within-group threshold changes were most probably due to an increase in monitor brightness, a factor known to improve measures of motion perception (Damson & DiLillo, 1990).

In Experiment 1A, six of the nine dyslexic children we consider here had abnormally high thresholds. Since the control group was so small for Experiment 1B, we determined an upper normal ($p < .01$) limit for the performance in the re-test by taking 65% of the upper limit from the first experiment. This value, 18.0% coherence, identified as abnormal all six of the previously identified dyslexic children plus one additional dyslexic child who appeared normal in Experiment 1A. None of the control children appeared abnormal on the re-test.

EXPERIMENT 2

In Experiment 1B, we found that with four-frame RDKs dyslexic children were abnormally insensitive to global motion. Previous research has suggested that cooperative motion mechanisms are normally engaged with such stimuli. This raises the question of whether dyslexic children are insensitive to motion *per se* or are unable to use cooperative processes effectively to mediate their perceptual judgements. Experiment 2 investigated this by manipulating the number of frames in the RDK.

Method

Participants. Nine dyslexics and four controls who participated in Experiment 1B participated in Experiment 2 (two conditions only). In addition, three inexperienced children with dyslexia and eight inexperienced normal readers participated in all three conditions. The inexperienced dyslexics (two boys, one girl, mean age = 12.0 years) had an average reading competency 3.6 years below normal. The inexperienced normal readers (5 girls, 3 boys) had the same

TABLE 2
Group Mean Motion Coherence Thresholds for the Same
Stimulus Conditions and Participants at Two Different
Times (Standard Error and Group Size in Parentheses)

Group	Mean Age at Time of Testing	
	10.4 years (Exp. 1A)	11.7 years (Exp. 1B)
Normal readers	22.45 (0.82, $n = 10$)	14.55 (0.62, $n = 4$)
Dyslexics	40.09 (5.58, $n = 10$)	26.55 (3.84, $n = 9$)

or lower readings level as the dyslexics and were 4 years younger (mean age = 8.0 years). In total, there were 12 dyslexics (mean age = 11.6 years) and 12 normal readers (mean age = 9.3 years).

Task and Procedure. The procedure was similar to that of Experiment 1B. Participants were tested using a single display monitor of a constant brightness in three conditions which differed in the number of frames in the RDK and the duration of the frames. Frame duration was 32 msec (brief-frame conditions) or 112 msec (long-frame condition). In the brief-frame conditions, RDKs consisted of two or seven frames, whereas in the long-frame condition, the RDK consisted of two frames. This yielded two conditions with equivalent total durations (seven brief frames and two long frames, total duration = 224 msec), two conditions with equivalent numbers of frames, and two with the same apparent speed (seven brief frames and two brief frames).

Although all children participated in the same number of conditions, only the inexperienced children participated in the three described above. The experienced children participated in the two brief-frame conditions (their third condition being that described in Experiment 1B).

Results and Discussion

The results are shown in Figure 3. We first consider the two conditions with brief frame durations. The two groups of children performed about the same when only two frames were present in the motion stimulus, the differences in the group means being non-significant. Additionally, there were no significant differences among the sub-groups tested, indicating that neither experience with the task nor age bestowed an advantage to any participant. In contrast to the two-frame condition, thresholds for the dyslexic children were significantly ($p < .001$) worse than those of the control children when the test stimulus had seven frames. With the longer RDKs, the group mean threshold for the control children dropped from a value of 25.4% coherence for two frames to a value of 10.5% coherence for seven frames. In contrast, the seven-frame group mean threshold for the dyslexic group only improved from 26.3% for two frames to 19.9% for seven frames.⁵

We next compared thresholds from the two RDK conditions that were matched for total stimulus duration, that is, the condition with seven brief

⁵To determine if task difficulty contributed to our pattern of results, we compared the standard deviation of thresholds obtained from each participant in each condition, since this measure reflects the slope of the underlying psychometric function. Neither the main effects nor the interaction effect were significant ($p < .25$), indicating that the task was equally difficult for both groups and for both two-frame and seven-frame stimuli, even though sensitivity varied.

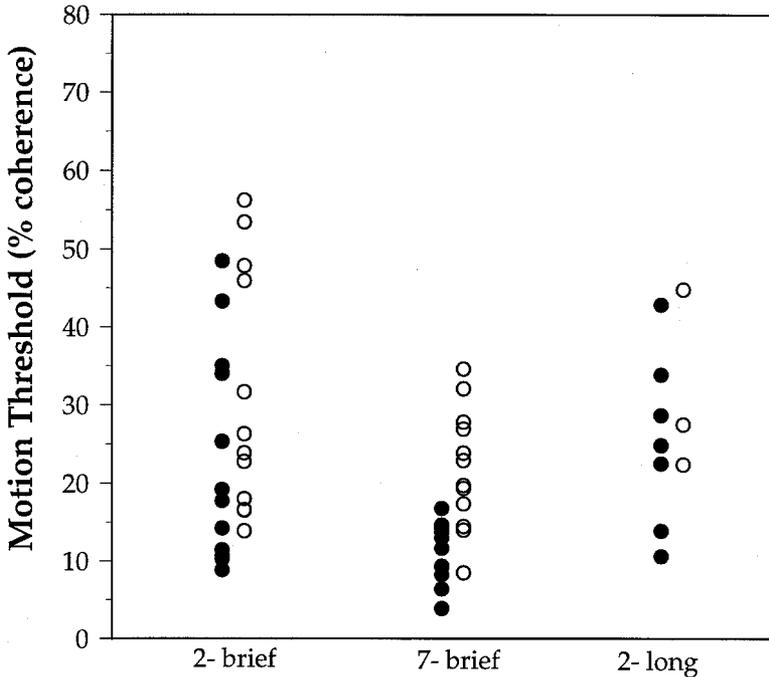


FIG. 3. Individual mean motion coherence thresholds obtained from normally reading children (●) and dyslexic children (○) for three different random dot stimuli. The stimuli differed in the number of frames used to create the random dot kinematogram and in the duration of each frame. "Brief" frames were 32 msec long and "long" frames were 112 msec long.

frames and the condition with two long frames. (Note that only three dyslexics participated in this condition.) Thresholds for seven frames were significantly lower than for two frames for both groups, $F(1,9) = 20.45$, $p < .01$. A comparison of thresholds for RDKs with two brief frames versus two long frames indicated that lengthening frame duration (and hence slowing apparent speed) produced a small but significant decrease in threshold for both groups, $F(1,9) = 6.48$, $p < .05$. Differences between groups for the two-long frames were non-significant. Together with the lack of group differences in the two-brief-frame condition, these data indicate that children in both groups have similar sensitivity to motion when a single displacement of dots is presented.

DISCUSSION

The principal finding of these experiments is that children with dyslexia have deficits in global motion perception. The results of Experiments 1A and 1B demonstrate that these deficits are large, reliable and persistent. The results of

Experiment 2 suggest that the motion perception deficits observed in the first two experiments do not reflect an inability to detect motion *per se*, but rather represent an abnormality in the perceptual integration of motion information.

Both the simple control tasks of Experiment 1A and the normal performance of the dyslexic children in the two-frame conditions of Experiment 2 provide strong evidence that the motion deficits in the multiple-frame conditions did not result from a lack of understanding of the task or an unusual difficulty in discriminating of left from right.

Since previous reports have indicated that dyslexia may be associated with abnormal visual persistence (DiLollo, Hanson, & MacIntyre, 1983; Shapiro, Ogden, & Lind-Blad, 1990), one possible explanation for abnormal motion coherence thresholds in dyslexic children is that the random dot patterns from the first frame in the RDK may have persisted for an abnormally long time, combining with the presentation of subsequent frames. There are two reasons why we can reject this as a mechanism for the observed deficits. First, such abnormal persistence should have exerted its effect in the two-frame stimulus conditions, but here dyslexic children appeared normal. Second, this hypothesis predicts that the motion coherence thresholds of the dyslexics should have increased with more frames in the RDK because more and more dots would have had an opportunity to persist. However, motion thresholds for seven-frame stimulus were significantly lower than those for two-frame stimuli.

Global motion perception deficits in dyslexic children with multiple-frame stimuli appear to result from abnormalities of information integration rather than poor sensitivity to local motion events. Integration of local motion information may be mediated by cooperative processes of neural networks of motion direction analysers. Cooperative mechanisms, although hypothetical, are thought to consist of facilitatory and inhibitory connections among low-level motion direction detectors. The idea is that if one direction detector becomes activated by a local motion event, then it will facilitate all nearby, like-direction motion detectors and concurrently inhibit other nearby, different-direction detectors. Such processes have been used to explain sequential recruitment effects (Snowden & Braddick, 1989), successive direction contrast effects (Snowden, 1989) and hysteresis effects (Chang & Julesz, 1984; Nawarot & Sekuler, 1990; Williams, Phillips, & Sekuler, 1986) in motion perception. The function of cooperative motion mechanisms in natural viewing is not well understood, but recent studies have suggested that such mechanisms may allow interpolation of object motion when visual information is sparse, interrupted or degraded (Welch, MacLeod, & McKee, 1997), thus promoting a more generally coherent visual experience. The results of Experiment 2 suggest that children with reading disabilities may have an abnormal, or possibly absent, cooperative mechanism in this visual domain.

Although little is known about the specific underlying physiology of cooperativity, two lines of evidence suggest that an area V5 (the functional human

homologue of area MT in the monkey) of the dorsal extrastriate pathway may play a significant role. First, Mikami et al. (1986) reported that MT neurons in monkey are highly responsive to RDK-type stimuli and to movement in general, but do not respond well to two-frame RDKs, requiring multiple frames to elicit a significant response. Second, damage to this area elevates motion coherence thresholds for multiple-frame stimuli in humans (Baker, Hess, & Zihl, 1991; Barton, Sharpe, & Raymond, 1995), and monkeys (Newsome & Paré, 1988), but does not produce impaired motion perception when stimuli are fully coherent. Thus deficits caused by damage to this area may be specific to tasks requiring information integration. On this view, the pattern of deficits observed here suggests abnormal function of the dorsal extrastriate system in children with dyslexia. Certainly, the recent fMRI results indicating an absence of activity in the normally motion-sensitive V5 area of the dorsal pathway in dyslexic men support this possibility (Eden et al., 1986).

Are the results of the present study consistent with the supposition of a magno-specific abnormality of early visual processing in reading disabilities? Lesion studies in monkeys have indicated that magno pathway integrity is necessary for normal motion processing of random dot stimuli (Schiller, Logothetis, & Charles, 1990). To the extent that this is true for humans, normal perception of the two-frame RDKs do not support the notion of magno system dysfunction in dyslexia. Cornelissen et al. (1995) have suggested previously that the constellation of evidence supporting magno-specific deficits in dyslexia could also be interpreted to reflect abnormal parietal lobe function. Our data support this view.

Cooperative processes may also play a role in stereopsis (Julesz & Chang, 1976), the perception of illusory contours (Grossberg & Mingolla, 1985a) and many other aspects of scene segmentation (Grossberg & Mingolla, 1985b). The presence of abnormal cooperative processes in visual motion perception in children with dyslexia may thus signal abnormalities of network connections in other perceptual and cognitive systems. Perhaps it is a collection of inefficient information-processing mechanisms that produce the characteristic symptoms of dyslexia.

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