

Low-level Visual Processing Skills of Adults and Children with Dyslexia

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Previous work by Lovegrove and colleagues (Lovegrove, Martin, & Slaghuis, 1986) suggested that dyslexic children show visual deficits specific to transient processing. We designed and examined a number of threshold and suprathreshold tasks to test the generality of their claims. We first compared the performance of adult dyslexics and child dyslexics to the performance of age-matched normal readers on a series of threshold flicker tasks. In contrast to the earlier results, dyslexics and normal readers did not differ in their contrast thresholds for flickering sinewave gratings. Dyslexic children and normal readers also showed similar performance on two suprathreshold visual search tasks that evaluated transient processing. The evidence suggests that a transient processing deficit is not a general characteristic of developmental dyslexia. Claims that visual factors play a role in dyslexia must address the confounding role of performance and attentional factors.

INTRODUCTION

Developmental dyslexia is a disorder in which children of at least average intelligence exhibit unusual difficulties in spelling and reading which are not a consequence of neurological, emotional, behavioural, or sensory difficulties. According to most common definitions, developmental dyslexia

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reflects fundamental cognitive deficits that are frequently constitutional in origin (e.g. Critchley, 1970). Over the last 100 years, a major goal of much of the research in this field has been to specify the exact nature of the "fundamental cognitive deficits" that underlie developmental dyslexia.

One of the earliest hypotheses about dyslexia was that it reflected a dysfunction in visual perception. According to this hypothesis, dyslexics suffered from a maturational lag in the development of hemispheric dominance, which resulted in unstable spatial organisation of letters and words (Orton, 1925, 1937). Since Orton's original hypothesis, theories attributing dyslexia to visual deficits have abounded. Proposed visual deficits have included deficits in short-term visual memory (e.g. Goyen & Lyle, 1973), deficits in processing sequential visual input (e.g. Bayliss & Livesey, 1985), deficits in spatial localisation (e.g. Solman & May, 1990), and deficits in visual analysis (e.g. Doehring, 1968).

In the 1970s, there was a major split in research focus. The work on visual perceptual difficulties was criticised on the grounds that dyslexics' poor performance on such tasks reflected the consequences rather than the causes of reading disability (Vellutino, 1977; see also Hulme, 1988; Lovegrove, 1991). In part due to the initial work by Vellutino and his colleagues, there has been mounting evidence that phonological, syntactic, and verbal memory deficits underlie the majority of cases of developmental dyslexia. Most current hypotheses focus on phonological deficits (e.g. Stanovich, 1992; Vellutino, 1987).

Although the preponderance of evidence suggests a linguistically based deficit for dyslexia, the role of visual deficits in developmental dyslexia forms a recurrent controversy in the field. This paper focuses on one prominent and influential model that has been used to account for the deficits underlying developmental dyslexia—the transient channel deficit model of dyslexia (e.g. Breitmeyer, 1984; Lovegrove et al., 1986). The transient channel deficit model makes two unique claims. In contrast to the earlier visual perceptual work, which focused on higher level perception (e.g. Bayliss & Livesey, 1985; Doehring, 1968; Goyen & Lyle, 1973), this newer model emphasises the role of low-level vision. In addition, the transient channel deficit model makes the claim that 75% of *all* dyslexics suffer from a transient channel deficit (Slaghuis & Lovegrove, 1985). Because multicausal theories of developmental dyslexia generally indicate that visual perceptual deficits only account for 10–15% of cases of dyslexia (e.g. Boder, 1973; Pirozzolo, 1979; Taylor, Fletcher, & Satz, 1982), this is a strong claim, although Lovegrove and his colleagues do note that many of these cases may experience phonological deficits as well as visual deficits (Lovegrove et al., 1986; Lovegrove, Garzia, & Nicholson, 1990).

Since the advent of the transient channel model, physiological studies

have moved away from the transient/sustained dichotomy that underlies the model to a magnocellular vs. parvocellular dichotomy. In primate visual systems, these two pathways start with different classes of ganglion cells in the retina and remain fairly separate up to and into some parts of the cortex. Although the correspondence between transient and sustained properties revealed by psychophysical techniques and the properties of the magnocellular and parvocellular pathways is not perfect, it is fairly strong (Lennie, 1980; Schiller, Logothetis, & Charles 1990). In particular, some authors claim that it is specific deficits in the magnocellular pathway of the primate visual system that contribute to reading disability (Bassi & Lehmkuhle, 1990; Livingstone, Rosen, Drislane, & Galaburda, 1991; Williams & LeCluyse, 1990). The deficits in visual transient processing fall within a larger class of temporal processing deficits which have been linked to dyslexia (see Farmer & Klein, 1995, for a review). In this article, we will concentrate specifically on the model of transient processing deficits in low-level vision.

The transient channel deficit model has provided the foundation for further hypotheses about the causes and remediation of reading disability. In particular, some researchers claim that disabled readers reveal deficits in visual attention that arise from the proposed transient system deficit (Brannan & Williams, 1987; Williams & LeCluyse, 1990). In addition, there are ongoing attempts to integrate this model with theories about the remediation of dyslexia by the use of coloured or tinted lenses and plastic overlays (Williams, 1990).

Given the claims and unique nature of the transient channel deficit model, it would be appropriate to examine the degree to which the model can be extended to other populations, such as adult dyslexics. In addition, we present another experimental paradigm which was intended to extend the scope and applicability of the transient-deficit model, and which was intended to be more engaging for children. This paper proceeds as follows. We describe the transient channel deficit model and review the evidence for the existence of a transient channel deficit. We then discuss four experiments that we designed to examine further the effect of transient channel deficits. Experiment 1, a temporal contrast sensitivity task, was designed to extend Lovegrove's results with dyslexic children to adults with childhood diagnoses of dyslexia. To preview the results, adult dyslexics' performance on the flicker contrast threshold task was similar to that of normal age-matched readers. Because the data did not support the hypothesis of transient pathway deficits in adults with childhood histories of dyslexia, Experiment 2 was conducted to examine the performance of dyslexic children on a similar task. Experiments 3 and 4 are suprathreshold visual search tasks that examine transient channel and sustained channel performance in dyslexic children.

The Transient Channel Deficit Model

In the 1970s and early 1980s, work in human perception and psychophysics revealed that responses to specific types of visual stimuli contained two components—a sustained component and a transient component (e.g. Kulikowski & Tolhurst, 1973; Tolhurst, 1975). Evidence from both lines of research has characterised the two psychophysical channels as follows. The transient channel is sensitive to the temporal qualities of stimuli (i.e. to movement and flicker); it responds best to low spatial frequency and high temporal frequency stimuli—in particular to rapid movement or abrupt onsets and offsets of large features. In contrast, the sustained channel is involved in pattern perception, and responds best at high spatial frequencies and low temporal frequencies.

Although there are some researchers who do not make claims about the relationship between transient deficits and dyslexia (e.g. Willows, 1993), Lovegrove and his colleagues have tended to adopt a strong position postulating a causal relationship between transient channel deficits and dyslexia. This causal relationship begins with Breitmeyer and Ganz's (1976; Breitmeyer, 1984, 1991) application of the sustained-transient model of vision to the process of reading. Breitmeyer and Ganz claim that, in reading, the two channels interact as a reader cycles through the normal sequence of fixations and saccades. The sustained channel primarily processes detailed pattern information (i.e. letter information) during the fixation on a word; when the word has been processed and it is time to fixate on the next word, the sustained channel response continues, resulting in visible persistence of the previously fixated word. The transient channel, which is activated by the saccade to the next fixation point, then inhibits the continued sustained channel processing of that word, thereby eliminating the visible persistence. The cleanly demarcated periods of sustained channel activity are then combined into a stable representation of the visual material across successive fixations. In essence, the inhibition of the sustained system results in a clear percept of the newly fixated material during each fixation and in the proper integration of visual material across a series of fixations.

Proponents of the transient-deficit model have argued that developmental dyslexia arises from the failure of the transient channel to inhibit the sustained channel effectively. Lovegrove and his colleagues contend that the failure of the transient channel to inhibit the sustained channel has important repercussions for reading. Specifically, when a dyslexic has made a saccade to, for example, the second word in a sentence, the processing of the letters of the first word will not have been fully inhibited by the transient channel during the saccade to the second word and the first word will still be "visible." The continued sustained channel activity

results in a confused and incoherent integration of visual information, and a confused perception of the words of the sentence (see Lovegrove et al., 1986, Fig. 3, for a graphic illustration of the purported reading difficulties). These perceptual deficits may result in deficits in the representation of orthographic components of words and, possibly, in phonological deficits as well (Lovegrove et al., 1986, 1990).

A number of studies have been conducted which examine the low-level visual processes of dyslexic children between the ages of 8 and 14 years. Evidence which putatively supports the transient-deficit model emerges from research on visible persistence, pattern contrast sensitivity, flicker masking, and flicker contrast sensitivity. Explaining their findings with reference to the transient-sustained model, Lovegrove and his colleagues conclude that dyslexics show selective deficits in transient channel functioning; sustained channel functioning is normal. They present the following lines of evidence.

First, according to the transient-sustained model, sustained channel activity should be inhibited by the transient channel, especially at low spatial frequencies where transient channel activity is strongest. A transient channel deficit should reduce inhibition of sustained channel activity so that activity will persist after the stimulus has been removed. Researchers have found that dyslexic children reveal longer visible persistence durations than normal readers at low spatial frequencies (Badcock & Lovegrove, 1981; Lovegrove & Heddle, 1980; Lovegrove, Heddle, & Slaghuis, 1980; Slaghuis & Lovegrove, 1985, 1986a, 1986b, 1987). However, this conclusion has been challenged by Georgeson and Georgeson (1985), who argued that the criterion-based methodology used in this research artificially inflates visible persistence durations, thereby obscuring any real differences that may exist; the response by Lovegrove and Slaghuis (1989) did not fully resolve this issue. Moreover, Howell, Smith, and Stanley (1981) and Walther-Müller (1995) found no differences in visible persistence between dyslexic and normal children.

Second, the transient channel processes contrast preferentially at low spatial frequencies. Therefore, transient channel deficits should result in poorer processing of contrast at these frequencies. To test this prediction, sinewave gratings of different spatial frequencies and contrasts were presented; dyslexics should require a higher contrast than normal readers to detect low spatial frequency gratings. This pattern has been reported: dyslexic children were less sensitive to contrast than normal readers at low spatial frequencies, whereas the two groups did not differ at high spatial frequencies (Lovegrove, Bowling, Badcock, & Blackwood, 1980; Lovegrove et al., 1982; Martin & Lovegrove, 1984). However, the results of the research on pattern contrast sensitivity have not always favoured the transient channel hypothesis. For example, whereas the results of

Experiment 2 of Martin and Lovegrove (1984) did yield supporting evidence, the results of Experiment 1 of the same paper did not. In addition, Walther-Müller (1995) found no differences in pattern contrast sensitivity between dyslexic and normal children at high or low spatial frequencies.

The third line of evidence comes from research on uniform field flicker masking. Uniform field flicker refers to a "field" or area which alternately increases and decreases in luminance. In flicker masking, a flickering field is superimposed upon the stimuli of a task (e.g. static sinewave gratings in a pattern contrast sensitivity task). According to Lovegrove and his colleagues, uniform field flicker masking should reduce transient system activity by submerging the transient system in noise. Therefore, transient system deficits should be less detectable when masking is introduced. This is what is reported: Masking by uniform field flicker minimised differences between normal and dyslexic children on contrast sensitivity or visible persistence tasks (Martin & Lovegrove, 1988; Slaghuis & Lovegrove, 1984; but see Smith, Early, & Grogan, 1986).

The evidence again is not uniformly positive. For example, of the three experiments reported in Martin and Lovegrove (1988), only one experiment unambiguously supports the transient-deficit model (Experiment 1); the other experiments do not. Furthermore, Badcock and Sevdalis (1987) observed that Slaghuis and Lovegrove's (1984) procedure produces unexpected changes in contrast, which may briefly make the stimuli more noticeable than intended. Thus, the claim that flicker masking provides insight on the processing of sustained and transient channels may not be appropriate (Badcock & Sevdalis, 1987, p. 641); "the basis for such a claim is weak."

Fourth, according to the model, the transient channel is responsible for processing flicker and motion. Therefore, inefficient transient channel processing should produce decreased sensitivity to motion/flicker, especially at high temporal frequencies and low spatial frequencies. To test this prediction, the performance of dyslexic children and normal readers was compared using rapidly flickering sinewave gratings (Hill & Lovegrove, 1993; Martin & Lovegrove, 1987) or uniform field flicker (Brannan & Williams, 1988; Evans, Drasdo, & Richard, 1994; Williams & LeCluyse, 1990). The predicted results were obtained: Dyslexic children showed poorer flicker sensitivity than normal readers. In particular, the differences in performance between dyslexic and normally reading children increased as the "flicker rate" or rate of alternation increased; in these experiments, the largest between-group differences were obtained at the highest temporal frequencies, a finding which provides strong, unambiguous evidence for the transient pathway deficit model. Again, however, Walther-Müller (1995) provides a counter-example, as he

reported no difference between dyslexic and normal children in contrast sensitivity for low or high temporal frequency stimuli. Nor did he find any significant differences between the two groups in measures of motion perception.

In some of these studies, differences between normal and dyslexic children were sometimes reduced or minimised when conditions required the processing of high spatial frequency information. Because the model proposes that the sustained system actively processes this information, these patterns of results provide support for a selective visual deficit to the transient channel. Additional support for a selective visual deficit is provided by two studies that examine sensitivity to orientation, information that is presumably processed by the sustained channel. Normal and dyslexic readers performed similarly on a tilt illusion task where the apparent orientation of the test bars is affected by the orientation of nearby bars (Lovegrove et al., 1986). Dyslexic and normal readers also showed the same "oblique effect" (Lovegrove et al., 1982); that is, the two groups showed similar increases in contrast sensitivity to vertical and horizontal gratings compared to oblique oriented sinewave gratings.

To summarise the support for the transient-deficit model, four lines of evidence emerge from research on visible persistence, pattern contrast sensitivity, flicker masking, and flicker contrast sensitivity. Differences between normal readers and dyslexics that are predicted by the model occur in all four lines of research, although there are also reports of null findings. In all cases, research indicates that the sustained channel functioning of dyslexics is normal. Although the support of the model is broad, it is not consistently positive. The most extensive test that reported null findings (Walther-Müller, 1995) was conducted on German-speaking children, which may have affected the comparability of the selection criteria. The issue of transient deficits in developmental dyslexia is therefore not yet resolved. Our first two experiments revisit this issue within the standard contrast sensitivity paradigm whereas our final two experiments call upon a new set of tests devised to be easier and more engaging for the subjects.

For the most part, the studies supporting transient channel deficits have only included children between the ages of 8 and 14 years. The limited range of ages included in these studies raises the question of whether transient channel deficits persist beyond childhood, or whether the results generalise to other ages. Previous research reveals that word recognition deficits and other important markers of childhood dyslexia (e.g. deficits in knowledge of spelling-sound relationships and in phonological awareness) persist from childhood into adulthood (Bruck, 1990, 1992, 1993; Felton, Naylor, & Wood, 1990). Given the fact that these basic deficits of dyslexia

remain, if visual deficits are major determinants of dyslexia, we may expect that the transient channel deficits identified by Lovegrove and his colleagues might also persist into adulthood. That transient system deficits are found in dyslexic children at all ages tested suggests that they might remain undiminished in adults. However, there is limited research which directly addresses whether transient channel deficits exist in adults. In particular, Winters, Patterson, and Shontz (1989) compared the ability of adult dyslexics and normal readers to discriminate between sequences of stimuli (i.e. the four sides of a small square) that were presented in different orders. Their results suggested that there was increased visible persistence for the dyslexics, and therefore that transient channel deficits may also underlie dyslexia in adults.

Our first experiment was designed to examine transient channel deficits in adults with childhood diagnoses of dyslexia. Given that the temporal contrast sensitivity research provided the clearest evidence for transient channel deficits, we compared the performance of dyslexic adults (the shortened term for adults with childhood diagnoses of dyslexia) and age-matched normal readers on a computerised counterphase flicker contrast threshold task. We changed the procedure to address two concerns we had about previous research: we used a simpler forced-choice response to reduce the attentional demands and we shortened the presentation of the stimuli to avoid eye movement artefacts.

EXPERIMENT 1: CONTRAST THRESHOLD TASK— ADULTS

In this experiment, we compared dyslexic and normal adults' contrast sensitivity thresholds for briefly presented flickering sinewave gratings. Subjects viewed flickering patterns of vertical bars and were required to indicate whether they could detect them. In the counterphase flicker contrast threshold task used by Martin and Lovegrove (1987, Experiment 1), the relative difference in contrast sensitivities between dyslexic and normal readers increased as temporal frequency increased; we examined whether dyslexic adults would show the same pattern of performance as Martin and Lovegrove's dyslexic children. Rather than sampling a large range of spatial and temporal frequencies, we chose two extreme combinations, which were prototypically transient and sustained, respectively. We selected a low spatial frequency target grating (2cpd) flickering at a temporal frequency of 33Hz for our "transient" condition. These values parameters were close to those that produced the largest between-group differences in contrast thresholds in Martin and Lovegrove's study. We also selected a high spatial frequency grating (12cpd), briefly presented without reversing contrast, for our "sustained" condition.

These temporal and spatial frequency parameters were close to those that produced little or no between-group differences in Martin and Lovegrove's study.

Methods

Subjects

Twenty adults with childhood histories of dyslexia and 20 normal adult readers participated in the study. At the time of testing, the visual acuity of each participant was measured on standard Snellen acuity charts; all subjects had normal or corrected-to-normal vision.

Dyslexics. The dyslexic participants were identified from childhood patient files of a clinic that specialises in assessment and treatment of childhood reading disorders. Information from childhood files was used to identify potential subjects who met the following exclusionary definition of developmental dyslexia. As children, the subjects had experienced difficulty learning to read despite at least average intelligence; their reading problems were not associated with social, emotional, cultural, pedagogical, or medical factors, as evidenced by detailed clinical assessments. Their childhood reading difficulties were associated with word recognition problems, as evidenced by their childhood performance on standardised tests of reading ability: the Word Recognition and Oral Reading subtests of the Durrell Analysis of Reading Difficulty (Durrell, 1955) or on the Word Recognition subtest of the Wide Range Achievement Test (WRAT; Jastak & Wilkinson, 1974). On the Durrell, the disabled readers had scored at least below grade level on both subtests. On the WRAT, they scored below the 30th centile. In childhood, the mean Verbal, Performance, and Full Scale IQ scores on the WISC or WISC-R were 101, 111, and 108 respectively. The average age of clinic assessment in childhood was 8.6 years. At time of follow-up testing, all subjects were over 17 years old and were no longer in high school. All subjects scored within the normal range on the Culture Fair Test (Scale 3; Catell & Catell, 1973); and the Peabody Picture Vocabulary Test-Revised (PPVT-R—Form L; Dunn & Dunn, 1981), which served as, respectively, tests of nonverbal and verbal intelligence. No dyslexic subjects were eliminated due to visual difficulties.

Normal Readers. Control participants were selected to match as closely as possible the age, gender, and educational status of the dyslexic adults. Potential subjects were interviewed to ensure they had a normal educational history, no history of reading or visual problems, and were native speakers of English. One control subject failed the screening

procedures due to colour blindness and was excluded. All subjects scored within the normal range on the Culture Fair Test (Scale 3; Catell & Catell, 1973) and the PPVT-R (Form L; Dunn & Dunn, 1981).

All participants received the following set of standardised tests: the Word Recognition, the Word Attack (nonword reading), and the Passage Comprehension subtests of the Woodcock Reading Mastery Test-Revised (Form G; Woodcock, 1987); the Spelling subtest of the Wide Range Achievement Test-Revised (WRAT—Level 2; Jastak & Wilkinson, 1974). Normal readers were admitted to the study only if they scored above the 50th centile on the Word Attack (a nonword reading test) and the Word Identification subtests of the Woodcock Reading Mastery Test and the Spelling subtest of the Wide Range Achievement. For the dyslexics, admission was not contingent upon adult reading scores, but upon childhood reading scores. The percentile rank scores for the standardised tests and the characteristics of the normal reading and dyslexic groups are given in Table 1.

The dyslexics had significantly lower scores than the normal readers on all the reading and spelling ability tests, all $F_s(1, 38) > 33.1$, $P > .001$. As was the case in previous studies with this population, dyslexic children continue to show word recognition and phonological deficits into adulthood; all dyslexic subjects performed poorly on the word recognition and word attack (nonword reading) standardised tests (e.g. Bruck, 1990, 1992, in press). Importantly, all dyslexic subjects scored below the 37% of the standardised word recognition task; all but two dyslexics scored below the 30th centile on this task.

TABLE 1
Group Characteristics and Standardised Test Percentile Rank Scores of
Normally Reading and Dyslexic Adults: Experiment 1 (Standard Errors in
Parentheses)

	<i>Normal Readers</i>	<i>Dyslexic Readers</i>
Mean Age (Years:Months)	24:2	23:6
Age Range (Years:Months)	17:5-35:0	18:9-31:10
% Male Subjects	70	70
Years of Education after High School	2.5	2.4
WRMT ^a Word Recognition (%)	67 (2.8)	11 (2.6)
WRMT Word Attack (%)	77 (3.1)	20 (3.5)
WRMT Read Comprehension (%)	85 (4.1)	43 (6.1)
WRAT ^b Spelling (%)	79 (2.5)	10 (2.8)

^aWRMT = Woodcock Reading Mastery Test.

^bWRAT = Wide Range Achievement Test.

Equipment

The contrast threshold task was presented on a Macintosh II microcomputer using a Macintosh II High-resolution video board and a Macintosh High-resolution RGB monitor (Model M0401). The visual display was 23.5×17.6 cm, with a spatial resolution of 640×480 pixels. The screen refresh rate was 66 Hz.

The computer had 8-bit digital-to-analogue converters for the red, green, and blue phosphors. The resulting intensity of each phosphor was linearised by adjusting a correcting gamma factor in the output lookup tables of the computer. The minimum luminance of the screen was first set so that the smallest output values of the converter were visible on the screen. This resulted in a luminance of 0.5 cd/m^2 when the output values were at a minimum of 0, 0, 0 for red, green, and blue, respectively. The relative luminances of the three phosphors were then adjusted so that the chromaticity of the maximum white (255, 255, 255) was at CIE coordinates 0.333, 0.333, as measured by a Minolta Chromameter II. The luminance of the display at maximum output was 100 cd/m^2 .

Stimuli

The stimuli were vertical sinewave gratings presented within a circular aperture. For all stimuli, the space- and time-averaged luminance remained constant at approximately 14 cd/m^2 . The remainder of the screen was filled with random black and white radial lines, with a background luminance of approximately 50 cd/m^2 .

For both conditions, a central fixation spot subtending a visual angle of 0.5° was positioned at the centre of the visual display and remained visible at all times. The stimulus grating, with a radius subtending an angle of 4.2° , was presented in the middle of the screen.

In the transient condition, the spatial frequency of the grating was 2 cpd. The luminance of alternate bars of the stimulus was modulated in counterphase at a rate (i.e. a temporal frequency) of 33 Hz. In the sustained condition, a static (non-flickering) high spatial frequency grating (12 cpd) was presented as a pulsed grating. The grating never reversed contrast.

To avoid the potentially confounding effects of eye movements, stimuli were presented for a duration of 105 msec. The presentation duration included onset and offset ramps of two frames each (30 msec), where the contrast increased and then decreased in steps of $\frac{1}{3}$ of the test contrast; the central presentation time was 3 frames (45 msec) at the test contrast. Note that over the 7 frames of the presentation, there is an imbalance of frames with positive and negative contrasts. With experienced observers, we found no difference in thresholds between this 7-frame presentation and an 8-frame presentation which has balanced positive and negative contrasts, indicating

that this was not a confounding factor in our results. The contrasts of the presented gratings were set at discrete levels, varying in increments of 1.25%. For each trial subjects indicated whether or not they perceived a grating.

Procedure

Participants were seated 114cm from the monitor in a darkened room; the visual display subtended an area of $11.75 \times 8.8^\circ$ of visual angle. The order of conditions was randomised across subjects. A yes/no detection task using the method of constant stimuli was employed to determine the contrast threshold of subjects. For each trial, a high-pitched tone, with a duration of 100msec, signalled the presentation of the pattern within the grating. The onset of the tone and the pattern occurred simultaneously. An identical tone indicated the offset of the stimulus. Subjects verbally indicated whether or not they could see the stimulus while looking at the central fixation point. The experimenter keyed the subject's responses into the computer.

A set of practice trials enabled the experimenter to adjust the parameters for the actual task. For these practice trials, an initial range of contrasts, delineated by a minimum (0%) and a maximum (35%) contrast, was set; subjects did not perceive the stimulus at the minimum contrast and always perceived the stimulus at the maximum contrast. This range was evenly divided into eight levels of contrast and subjects received two presentations of the stimulus at each level of contrast in random order. One of the eight levels of contrast was set at 0% and served as catch trials. At the conclusion of the initial set of trials, the maximum contrast value was reduced, while the minimum contrast was increased. This served to produce a finer division of contrast levels, enabling the contrast threshold to be more precisely determined. Most subjects required two or three additional sets of practice trials in order to set a range of contrast consistently (approximately 10%) for the experimental trials. Using the contrast parameters established in these practice trials, subjects then received 64 experimental trials (8 presentations at 8 levels of contrast). In order to measure and correct for bias in subject response rates, catch trials (i.e. 0% contrast trials) were included in the practice and experimental trials.

Each condition required about 10 minutes to complete. The order of the two conditions was counterbalanced across subjects.

Results

Two individual contrast thresholds were calculated for each subject. For each condition, the threshold was calculated to be the corresponding contrast for the "corrected" 50% response rate. The rate of false alarms

TABLE 2
 Mean Contrast Thresholds of Normally Reading and
 Dyslexic Adults: Experiment 1 (Standard Errors in
 Parentheses)

<i>Condition</i>	<i>Normal Readers</i> (<i>N</i> = 19)	<i>Dyslexic Readers</i> (<i>N</i> = 19)
Transient	7.6% (0.7)	8.6% (0.8)
Sustained	8.8% (1.4)	10.5% (1.5)

during the 0% contrast trials for each condition was used to correct for subject bias to respond "yes" even if no signal were present; the "corrected" 50% response rate was determined by averaging the lowest response rate (the rate of false alarms during the 0% contrast trials) with 100% (the highest response rate). The overall rates of false alarms were low for both groups: 3.8% for dyslexics and 4.0% for control subjects in the transient condition and 4.3% for dyslexics and 3.5% for control subjects in the sustained condition.

The mean contrast threshold scores of normal and disabled readers are shown in Table 2. Two of the 80 cells contained missing data because the subjects' performance was too inconsistent within a given set of trials to obtain an accurate estimate of the contrast threshold. This resulted in a full set of data for 19 dyslexics and 19 normal subjects.

An analysis of variance with repeated measures was carried out on the contrast threshold scores. The independent variables were reading group (normal readers vs. dyslexics) and condition (transient vs. sustained), with repeated measures on the last factor. The main effects of condition and reading ability were not significant, and there was no interaction between reading ability and condition (all *P*s > .1). Thus, contrast thresholds of dyslexic adults were the same as those of the normal readers in both the sustained and the transient conditions.

Discussion of Experiment 1

The finding that the contrast thresholds of dyslexic adults did not differ from those of age-matched normal readers implies that transient system deficits as measured by our task do not persist into adulthood. However, it could be argued that our failure to detect transient deficits reflects certain methodological differences between the present task and that of Martin and Lovegrove.

First, the failure to replicate Martin and Lovegrove's (1987) findings with adults may reflect between-study differences in the stimulus durations

of the flicker contrast threshold task. Presentation times were 500msec in the Martin and Lovegrove study as compared to 105msec in the present study. Lovegrove et al. (1980; Slaghuis & Lovegrove, 1986b) have suggested that transient deficits may not be detectable at short stimulus durations, but only become noticeable at durations which approach those of normal eye fixations. However, the longer presentation times also allow for the greater contribution of performance factors such as eye movements and attentional differences.

In a pilot study, we examined flicker contrast thresholds where the stimuli for the flicker contrast task had been presented until a response was made (approximately 400–650msec). In this study, there were seven normal readers and eight adult dyslexics. The stimuli and procedures were identical to those just described except for the duration of the stimulus presentation. Although the effect of condition (transient vs. sustained) was significant [$F(1, 13) = 4.9, P < .05$], neither the effect of reading ability, nor the interaction between reading ability and condition, was significant, both $P_s > .1$. The mean contrast thresholds for the transient condition were: control subjects, 7.3% (SE = 0.8); dyslexic subjects, 6.9% (SE = 0.7). The mean contrast thresholds for the sustained condition were: control subjects, 5.3% (SE = 0.9); dyslexic subjects, 5.9% (SE = 0.6).

This study made us very aware of potential eye movement artefacts. The pilot subjects, as well as the experimenters who performed the same task, sometimes reported that, as an eye movement occurred, the grating appeared to "pop out," rendering the stimuli more salient. Specifically, in the counterphase presentation, positive and negative versions of the grating are alternated very rapidly. The grating is therefore hard to detect because the two images tend to cancel each other out. However, the slightest eye movement during the presentation will bring the two versions out of register so they no longer cancel. This raises the concern that previously obtained reports of differences in contrast thresholds between normal and disabled readers may reflect a confounding factor related to eye movements. On the other hand, even with potential eye movement artefacts, our pilot study did not demonstrate any differences between normal and dyslexic adult readers.

A second methodological difference is that we employed a simple forced-choice procedure (yes/no), whereas Lovegrove and colleagues employed a temporal two-alternative, forced-choice procedure. In the temporal two-alternative case, subjects must compare two successively presented stimuli to decide which contained the grating pattern (the other was a uniform field). This task controls for response bias more effectively than does the single-choice procedure, but places higher task demands on the subject (see following). It is possible that biases to report a grating even when it was not seen may have lowered our estimates of contrast

thresholds for dyslexic subjects. However, we found very few of the instances of false positives to the catch trials (at 0% contrast) that such a bias would produce. Furthermore, we corrected our results for the proportion that we did find. We do not believe that the procedure was the cause of the failure to replicate with adults but if, in fact, the original findings from Lovegrove and his colleagues are only observable with a two-alternative, forced-choice procedure and do not generalise to a yes/no procedure, then this would represent a significant constraint on the generality of their model. In any case, it seems unlikely that this methodological difference accounts for our failure to replicate Martin and Lovegrove's (1987) findings; similar results (i.e. no difference between dyslexic and normal readers in temporal-contrast sensitivity) were reported by Walther-Müller (1995), who did use a temporal two-alternative forced-choice task.

It is possible, moreover, that there are limitations to the conventional temporal two-alternative forced-choice task that may inflate the contrast thresholds of dyslexics. In Martin and Lovegrove's (1987) contrast threshold task, the first interval of 500msec was followed by a 500msec pause, and a second 500msec interval; the target grating appeared during one of the two intervals. This procedure requires that subjects' attention be maintained on a difficult task for a relatively long time (1500msec). Thus, performance on this task could reflect attentional factors as well as visual factors. The requirement that attention be maintained for a reasonably long period may work against dyslexics. It was this concern that led us to select the simpler yes/no procedure.

The results of this experiment suggest that dyslexics and normal reading adults do not differ in early visual processing skills. Two different conclusions are consistent with these results. The first is that transient channel deficits thought to be characteristic of dyslexic children do not persist to adulthood. An alternative conclusion is that the difference between these results and previous results with dyslexic children may reflect more general performance and attentional factors. These hypotheses are examined in the following experiment, where we use counterphase flicker contrast threshold tasks to evaluate the early visual processing skills of dyslexic children.

EXPERIMENT 2: CONTRAST THRESHOLD TASK— CHILDREN

In this experiment, we compared dyslexic and normal children's contrast sensitivity thresholds to briefly presented, flickering gratings. We first attempted to use the same task that we had administered to the adults in Experiment 1. The results again suggested no difference in contrast

thresholds, but they also suggested that this task was not appropriate for children. There was a high percentage of children for whom the data were too unstable to allow accurate threshold estimates and there was also a high percentage of false positives to the blank control trials. These preliminary results suggested that the task was at or beyond the limits of many of the children. To address these problems, four modifications were made to the procedure. First, a shrinking outline circle signalled the onset of the stimulus; this had the effect of capturing the children's attention and making the stimulus more salient. Second, the total presentation time for the stimulus was increased from 105msec to 240msec to make the task easier and less stressful. Although this was quite a bit longer than the 105msec of the first experiment, it was still short enough (180msec at full test contrast) to restrict the possibility of eye movements. Third, during practice and experimental trials, subjects were given negative feedback when they responded positively to 0% contrast catch trials to encourage them to pay attention to what they were seeing. Finally, the luminance level was increased.

To recapitulate, in the transient condition, a flickering low spatial frequency grating was presented. If dyslexic children have a transient channel deficit, they should show greater difficulty in detecting the flickering grating, and, as a result, their contrast thresholds should be higher than those of normal readers. In the sustained condition, a brief, high spatial frequency grating was presented without reversing contrast. According to the transient channel deficit model, the sustained pathway of dyslexics functions normally; therefore, dyslexics and normal readers should have similar contrast thresholds in the sustained condition.

Methods

Subjects

There were 24 dyslexic children and 35 control children. The following procedures were used to identify and classify children as dyslexic and as normal readers. The same procedures were followed for the remaining experiments reported in this paper.

Dyslexics. The dyslexic participants were selected from a patient population of a clinic that specialises in the assessment of reading disabilities. Children were recruited into this study if they met the following criteria: they met the standard exclusionary definition of dyslexia, they were from English-speaking backgrounds, and they had at least two years of instruction in English reading. Poor reading skills were not associated with social, emotional, cultural, pedagogical, or medical factors, as evidenced by detailed clinical assessments. All children had full

scale IQs of 80 or higher, as measured by the WISC-R or the WISC III. The children's reading disabilities were associated with poor word identification skills; all subjects scored below the 30th centile on the word recognition subtest of the Woodcock Reading Mastery Test-Revised (Form G; Woodcock, 1987).

Although we did not deliberately screen for attention deficit disorder, it should be noted that there were few (less than 10%) children who met these criteria in our dyslexic samples. The reason for this is that there were three other programmes that specialised in the assessment and treatment of attention deficit disorder in the same hospital setting that housed the reading clinic. Therefore, when attentional problems were primary, these children were referred to other sources.

Normal Readers. The normal reading participants were recruited through advertisements in the schools and in local newspapers. Normal readers were first screened to ensure that they were from English-speaking backgrounds and that they had at least two years of reading instruction in English. All control subjects scored above the 40th centile on the word recognition subtest of the Woodcock Reading Mastery Test-Revised (Woodcock, 1987). All subjects also had full scale IQs of 80 or higher as measured by two subtests (vocabulary and block design) on the WISC-R or the WISC III. As well, the DSM III-R structured interview for attention deficit disorder was administered to the parent¹. Any child with scores above the cutoff was eliminated from the subject pool. Control subjects were paid \$10.00 for their participation in this study.

In addition to the standardised tests of word recognition and intelligence, all children were also given the Word Attack (nonword reading) and Passage Comprehension subtests of the Woodcock Reading Mastery Test-Revised (Form G; Woodcock, 1987); and the Spelling subtest of the Wide Range Achievement Test-Revised (WRAT—Level 1; Jastak & Wilkinson, 1974).

¹The rationale for including dyslexic children who met the criteria for attention deficit disorder (ADD) and for excluding normal controls who met ADD criteria was as follows. There were a small number of dyslexic children whose parents or teachers reported a number of symptoms associated with ADD. However, the psychologist who assessed these children did not consider these children to have severe or primary attentional problems. None of these dyslexic children were on medication or receiving other treatment for behavioural problems. On the other hand, children in the control group whose parents reported a high number of ADD symptoms were excluded because it was possible that these children did have primary ADD; this possibility could not be confirmed because the control children did not have full psychological evaluations. Our procedures could only favour better performance by control subjects than by dyslexic subjects—a pattern that did not occur.

TABLE 3
Group Characteristics and Standardised Test Percentile Rank Scores of
Normally Reading and Dyslexic Children: Experiment 2 (Standard Errors in
Parentheses)

	<i>Normal Readers</i>	<i>Dyslexic Readers</i>
Mean Age (Year:Months)	10:4	10:8
Age Range (Year:Months)	7:8-12:11	8:5-13:1
% Male Subjects	60	79
WRMT ^a Word Recognition (%)	71 (2.8)	10 (1.8)
WRMT Word Attack (%)	58 (3.2)	9 (1.6)
WRMT Read Comprehension (%)	68 (3.3)	12 (1.8)
WRAT ^b Spelling (%)	56 (5.4)	6 (1.5)

^aWRMT = Woodcock Reading Mastery Test.

^bWRAT = Wide Range Achievement Test.

All participants had normal or corrected-to-normal vision. Only one participant, a dyslexic, was excluded due to visual problems. Table 3 shows the percentile rank scores for the standardised tests and the characteristics of the normal and dyslexic children who were included in the analyses of the threshold tasks. The dyslexic children consistently reveal word recognition and phonological deficits (as evidenced by performance on the Word Attack subtest, a nonword reading test) compared to the normal readers.

Equipment

The equipment was identical to that used in Experiment 1.

Stimuli

With the exception of the changes mentioned here, the stimuli were the same as in Experiment 1. The presentation of the gratings (with a radius subtending an angle of 2.2°) was signalled by an outline circle which shrank rapidly inward to encircle the spot where the test disk was to be presented. The ring had a width of 0.6° , with an initial inner radius of 5.2° , and appeared for a total presentation time of 20 frames (333msec). At the end of every four frames, the circle shrank inward until the inner radius was adjacent to, and surrounded the position of, the stimulus grating; the onset of the grating then occurred simultaneously with the offset of the circle. The warning ring had a luminance of approximately 99cd/m^2 and the background had a uniform luminance of 50cd/m^2 . The mean luminance of the test gratings was also 50cd/m^2 .

In both conditions, the gratings were presented for 240msec, including a central presentation time of 12 frames (180msec) at the test contrast and

onset and offset ramps of 2 frames (30msec) each, where the contrast increased and then decreased in steps of $\frac{1}{3}$ of the test contrast.

Procedures

With the exception of the changes mentioned here, the procedures were the same as in Experiment 1. Each trial began with the presentation of the shrinking warning circle. This event drew subjects' attention to the central portion of the screen, where the grating was presented at a selected level of contrast. Subjects indicated, by keying their response into the computer, whether or not they could see the stimulus while looking at the central fixation point.

Within each condition, subjects began with a set of 16 demonstration trials in which the contrast of the gratings was set at either 0% contrast (not visible) or 100% contrast (highly visible). Eight trials were presented for each level of contrast. Feedback was given at the end of each trial for correct (a short series of high-pitched tones) and incorrect (a low-pitched tone) responses. If subjects made any errors during the demonstration trials, the 16 trials were repeated until there were no errors.

After the demonstration trials, a set of practice trials enabled the experimenter to adjust the parameters for the actual task. For these practice trials, an initial range of contrasts was set; this range was evenly divided into eight levels of contrast and subjects received two presentations of the stimulus at each level of contrast in random order. One of the eight levels of contrast was set at 0% and served as catch trials. Negative feedback was given for all false positive trials during practice.

Subjects then received a full set of 64 trials (8 presentations at 8 levels of contrast) for that condition. Eight of these trials were always 0% contrast. When children inaccurately responded to these 0% trials, they were given feedback from the computer (a low-pitched tone).

Results

Two individual contrast thresholds were calculated for each subject, one for the transient condition and one for the sustained condition. The contrast level corresponding to the "corrected" 50% response rate of the subject was taken as the contrast threshold, as described in Experiment 1. For the transient trials, the rate of false alarms were 9% for dyslexics and 7% for control children; for the sustained trials, the false alarm rates were 13% for the dyslexics and 15% for the control children.

The mean contrast thresholds are shown in Table 4. For the sustained condition, data were too unstable for accurate threshold estimates for two dyslexic and five control children. For the transient condition, data were too unstable for threshold estimates for one control subject. This

TABLE 4
 Mean Contrast Thresholds of Normally Reading and
 Dyslexic Children: Experiment 2 (Standard Errors in
 Parentheses)

<i>Condition</i>	<i>Normal Readers</i> (<i>N</i> = 29)	<i>Dyslexic Readers</i> (<i>N</i> = 22)
Transient	4.2% (0.3)	4.9% (0.6)
Sustained	4.8% (0.6)	4.4% (0.3)

resulted in a full set of data for 22 dyslexics and 29 normal subjects. An analysis of variance with repeated measures was carried out on the contrast threshold scores. The independent variables were reading ability (normal readers vs. dyslexics) and condition (transient vs. sustained), with repeated measures on the last factor. There were no significant main effects, and no interaction between reading ability and condition (all $P_s > .1$).

Discussion of Experiment 2

Using the contrast threshold task, we found no significant differences between dyslexic and normal children's detection of gratings in transient conditions. The stimuli for Experiment 2 were designed to make the task easier and more engaging for children. Compared to the preliminary experiment, where we attempted to use the same 105msec presentations with the children as we had for the adults, the performance with the longer presentations and the warning circle improved: thresholds were lower, fewer children were excluded, and the rates of false positive responses were reduced for the transient condition (although not for the sustained condition). Under these improved circumstances, there were no between-group differences on any measures; and, most importantly, control and dyslexic children did not differ in contrast threshold in the transient condition.

The threshold values obtained in Experiment 2 are considerably lower than those obtained with adult subjects in Experiment 1. This decrease reflects the combined effects of attentional factors, increased luminance, and an increase in the stimulus presentation time (180msec at maximum contrast). Lovegrove and colleagues suggest that transient channel deficits only occur at presentation durations approximating normal fixation durations. Even with the increased stimulus presentation time used in this experiment, however, we still found no evidence of transient channel deficits.

EXPERIMENT 3: VISUAL SEARCH—CHILDREN

Although the children performed adequately in Experiment 2, the rates of false positives were still high for both the dyslexic and control groups. This result may indicate that the task was still too difficult for the children to master completely. In order to determine whether dyslexic children and normal children would perform similarly on visual processing tasks when the attentional demands were even further reduced, we compared their performance on "pop-out" visual search tasks (i.e. Treisman's visual search paradigm; Treisman, 1986; Treisman & Gelade, 1980; Treisman & Gormican, 1988).

Treisman's visual search paradigm was adapted to examine transient and sustained channel functioning. The Treisman visual search paradigm is regarded as sensitive to the presence of low-level visual deficits (Arguin & Bub, 1994; Mapelli & Behrmann, 1994), but avoids the limitations of conventional psychophysical tasks by placing minimal demands on attention and memory, and it readily captures the attention and interest of subjects. Children, especially, find it comparable to video arcade games, and are used to the competitive challenge of reaction time measures in this context. Thus, tasks such as the Treisman paradigm are automatic and engaging rather than attention demanding—a true test of early visual processing rather than a measure of attentiveness.

Furthermore, suprathreshold tasks such as the Treisman paradigm provide an intermediate measure between threshold tasks, which are of weak external validity when applied to reading, and actual tests of reading, in which visual processes are secondary to linguistic processes. Hitherto, evidence for low-level visual deficits has typically involved comparing normal and dyslexic readers' performance on threshold or near-threshold tasks, generally under low luminance conditions. However, reading is a suprathreshold task that is typically performed under high luminance (regular classroom lighting) conditions. If the results of the threshold level research are to be generalisable to the suprathreshold conditions under which reading normally occurs, low-level visual deficits should be observable in suprathreshold tasks, such as the Treisman paradigm, as well (see Evans, Drasdo, & Richards, 1994, for a similar argument).

In this experiment we presented participants with four different visual search tasks where participants indicated if a target appeared among distractors. The number of distractors was manipulated and errors and reaction time were recorded. All the conditions required single feature searches. Two control conditions (colour search and orientation search) used stimuli which should activate sustained more than transient mechanisms and two conditions (low spatial frequency search at low

and high contrast) used stimuli which should activate transient more than sustained mechanisms.

Treisman's visual search experiments have shown that the time required to detect a target among distractors may be independent of the number of distractors. In this case, the processing of all the items in the display must occur, in some sense, in parallel. Whether or not search is parallel depends first on the feature which distinguishes the target from the distractors. For example, targets which differ in colour, orientation, or size from the distractors can all lead to parallel search, where the target "pops out" without requiring any directed attention (Treisman, 1986; Treisman & Gelade, 1980). Conversely, some features cannot be processed so rapidly and can only be found among an array of distractors by focusing attention on each item in turn (i.e. by searching serially through the array) until the target object is processed. For example, straight line targets among curved distractors or vertical targets among tilted distractors produce serial search patterns (Treisman, 1991; Treisman & Gormican, 1988). However, it is not only the type of feature that determines whether the search is parallel or serial, but also the degree of difference along that feature. Long lines might "pop out" of a field of short lines, but if the length difference were made very small, search becomes slow and serial (Treisman, 1991; Treisman & Gormican, 1988). In this respect, the effect of number of distractors on reaction time can be taken as a measure of the discriminability of stimuli: More discriminable differences between target and distractors are processed more rapidly (Pashler, 1987). We used this aspect of the search task to compare the discriminability of targets which require transient system processing.

We predicted that if dyslexics have transient processing deficits, then dyslexics would perform more slowly than normal readers on targets that are distinguished from distractors by a feature requiring primarily transient channel processing (i.e. spatial or temporal frequency differences in the low spatial and high temporal frequency ranges); dyslexics will be slower because the differences will be less distinguishable to their impaired transient channel. However, dyslexics and normal readers should exhibit no differences in performance for targets differing in features processed preferentially by the sustained channels (i.e. colour or orientation differences).

To test the transient channels we chose two spatial frequency search conditions. Subjects searched for a small patch of low (1cpd) spatial frequency grating amid arrays of distractor patches filled with medium (4cpd) spatial frequency gratings. They did so under high contrast or low contrast conditions. Although squarewave gratings do contain high spatial frequency components (e.g. due to the sharp edges), at the spatial frequencies of the stimuli used in this experiment, the transient channel is more sensitive than the sustained channel, and will therefore be likely to

mediate detection of the gratings (Breitmeyer, 1984; Green, 1981, 1984). According to the transient-deficit model, dyslexics should perform more slowly than normal readers on both spatial frequency search conditions.

It is possible that the two gratings are so highly discriminable that they remain easy to detect even with transient deficits. Therefore, the experiment was also run at low contrast where the gratings were only just visible. Through pilot testing, the contrast level for low contrast stimuli was set to be as low as possible while still maintaining parallel search for normal subjects. Because the low contrast stimuli are just above threshold for normal readers, and because, according to the transient deficit model, dyslexics are claimed to have contrast thresholds that are higher than the contrast thresholds of normal readers, then the difficulty dyslexics have in processing transient channel stimuli will be exacerbated, and differences between normal readers and dyslexics should be readily apparent.

Finally, two conditions (colour and orientation) testing the sustained channels were added as controls to show that the dyslexic readers do not show any general deficits in visual search tasks. Colour vision is mediated preferentially by sustained mechanisms (Breitmeyer, 1984; Williams, Breitmeyer, Lovegrove, & Guteirrez, 1991), so we predicted similar search patterns for normals and dyslexics in the colour search condition (a red target among green distractors). Similarly, given that the sustained channel is more sensitive to orientation than the transient channel (Breitmeyer, 1984; Green, 1984) and that orientation tuning does not differ between normal readers and dyslexics (Lovegrove et al., 1986), we predicted no differences in visual search patterns between controls and dyslexics in the orientation search condition (a 45° diagonal bar among vertical bars).

Methods

Subjects

There were 22 dyslexic children and 22 control children. The background characteristics and the standardised test percentile rank scores for each group are presented in Table 5.

Equipment

The visual search task was run on the same equipment as in the contrast threshold experiments.

Stimuli

There were two control conditions. In the first condition, "colour search," the target was a red circle, 1cm in diameter, subtending a visual

TABLE 5
Group Characteristics and Standardised Test Scores of Normally Reading and
Dyslexic Children: Experiment 3 (Standard Errors in Parentheses)

	<i>Normal Readers</i>	<i>Dyslexic Readers</i>
Mean Age (Years:Months)	10:2	10:0
Age Range (Years:Months)	8:2-11:11	8:1-12:8
% Male Subject	73	68
WRMT ^a Word Recognition (%)	82 (3.8)	10 (1.9)
WRMT Word Attack (%)	70 (4.2)	12 (3.3)
WRMT Read Comprehension (%)	73 (3.9)	13 (2.8)
WRAT ^b Spelling (%)	69 (6.3)	5 (1.1)

^aWRMT = Woodcock Reading Mastery Test.

^bWRAT = Wide Range Achievement Test.

angle of 1°. The distractors were green circles of equivalent size. The luminance of both the target and distractors was approximately 62cd/m². For this and all other visual search conditions, the background screen luminance was approximately 75cd/m².

In the second control condition, the "orientation search" condition, the target was a black bar, subtending 0.15° × 1° of visual angle and tilted at a 45° angle with the top of the bar to the right. The distractors were vertical black bars the same size as the target.

There were two transient condition search tasks. The stimuli were vertical squarewave gratings presented within a square aperture subtending 1° of visual angle horizontally and vertically. The target grating patch had a spatial frequency of 1cpd (a single pair of light and dark bars); the distractor grating patches had a spatial frequency of 4cpd. The spatial frequencies span the range of font sizes for optimal reading conditions (Legge, Pelli, Rubin, & Schleske, 1985; Parish & Sperling, 1991). The target and distractors were the same size, although they were of different spatial frequencies, thereby eliminating size as a possible cue. In one spatial frequency search condition, stimuli were high contrast. The target and distractors were presented at a Michelson contrast of 99%; at this contrast, squares of different spatial frequencies are readily distinguishable from each other and from the background, both of which have a mean luminance of 50cd/m². In the second spatial frequency search condition, the stimuli were low contrast. The targets and distractors were presented at a Michelson contrast of 4%. Pilot testing revealed that normal readers were unable to detect the target in the visual search display when the contrast was less than 2%. Because some normal readers were unable to discriminate between stimuli at a contrast of 3% (also see Moraglia, 1989; Treisman, 1986), we set the contrast at 4%. At this contrast level, normal readers were able to maintain parallel search strategies.

Procedure

Participants were seated 57cm from the visual display which subtended an area of $23.5^\circ \times 17.6^\circ$. A fixation point, subtending 0.5° of visual angle, was maintained on the screen at all times. The positions of the target and the distractors were randomly determined for each trial. The stimuli were randomly assigned to one position in a grid of 18 possible locations; if a location had already been "filled" by another object, a new location was assigned. (The grid, which was not visible, consisted of three circles of varying radii. Six radial lines intersected each circle, resulting in 18 intersections and potential locations. The radial lines were equally spaced at intervals of 60° , the position of the lines was different for each of the 3 circles.) In all conditions there were 6 levels of distractor: 2, 4, 6, 8, 10, and 12 distractors. When the target was present, it replaced one of the distractors.

In each condition, the subject was shown the target and the distractor stimuli before any of the trials commenced. Then, the subject heard a short warning tone, and after a pause of 500msec, the stimuli appeared on the screen. Subjects responded on a keyboard whether the target was present or absent. Reaction time (in msec) and response accuracy was recorded. After a 500msec pause, the next trial began. For each condition, there was a block of 24 practice trials, followed by a block of 96 experimental trials (8 trials at each of 6 levels of distractor for target present and target absent trials).

Conditions within the visual search task were presented in two blocks of three tasks each, with one block occurring at the beginning of a larger battery of tests and the other block occurring at the end of the battery. The order of conditions within each block was fixed for all subjects. The first block of visual search tasks included colour search and low contrast spatial frequency search in that order. The second block included orientation and high contrast spatial frequency search in that order. The two blocks were separated by approximately 80 minutes. Each individual visual search condition lasted about seven minutes.

Results

Analyses of variance with repeated measures were carried out on the error data and then on the reaction time data. Each of the four conditions was analysed separately. For each condition, absent target trials and present target trials were analysed separately. For each analysis, the independent variables were group (control vs. dyslexic) and number of distractors (2, 4, 6, 8, 10, 12), which was a repeated measure. When significant main effects of distractor occurred, trend analyses were conducted.

Additional analyses were carried out to compare directly the high and low contrast spatial frequency search conditions; contrast level was added as an independent variable to the model.

Error Data

Due to equipment errors, data were lost for one dyslexic subject and for one control subject on the colour task, and for one dyslexic subject on the orientation task. The rate of errors on each task (collapsed across distractors) is shown in Table 6.

For the eight analyses of the error data, there were no group by distractor interactions. In fact, analyses of the data indicated that there were never any results suggesting linear error trends for the dyslexic or normal control subjects. The dyslexics had higher error rates in 3 cases: colour present [$F(1, 41) = 5.16, P < .05$] orientation present [$F(1, 41) = 9.67, P < .01$], and high contrast spatial frequency absent trials [$F(1, 42) = 6.55, P < .01$]. These data are slightly supportive of the transient-deficit hypothesis in that dyslexic subjects did have higher error rates than controls on one of the four transient measures. However, the finding that dyslexics also had significantly higher error rates on two sustained tasks suggests that dyslexics made more errors than control subjects on visual tasks in general.

Analyses were conducted to compare the low contrast condition of the

TABLE 6
Visual Search Error Rates (%) of Normally Reading and Dyslexic
Children: Experiment 3^a

<i>Task/Condition</i>	<i>Normal Readers</i>	<i>Dyslexic Readers</i>
<i>Colour</i>	(<i>N</i> = 21)	(<i>N</i> = 21)
Present	3.0	6.3 ^c
Absent	3.9	4.6
<i>Orientation</i>	(<i>N</i> = 22)	(<i>N</i> = 21)
Present	2.1	4.6 ^b
Absent	2.4	5.2
<i>Low Spatial Frequency</i>		
High Contrast	(<i>N</i> = 22)	(<i>N</i> = 22)
Present	2.8	4.5
Absent	2.0	5.3 ^c
Low Contrast	(<i>N</i> = 22)	(<i>N</i> = 22)
Present	2.1	4.1
Absent	3.0	2.9

^aThere were 48 absent trials and 48 present trials in each condition.

^b $P < .05$; ^c $P < .01$.

spatial frequency search task to the high contrast condition of the spatial frequency task. The independent variables were group (normal vs. dyslexic), condition (high vs. low contrast), and number of distractors (2, 4, 6, 8, 10, 12). There was no significant group by contrast interaction. Thus, dyslexic subjects did not make relatively more errors than normal subjects under low contrast conditions.

Reaction Time Data

The overall reaction times for the dyslexics and normal readers (collapsed across distractors) are presented in columns 4 and 5 of Table 7. The slopes for the normal readers and the dyslexics are presented in columns 2 and 3 of Table 7.

For the eight analyses, there were no significant interaction effects between group and distractor, indicating that the same types of searches were found both for normal and for dyslexic children. Furthermore, analyses of the variable of "distractor" revealed that the searches were parallel for all subjects; there were no significant changes in search time as a function of the number of distractors.

There were between-group differences on two of the eight analyses. Dyslexics were reliably slower than control subjects on orientation-present trials [$F(1, 41) = 5.80, P < .05$] and orientation-absent trials [$F(1, 41) = 7.40, P < .01$].

TABLE 7
Visual Search Slopes and Reaction Times: Experiment 3 (Standard Errors in Parentheses): Slopes Given in Msec Per Distractor

	<i>Normals'</i> <i>Slope</i>	<i>Dyslexics'</i> <i>Slope</i>	<i>Normals'</i> <i>Means</i>	<i>Dyslexics'</i> <i>Means</i>	<i>Difference</i> <i>Means</i>
<i>Colour</i>					
Present	0.1 (1.2)	2.0 (1.4)	642 (15)	713 (17)	71
Absent	-0.8 (1.8)	0.8 (1.4)	664 (14)	779 (27)	115
<i>Orientation</i>					
Present	0.2 (1.4)	-0.4 (2.4)	701 (16)	824 (20)	123 ^a
Absent	0.7 (1.4)	-1.8 (2.7)	758 (19)	953 (29)	195 ^b
<i>Low Spatial Frequency</i>					
<i>High Contrast</i>					
Present	1.9 (0.8)	1.2 (2.6)	721 (18)	768 (15)	47
Absent	-3.0 (1.2)	-2.8 (1.4)	760 (19)	850 (20)	90
<i>Low Contrast</i>					
Present	0.9 (2.4)	-2.0 (1.6)	837 (21)	946 (20)	109
Absent	-8.1 (5.0)	-9.5 (4.3)	1090 (28)	1249 (38)	159

^a $P < .05$; ^b $P < .01$.

Analyses were carried out to compare performance on the low and high contrast conditions of the spatial frequency task. There were no significant group or group by contrast effects. However, for both the absent and present trials, low contrast stimuli produced longer reaction times than high contrast stimuli [$F(1, 42) = 111.84, P < .01$ for absent trials, and $F(1, 42) = 47.86, P < .01$, for present trials].

Although dyslexic subjects had longer reaction times than normal readers on the orientation search task (present and absent trials), these results do not support the hypothesis for a transient deficit in dyslexia, as this task reputedly assesses a sustained channel function.

EXPERIMENT 4: VISUAL SEARCH FOR FLICKERING TARGETS

We next examined whether dyslexics would perform more poorly than normal readers on detecting a flickering target disc among static distractors. As the transient channel is the flicker, or motion-processing channel (e.g. Breitmeyer, 1980, 1984; Green, 1981, 1984), the transient channel should mediate detection and processing of the target stimuli. If dyslexics have a transient channel deficit, they should be poorer at detecting the target and distinguishing it from the distractor stimuli.

As in the spatial frequency search conditions, a low contrast condition was included to exacerbate the difficulty of distinguishing the flickering target. The contrast level for the low contrast flicker search condition was based on results of pilot studies that indicated the lowest possible contrast level at which normal readers would maintain parallel search strategies.

Finally, it is important to note that flickering patches and static patches of the same mean physical luminance appear to have different brightness (Magnussen & Glad, 1975). We observed in our display that flickering stimuli appeared darker than the static distractors even though they were, in fact, of equal luminance. To eliminate this unwanted cue to the identity of the target, we assigned the brightnesses of distractor discs randomly within a range that included both the physical and the apparent brightness of the flickering disc.

Methods

Subjects

There were 26 dyslexic children and 26 control children. The background characteristics and the standardised test percentile rank scores for each group are presented in Table 8. All of the dyslexic and 14 of the control children were subjects in pilot contrast threshold

TABLE 8
 Group Characteristics and Standardised Test Percentile Rank Scores of
 Normally Reading and Dyslexic Children: Experiment 4 (Standard Errors in
 Parentheses)

	<i>Normal Readers</i>	<i>Dyslexic Readers</i>
Mean Age (Years: Months)	10:6	10:5
Age Range (Years: Months)	7:8-13:7	7:6-13:11
% Male Subjects	77	73
WRMT ^a Word Recognition (%)	79 (2.7)	13 (1.9)
WRMT Word Attack (%)	55 (3.5)	11 (2.1)
WRMT Read Comprehension (%)	75 (3.2)	13 (2.8)
WRAT ^b Spelling (%)	69 (5.0)	9 (2.0)

^aWRMT = Woodcock Reading Mastery Test.

^bWRAT = Wide Range Achievement Test.

experiments; 12 control children had been participants in Experiment 2, also a contrast threshold experiment.

Equipment

The equipment and presentation of the stimuli were identical to the descriptions given in Experiment 3.

Stimuli

There were two sustained (or control) search conditions and two transient search conditions. The sustained search conditions were again colour search and orientation search, as described in Experiment 3. In addition, there were two flicker search conditions to evaluate transient processing. The two transient condition tasks required subjects to search for a flickering target among static distractors. Targets and distractors were 1° circles. The target underwent squarewave modulation in luminance around a mean predetermined luminance. The value of the predetermined luminance was darker than the screen luminance. Because subjects might rely on "perceived" luminance as a cue for the flicker search conditions (see Magnussen & Glad, 1975), there were three possible distractor luminances. The luminance of the distractors was set so that the apparent brightness of the flickering target fell within the range of luminances of the static patches, thereby eliminating luminance as a possible cue. The actual distractors presented at any one trial were randomly selected from the possible distractors.

The two search conditions differed in terms of the temporal frequency of the target. In the "medium flicker rate" condition, the target circle alternated in luminance at a rate of 16.65Hz. The time-averaged luminance

of the target was set to be 5% darker than the screen luminance (approximately 70cd/m^2). The contrast or modulation depth of the target was 4%. The first distractor was equivalent in luminance to the time-averaged luminance of the target. The 3 luminance levels randomly assigned to the distractors were approximately 60cd/m^2 , 64cd/m^2 , and 70cd/m^2 .

In the "high flicker rate" condition the target was modulated in luminance at 33.33Hz. The time-averaged luminance of the target was set to be 6% darker than the screen luminance (approximately 67cd/m^2); the contrast or modulation depth was 6%. The 3 luminance levels randomly assigned to the distractors were approximately 57cd/m^2 , 62cd/m^2 , and 67cd/m^2 .

As in Experiment 3, the contrast levels for the flicker conditions were based on results of pilot studies that indicated the lowest levels at which normal readers would maintain parallel search strategies.

Procedures

The presentation of the stimuli was identical to the procedures given in Experiment 3. All subjects performed the four visual tasks in two different blocks (each consisting of two tasks). The ordering of tasks within and between blocks was randomised across subjects. The blocks were part of a larger battery of tests. The two blocks were separated by approximately 60 minutes. Each individual visual search condition lasted about seven minutes.

Results

The data were analysed using the same procedures as described for Experiment 3.

Error Data

As can be seen from Table 9, the error rates were low for all tasks and for both groups of subjects. The results of the analyses of variance on the error data yielded one significant group by distractor interaction. This occurred for the medium flicker rate present trials [$F(5, 250) = 2.88$, $P < .05$]. Trend analyses revealed significant quadratic trends for both normal and dyslexic groups. The interaction was obtained because the 2 groups performed similarly in conditions of 2 and 12 distractors, whereas dyslexics made more errors than normal in conditions of 6 and 10 distractors. These data by themselves are not reflective of particular deficits in transient channel processing.

There were significant between-group differences on two measures. Dyslexics made more errors than normal readers on orientation absent

TABLE 9
Visual Search Error Rates (%) of Normally Reading and Dyslexic
Children: Experiment 4^a

<i>Task/Condition</i>	<i>Normal Readers</i> (<i>N</i> = 26)	<i>Dyslexic Readers</i> (<i>N</i> = 26)
<i>Colour</i>		
Present	2.2	3.1
Absent	2.2	2.7
<i>Orientation</i>		
Present	2.0	2.9
Absent	1.8	4.3 ^b
<i>Medium Flicker Rate</i>		
Present	2.1	3.1
Absent	1.6	3.9
<i>High Flicker Rate</i>		
Present	1.9	4.8
Absent	1.5	3.0 ^b

^aThere were 48 absent trials and 48 present trials in each condition.

^b $P < .05$.

trials [$F(1, 50) = 7.55, P < .01$] and fast flicker absent trials [$F(1, 50) = 8.18, P < .01$]. There was no systematic trend for dyslexics to make more errors on the flicker tasks than on the sustained tasks.

Analyses of error rate were conducted to compare the medium flicker rate conditions to the high flicker rate condition of the flicker search task. The independent variables were group (normal vs. dyslexic), condition (medium vs. high flicker rate), and number of distractors (2, 4, 6, 8, 10, 12). There was no significant group by condition interaction. Thus, dyslexic subjects did not make relatively more errors than normal subjects under either flicker rate condition.

Reaction Time Data

The visual search slopes for the normal and dyslexic children, as well as their average reaction times (collapsed over distractors) for each task, are shown in Table 10.

There were no significant group by distractor interactions for any of the analyses, all $P_s > .1$. Analyses of the effect of number of distractors on search times produced no significant main effects for the eight analyses, all $P_s > .1$. Between-group differences were obtained for the orientation task only. Dyslexics were slower than normal readers for both present and absent trials [$F_s(1, 50) > 3.89, P_s < .05$]. In addition, analyses were carried

TABLE 10
 Visual Search Slopes and Reaction Times: Experiment 4 (Standard Errors in
 Parentheses): Slopes Given in Msec Per Distractor

	<i>Normals'</i> <i>Slope</i>	<i>Dyslexics'</i> <i>Slope</i>	<i>Normals'</i> <i>Means</i>	<i>Dyslexics'</i> <i>Means</i>	<i>Difference</i> <i>Means</i>
<i>Colour</i>					
Present	1.8 (0.9)	0.9 (0.8)	690 (16)	708 (13)	18
Absent	-1.6 (1.5)	-3.8 (1.4)	746 (20)	775 (16)	29
<i>Orientation</i>					
Present	-0.1 (0.5)	-0.6 (1.8)	718 (12)	831 (23)	113 ^a
Absent	1.6 (1.1)	1.3 (2.7)	795 (17)	976 (31)	181 ^a
<i>Medium Flicker Rate</i>					
Present	1.5 (0.8)	0.8 (0.9)	832 (17)	877 (18)	45
Absent	-0.9 (2.2)	4.3 (1.2)	1040 (24)	1192 (35)	152
<i>High Flicker Rate</i>					
Present	1.5 (1.3)	2.6 (2.5)	862 (16)	957 (26)	95
Absent	3.9 (1.8)	5.1 (2.5)	1112 (26)	1178 (33)	66

^a $P < .05$.

out to compare performance on the medium flicker rate condition to the high flicker rate condition of the flicker search task. There were no significant group or group by flicker rate condition effects. High flicker rate stimuli produced longer reaction times than medium flicker rate stimuli for present trials only [$F(1, 50) = 7.66, P < .01$]. Thus, in this study, the dyslexics did not perform more poorly than the normal readers on the flicker detection task, although there were other visual search tasks where their performance was poorer.

Discussion of Experiments 3 and 4

There was no evidence of systematic transient channel deficits associated with childhood dyslexia. The one systematic finding of Experiments 3 and 4 pertained to the orientation tasks. In Experiment 3, dyslexics made more errors than normal readers on orientation-present trials, and they were reliably slower on the orientation-present and orientation-absent trials. In Experiment 4, the dyslexic children made more errors than normal readers on the orientation-absent trials, and again they were reliably slower on the orientation-present and orientation-absent trials.

These consistent differences on the orientation task might reflect differences in the reading levels of the children, rather than potential visual processing deficits associated with dyslexia. Specifically, better readers may have more detailed representations of letters, including

information about their shape and the orientations of their parts. As a result, performance on the orientation task may be associated with level of reading skill.

One way to examine this hypothesis is to compare dyslexic and normal readers who have similar levels of word recognition skills. If dyslexics do have a basic visual processing deficit, then they should perform more poorly than their reading-matched peers on the orientation tasks. However, if reading level contributes to visual search performance, then there should be no differences between dyslexics and normal readers of the same reading level. Because of an insufficient number of children in any one experiment to make this comparison, we pooled the data from Experiments 3 and 4. We selected normals and dyslexics who had raw word identification scores in the same range, thus eliminating the dyslexics with the very lowest scores, and the normals with the highest scores. This resulted in the selection of 13 normal subjects and 21 dyslexic subjects with raw scores between 50 and 73. The average age of the dyslexics was 11:0 and that of the normals was 8:8. The two groups were well matched in terms of raw word identification scores (65 and 62 for the normals and dyslexics respectively), but because of age differences there were large differences in terms of the percentile scores (72 and 17 for the normals and dyslexics respectively). The percentile scores for the dyslexics are slightly higher than those for the entire group, and the percentile scores for the normals are slightly lower than those for the entire group.

The orientation error and reaction time data were re-analysed using this subsample of subjects. Because preliminary analyses showed large correlations between age and performance on these search tasks, age was added as a covariate to the model. (Age was not used as a covariate in our previous analyses, as the subjects were matched for age.) None of the main effects of group for the error or reaction time analyses were significant, suggesting that reading level does contribute to visual search performance.

GENERAL DISCUSSION

In Experiment 1, adult dyslexics' performance on a flicker contrast threshold task was similar to that of normal age-matched readers. These data do not support the hypothesis of transient channel deficits in adults with childhood histories of dyslexia. Because Experiment 1 was not a developmental study, we were unable to determine whether the results reflected the fact that transient channel deficits subside after childhood or whether earlier reports showing transient channel deficits in dyslexic children were influenced by other factors. In order to address these issues, we conducted a contrast threshold study to examine the early visual

processing skills of dyslexic children. In addition, we attempted to apply another paradigm, the suprathreshold Treisman visual search paradigm, to the study of transient deficits. The contrast threshold studies and the visual search studies did not reveal any of the differences between dyslexic and normal children predicted by the transient deficit model.

For the contrast threshold tasks administered to children (Experiment 2), we did not find higher flicker contrast thresholds for dyslexics than for normals in the transient conditions. It could be argued, of course, that our failure to find differences reflects the fact that we failed to use precisely the same methods as Lovegrove and his colleagues. For example, our stimuli were of slightly shorter duration than those of Martin and Lovegrove (1987). However, similar patterns were also reported for the adult subjects in Experiment 1: Dyslexics and normal reading adults showed the same contrast thresholds whether the stimuli were presented for a brief time (105msec) or until a response was made.

In addition, we used a single stimulus procedure, whereas Martin and Lovegrove (1987) used a two-alternative forced-choice task. However, the difference in methods is unlikely to account for the differences in results; other researchers have used two-alternative temporal forced-choice tasks, but still found no differences between dyslexic and normal readers (e.g. Walther-Müller, 1995). Furthermore, if the original findings of differences between normal and dyslexic readers cannot generalise from a two-alternative temporal forced-choice procedure to a single stimulus procedure, then the original findings and the support they provide for the transient-deficit model are not very robust.

Is the contrast threshold task a fair measure of low-level processing in children? The rates of false alarms in Experiment 2 were fairly high, despite adapting the task to promote greater interest. Although the false alarm rates were similar for dyslexic children and normal subjects, the high rates suggest that these threshold tasks may not be well suited to children in general. There were, as well, a sizeable number of children excluded because of unstable response patterns (e.g. reporting fewer detections of the stimuli at higher contrast than at lower contrasts). Similar difficulties with high subject exclusion rates have been reported by other researchers investigating contrast sensitivity in dyslexic and normally reading subjects (e.g. Evans et al., 1994). Certainly, the high subject exclusion rates and fairly high rates of positive responses to catch trials in the threshold tasks in this study indicate that measurement of transient pathway deficits in children using this type of task may be problematic. Similar concerns must be raised for previous studies as well.

In Experiments 3 and 4, we presented a suprathreshold Treisman visual search paradigm, which was intended to extend the applicability of the transient-deficit model, and which provided a more hospitable environ-

ment for measuring transient pathway functioning in children. The children enjoyed performing these short tasks. One measure of its success was the low rates of false positive responses; these low rates were even found for the low contrast tasks, which were just above threshold for normal readers.

There were several findings across the two experiments in which visual search tasks were administered. First, for all tasks, both dyslexic and normal children engaged in parallel searches. Introducing targets that require more transient processing did not disrupt this pattern for the dyslexics. Second, in some instances, dyslexic subjects were slower and made more errors on search tasks than normal subjects. Specifically, dyslexic subjects were slower in the orientation conditions of both visual search experiments (Experiments 3 and 4).

The slower response times of dyslexics is a widespread finding (Ackerman, Anhalt, Holcomb, & Dykman, 1986; Blank, 1978; Hardy, McIntyre, Brown, & North, 1989; Nicolson & Fawcett, 1990), which may reflect a number of deficits such as decision-making factors or motoric deficits. Post-hoc analyses of the orientation data suggest that between-group differences on visual tasks, even those purporting to measure low-level visual processing, may reflect the subjects' reading experiences. When reading levels of dyslexics and normal readers are roughly equated, as was attempted in this study, differences in at least one task disappear. Thus, the visual search experiments (Experiments 3 and 4) failed to provide evidence for transient channel deficits under conditions which approximated normal reading conditions.

Based upon the research presented here, we suggest that there are three factors that require further consideration in research on the role of low-level visual deficits in developmental dyslexia. One factor involves the generalisability of the transient model to conditions under which reading normally occurs. Our studies using the Treisman visual search paradigm found no evidence for transient channel deficits under conditions which more closely approximated normal reading conditions (see also Evans et al., 1994). Further consideration should be given to exploring the transient-deficit model by applying other experimental paradigms. At present, the model is supported by a limited number of paradigms which are not representative of normal reading conditions. And even within this limited range, support is not consistently found (Walther-Müller, 1995; this paper, Experiments 1 and 2).

A second factor in research on the role of low-level visual deficits in dyslexia is that the assessment of visual processing in children in general may be confounded by attentional and performance factors such as fatigue, boredom, and distractibility. For example, in the present studies, a number of normal and dyslexic subjects experienced fatigue and eye strain

during the contrast threshold task; several subjects, including adults, commented on the subjective difficulty of detecting the stimuli and of focusing attention on the appropriate portion of the display. It is likely that children respond less consistently in such situations. This suggestion is buttressed by the high false alarm rates and the exclusion rates among children in the contrast threshold tasks. The history of academic failure and learning difficulties experienced by dyslexics, especially as children, makes them even more vulnerable than normal children to such interference (e.g. Hallahan, Gajar, Cohen, & Tarver, 1978).

Similarly, with regard to contrast threshold tasks, the long presentation times involved in two-alternative temporal forced-choice tasks may also introduce confounds from performance and attentional factors. The two-alternative temporal forced-choice task in Martin and Lovegrove (1987) required about 1500msec per trial compared to less than 500msec for the present tasks using the method of constant stimuli. The long presentation times of the former method requires attention to be maintained over about 1500msec and this might place greater demands on dyslexics' attentional resources than on those of normals. In contrast, detection response to a single stimulus presentation requires a lower level of attentional allocation for a short period of time. Perhaps as attentional demands are lowered, threshold values between dyslexics and normals become more similar.

A third factor that must be considered in research on visual deficits in dyslexia is the high comorbidity between reading disabilities and attention deficit disorder (August & Garfinkel, 1990; Bruck, 1989). Given that the tasks used in these experiments do require attention at both the encoding and response stages, poor performance might reflect characteristics associated with attentional difficulties rather than characteristics of dyslexia (see Evans et al., 1994, for a similar argument). Pooling across the dyslexic samples in the present sample, only 10% of the children met one of the traditional criteria for attention deficit disorder; these children obtained high scores on both the Parent and Teacher forms of the Conners Rating Scales. Thus, there were very few children in our studies with comorbid attentional problems. For reasons mentioned in the Introduction (availability of hospital clinics specialising in attention deficit disorder), this sample of dyslexics is atypical in terms of the low rates of concomitant attentional problems. If excluding children with possible attentional problems from our sample resulted in a dearth of evidence for transient deficits, this suggests that the evidence supporting transient channel deficits may be attributable to attentional factors. There is little information on the characteristics of the children tested by Lovegrove and his colleagues; if these were simply drawn from school samples, it is highly likely that there were a number of children with primary attentional problems which

could affect performance on the psychophysical tasks. Perhaps previous studies on the visual processing skills of dyslexic children included a large proportion of children with attentional problems.

To conclude, the data suggest that several factors must be considered when investigating the possible role of transient deficits in developmental dyslexia. First, in order to be a plausible causal model of developmental dyslexia, researchers must be able to demonstrate the existence of transient channel deficits under conditions that more closely approximate normal reading conditions. Second, attentional and performance factors contribute to differences between normal readers and dyslexics on psychophysical tasks that require a high degree of vigilance and attention. Research into the existence of visual deficits in dyslexia must take these factors into account. Third, the characteristics of subject samples should be carefully examined; the comorbidity of attentional problems and dyslexia poses a potentially serious confound to research into the existence of visual deficits in dyslexia. Finally, following these guidelines and particularly using tasks which more effectively engage the interest and attention of the subjects, we have been unable to find the performance losses predicted by the transient deficit model.

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