

Psychophysical Indexes of Temporal Processing Abnormalities in Children With Developmental Dyslexia

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Children with dyslexia and children progressing normally in reading performed several perceptual tasks to determine (a) the psychophysical measures that best differentiate children with dyslexia from children with average reading abilities; (b) the extent of temporal processing deficits in a single, well-defined group of children with dyslexia; and (c) the co-occurrence of visual and auditory temporal processing deficits in children with dyslexia. 4 of our 12 psychophysical tasks indicated differences

in temporal processing ability between children with dyslexia and children with good reading skills. These included 2 auditory tasks (dichotic pitch perception and FM tone discrimination) and 2 visual tasks (global motion perception and contrast sensitivity). The battery of 12 tasks successfully classified 80% of the children into their respective reading-level groups. Within the group of children with dyslexia who had temporal processing deficits, most were affected in either audition or vision; few children were affected in both modalities. The observed deficits suggest that impaired temporal processing in dyslexia is most evident on tasks that require the ability to synthesize local, temporally modulated inputs into a global percept and the ability to extract the resultant global percept from a noisy environment.

A body of psychophysical and physiological research suggests a temporal processing deficit in individuals with dyslexia. This research has focused on the perception and integration of rapid, successive visual and auditory stimuli. In both vision and audition, temporal processing ability has been examined using a variety of behavioral and physiological measures. Across different tasks, outcomes have sometimes been mixed. In this study, we investigated the degree to which different behavioral measures of temporal processing ability discriminate between children with dyslexia and children who are succeeding at reading.

VISUAL TEMPORAL PROCESSING IN DYSLEXIA

Concurrent Processing Streams in Vision

In vision, the temporal processing deficit is associated with abnormal functioning of the magnocellular (M) pathway. Together, the M and parvocellular (P) pathways constitute the major anatomical projections from retina to visual cortex, proceeding via the lateral geniculate nucleus (LGN) in the thalamus (Leventhal, Rodieck, & Dreher, 1981). In the cortex the pathways pass through separate yet interacting regions of V1 and V2 (De Yoe & Van Essen, 1988; Leventhal et al., 1981). The M pathway continues dorsally to areas V5 and the medial superior temporal area (MST) and on to the posterior parietal cortex (DeYoe & Van Essen, 1988; Maunsell & Newsome, 1987). The P pathway continues ventrally to V4, terminating in the inferior temporal cortex. This description of the visual system, which omits much of its complexity, is shown schematically in Figure 1.

In the retina and LGN, cells that form the M and P pathways possess distinct physiological response properties. P cells have small receptive fields, respond in a slow sustained fashion, are sensitive to differences in wavelength, and prefer stimuli of high contrast and high spatial frequency. M cells have larger receptive fields, respond in a fast transient fashion, have broadband wavelength sensitivity, prefer low spatial frequencies, and are sensitive to low contrast stimuli (Shapley & Perry,

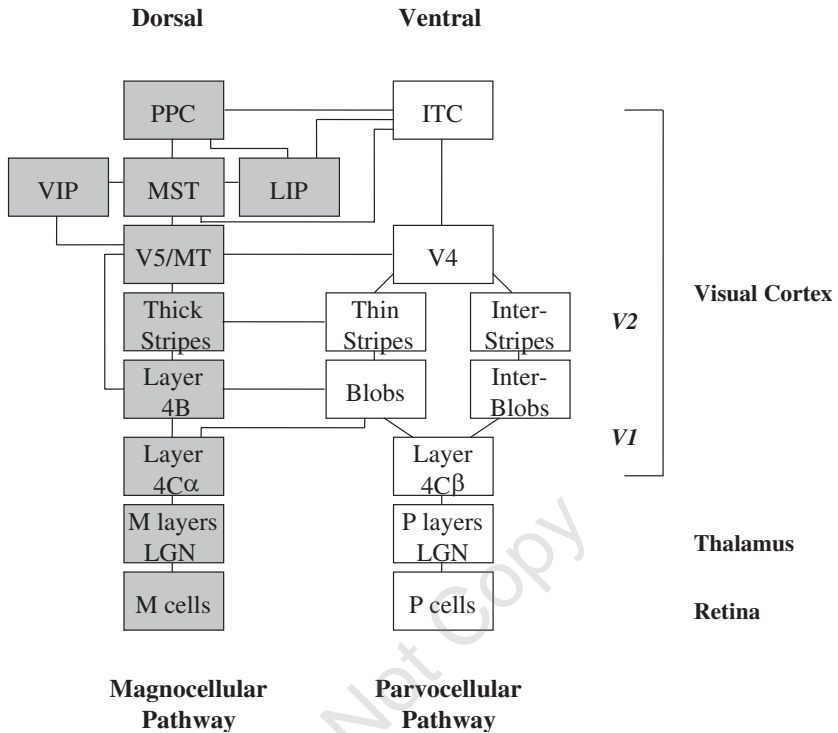


FIGURE 1 Parallel pathways in the primate visual system (adapted from Merigan & Maunsell, 1993). *Note.* M = magno; P = parvo; MT = middle temporal area; VIP = ventral intraparietal area; MST = medial superior temporal area; LIP = lateral intraparietal area; PPC = posterior parietal cortex; ITC = inferior temporal cortex.

1986). Functionally, the P pathway is involved in processing chromatic information and is tuned to low temporal and high spatial frequencies. The M pathway is involved in processing temporal change, low-contrast information, and low spatial frequencies. At the cortical level, cells in the dorsal (M) pathway are highly selective for the direction of motion, particularly in the putative motion centers: V5/MT and MST. Cells in the ventral (P) pathway do not usually show strong direction selectivity but are again more selective for color (see Lennie, Trevarthen, Van Essen, & Wassele, 1990).

Lesions in different locations along the M pathway affect the various functions for which it specializes. Magnocellular lesions of the LGN (in non-human primates) impair critical flicker frequency thresholds and contrast sensitivity for moving, low spatial frequency patterns (Schiller, Logothetis, & Charles, 1990; Merigan & Maunsell, 1990). Responses in V5/MT are also reduced or eliminated

when the magnocellular layers of the LGN are inactivated (Maunsell, Nealy, & DePreist, 1990). Moreover, lesions in cortical area V5/MT itself produce elevated motion coherence thresholds (Newsome & Paré, 1988), deficits in velocity discrimination, and deficits in the detection of motion-defined form (Schiller, 1995).

Visual Temporal Processing Deficits: Psychophysics

Early behavioral studies of visual temporal processing in dyslexia focused on contrast sensitivity. Results revealed that contrast sensitivity for uniform field flicker is reduced in children with dyslexia (Brannan & Williams, 1988; Evans, Drasdo, & Richards, 1994). Moderate reductions in contrast sensitivity for brief, static, low spatial frequency gratings have also been reported (Lovegrove, Bowling, Badcock, & Blackwood, 1980; Lovegrove, Martin, Bowling, Blackwood, Badcock, & Paxton, 1982; Martin & Lovegrove, 1984, 1988). The contrast sensitivity of children with dyslexia is normal, however, if static gratings are presented for a prolonged duration (Lovegrove, Martin, & Slaghuis, 1986).

Larger reductions in contrast sensitivity have been found for flickering or moving gratings, particularly with patterns of low contrast and low spatial frequency (Martin & Lovegrove, 1987; Slaghuis & Ryan, 1999), and with high frequencies of flicker (Felmingham & Jakobson, 1995). These findings are limited to situations in which the stimuli are presented at low levels of illumination. Under photopic viewing conditions, the contrast sensitivity of individuals with dyslexia appears normal (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Gross-Glenn et al., 1995).

Recently, subtle deficits in motion processing have been associated with dyslexia. People with dyslexia perform poorly on motion tasks measuring speed discrimination (Demb, Boynton, Best, & Heeger, 1998), global motion detection (Cornelissen et al., 1995), global motion direction discrimination (Everatt, Bradshaw, & Hibbard, 1999; Raymond & Sorensen, 1998; Slaghuis & Ryan, 1999; Talcott, Hansen, Assoku, & Stein, 2000; Talcott, Hansen, Willis-Owen, McKinnell, Richardson, & Stein, 1998), motion-defined form identification (Felmingham & Jakobson, 1995), and minimum and maximum displacement limits for direction discrimination (Everatt et al., 1999). These deficits are apparent when the mean performance of groups of children or adults with dyslexia is contrasted against the mean performance of an appropriate control group. Examination of distributions of motion processing scores reveals, however, that only a subset of individuals with dyslexia is affected. Distributions of psychophysical thresholds have been published from several studies of global motion perception (Cornelissen et al., 1995; Everatt et al., 1999; Raymond & Sorensen, 1998), which show that the thresholds of many participants with dyslexia fall within the 95% confidence band around the mean thresholds of the control groups. The proportion of dyslexic individuals with elevated motion coherence thresholds (i.e. thresholds exceeding the upper confidence limit of the control group's distribution of scores) ranges from approximately 21%

(Cornelissen et al., 1995) to 70% (Raymond & Sorensen, 1998) across studies. Unlike the contrast sensitivity findings, deficits in global motion perception have been found in high luminance conditions that correspond more closely to the light conditions in which reading takes place (Cornelissen et al., 1995).

Visual Temporal Processing Deficits: Physiology

Some physiological evidence indicates an M-pathway deficit in dyslexia. For example, Livingstone and colleagues measured visual evoked potentials (VEPs) over the occipital cortex in response to contrast-reversing checkerboard patterns (Galaburda & Livingstone, 1993; Livingstone, Rosen, Drislane & Galaburda, 1991). With low contrast, high temporal frequency stimuli, they found the amplitude of the steady-state pattern-reversal VEP was reduced in adults with dyslexia. VEPs to higher contrasts or lower temporal frequencies were similar for adults with and without reading difficulties. Although subsequent studies have confirmed this finding in both children (Lehmkuhle, Garzia, Turner, Hash, & Baro, 1993) and adults (McKinnell, Talcott, Hansen, Winter, Bacon, & Stein, 1997) with dyslexia, there have also been several failures to replicate (Johannes, Kussmaul, Munte, & Mangun, 1996; Victor, Conte, Burton, & Nass, 1993).

Motion-onset VEPs, which may provide a better test of M-pathway function than pattern-reversal VEPs (Kubova, Kuba, Peregrin & Novakova, 1995), have produced more reliable evidence of impaired M-pathway activation in dyslexia. Relative to controls, longer latency and smaller amplitude VEPs have been recorded in response to the onset of movement in a checkered pattern in children (Kubova et al., 1995) and adults (McKinnell et al., 1997) with dyslexia.

Results from functional magnetic resonance imaging (fMRI) on adults with dyslexia are consistent with psychophysical reports of impaired motion processing in area V5/MT. Eden and colleagues first showed this by measuring the hemodynamic response in V5/MT during perception of a low-contrast, random-dot stimulus moving at 10 deg/sec (Eden, Van Meter, Rumsey, Maisog, Woods, & Zeffiro, 1996). Data from six adult males with dyslexia revealed a complete lack of activation to this stimulus. In comparison, normal activation was observed in V1 and extrastriate cortex in response to a high-contrast, stationary pattern included as a control. A subsequent fMRI study on adults with dyslexia revealed reduced activity in V1 and V5/MT to low luminance, low spatial frequency gratings moving at 20.8 deg/sec (Demb, Boynton, & Heeger, 1997). At high mean luminance levels, there was no difference in activation between adults with dyslexia and adult control subjects. Activation levels in V1 and V5/MT have further been shown to correlate with speed discrimination thresholds and reading speed (Demb, Boynton, & Heeger, 1998).

Contrary to the fMRI findings, Vanni, Uusitalo, Kiesila, and Hari (1997) reported a magnetoencephalography (MEG) finding which they claimed showed

equal levels of V5/MT activation in reading disabled and non-disabled adults. This finding was obtained using moderate spatial frequency, high-contrast transient gratings. With this stimulus, however, the participants with dyslexia tended toward longer response latencies, and with low-contrast stimuli they had weaker activation compared to the control participants. Some aspects of these data are therefore consistent with an M-pathway deficit in dyslexia.

AUDITORY TEMPORAL PROCESSING IN DYSLEXIA

Concurrent Processing Streams in Audition

There is evidence that the auditory system is organized as concurrent processing streams analogous to the M and P streams found in the visual system (Konishi, 1995). As with the visual M pathway, the large-cell auditory analog seems to be specialized for processing rapidly changing stimuli. Separate auditory pathways begin in the cochlear nucleus and are evident in the superior olivary nucleus of the brainstem (see Figure 2).¹ Cells in the medial superior olive (MSO) are sensitive to interaural time differences and cells in the lateral superior olive (LSO) are sensitive to interaural intensity differences. Time and intensity differences between signals arriving from each ear are important for sound localization. Sounds originating from the left hemispace, for example, will arrive at the left ear up to a msec sooner and with a higher intensity than at the right ear.

Auditory Temporal Processing Deficits: Psychophysics

Behavioral studies on auditory processing in dyslexia have revealed a deficit in the processing of rapidly presented sounds. Tallal (1980) reported that a subset of children with dyslexia performed poorly when required to discriminate and sequence two brief tones presented in rapid succession. When the interval between the tones was extended, these children performed as well as their non-reading-disabled peers. Other studies have confirmed a deficit in children with dyslexia on temporal order judgement tasks and on temporal sequence matching tasks (see Farmer & Klein, 1995 for a comprehensive review). It is not clear however, that these deficits reflect impaired rapid auditory processing, because they would also result from a more fundamental deficit in auditory discrimination ability, which has seldom been controlled for in research on dyslexia (McArthur & Hogben, 2001). There is also evidence that rapid auditory processing deficits in children with dyslexia are

¹The functional circuitry from the cochlear nucleus to the auditory cortex is complex. Figure 2 provides a basic schematic representation of the aspects of the pathways that are relevant to this discussion.

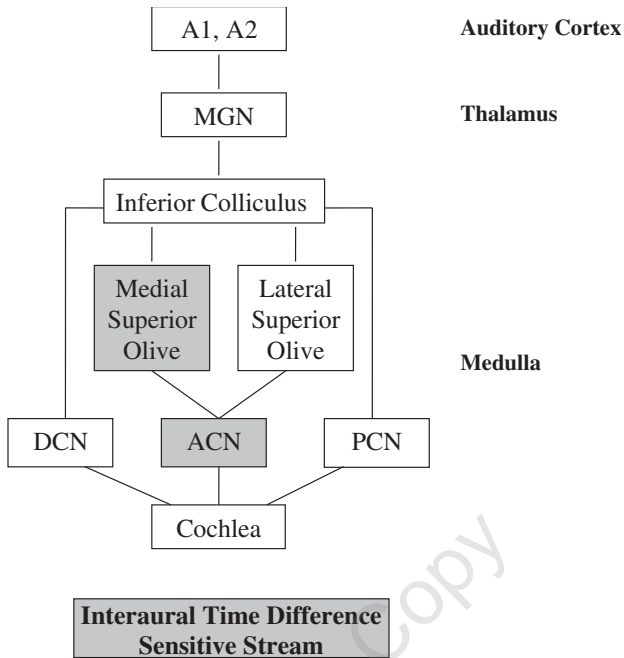


FIGURE 2 Pathways in the auditory system. The pathway sensitive to interaural time differences is highlighted. DCN = dorsal cochlear nucleus; ACN = anteroventral cochlear nucleus; PCN = posteroventral cochlear nucleus; MGN = medial geniculate nucleus.

related more to oral language difficulties than to reading difficulties as such (Heath, Hogben, & Clark, 1999).

Several other reported auditory deficits suggest that the processing of frequency and interaural time differences is affected in dyslexia. Relative to control subjects, adults with dyslexia have been found to be poor at frequency discrimination and at detecting a tone in background noise based on interaural phase differences (McAnally & Stein, 1996; although see Hill, Bailey, Griffiths, & Snowling, 1999 for conflicting results). Further studies with adults have revealed a deficit in detecting changes in the rate of change of frequency modulated (FM) tones (Stein & McAnally, 1995; Witton et al., 1998). FM-tone sensitivity has not yet been reported in reading disabled children, but it has been shown to account for 40% of the variability in reading skills of children making normal reading progress (Talcott et al., 1999).

Dichotic pitch (DP) perception has revealed a deficit in the processing of interaural time differences in children with dyslexia (Dougherty, Cynader, Bjornson, Edgell, & Giaschi, 1998). Detection of DP requires the auditory system to binaurally fuse filtered acoustic white noise patterns to extract pitch and location

information that is not available to either ear alone. It requires sensitivity to the fine temporal structure of the acoustic signals and is therefore a good test of precise neural timing mechanisms. DP is also useful for probing the auditory system's ability to extract signals from noise and to compute sound location.

Auditory Temporal Processing Deficits: Physiology

Longer latency (although greater amplitude) auditory evoked responses to brief, successive two-tone stimuli have been recorded in the left parietal cortex of children with dyslexia (Duffy, McAnulty, & Waber, 1999), supporting the behavioral observations of temporal order judgement deficits in this group. In addition, abnormal MEG responses evoked by brief tone-pair sequences have been recorded from primary auditory cortex in adults with dyslexia (Nagarajan, Mahncke, Salz, Tallal, Roberts, & Merzenich, 1999).

In a recent fMRI study, reduced activation in left prefrontal cortex to rapidly changing auditory stimuli was found in adults with dyslexia (Temple et al., 2000). The adults in this study had oral language difficulties as well as reading difficulties, and they performed poorly on a behavioral measure of rapid auditory processing. Due to the combined language and reading difficulties of this group, neither the physiological deficit nor the behavioral deficit can be unambiguously related to reading failure.

Auditory processing in dyslexia is also aberrant on the mismatch negativity (MMN) component of the event-related potential waveform. The MMN reflects pre-attentive changes in neural responses elicited by deviations in either the frequency or temporal properties of auditory input. MMN responses to frequency deviations, in particular, are abnormal in adults and children with dyslexia (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Hugdahl et al., 1998; although, see Schulte-Korne, Deimel, Bartling, & Remschmidt, 1998). The MMN response to deviations in tone duration or intertone-interval tends to be normal in dyslexia (Baldeweg et al., 1999; Kujala et al., 2000), except for stimuli with complex temporal variations (Kujala et al., 2000; Schulte-Korne, Deimel, Bartling, & Remschmidt, 1999). In adults with dyslexia, MMN outcomes for frequency deviant stimuli have been shown to correlate with performance on regular word and nonword reading tasks (Baldeweg et al., 1999).

TEMPORAL PROCESSING DEFICITS: SUMMARY

Behavioral and physiological evidence suggests abnormal temporal processing ability in individuals with dyslexia. There are, however, a significant number of studies in which temporal processing ability of people with dyslexia has been found to be normal. These inconsistent outcomes raise questions about the preva-

lence and severity of temporal processing deficits in dyslexia and the significance of such deficits for reading development.

Conflicting findings across studies may have resulted from differences in the way in which dyslexia is characterized (Hogben, 1996). For example, temporal processing ability may vary with the type and severity of reading difficulties, oral language abilities, and age of research participants. Inconsistent results may also be related to differences between studies in the sensitivity of the tasks used to measure temporal processing ability. The aim of this research was to determine the degree to which different auditory and visual temporal processing tasks distinguish children with dyslexia from their non-reading disabled peers. To overcome the problems associated with comparing outcomes from reading disabled groups defined in different ways, a single group of children with dyslexia was examined on a broad set of temporal processing tasks.

The temporal processing deficit theory proposes that dyslexia is characterized by multi-modal temporal processing deficiencies (e.g., Farmer & Klein, 1995; Tallal, Miller, & Fitch, 1993). Most research, however, has been completed within a single modality. It is, therefore, unclear whether temporal processing deficits are associated across modalities within the same individuals, or whether individuals are affected in a single modality (Richardson, 1995). A recent study revealed a moderate correlation between global motion direction discrimination and FM tone detection in a group of adults with dyslexia (Witton et al., 1998). In our research, the co-occurrence of visual and auditory temporal processing deficits in children with dyslexia was examined.

AIMS

The goal of this research was to determine which of numerous measures of temporal processing ability best discriminate children with dyslexia from their non-reading disabled peers. The prevalence of temporal processing deficits in children with dyslexia and the co-occurrence of temporal processing deficits in vision and audition were also examined. Visual tasks that have revealed deficits in monkeys with lesions of the magnocellular layers of the LGN, in monkeys with lesions of cortical area MT, in humans with lesions in V5/MT, in humans with diseases affecting M-pathway function (e.g., glaucoma), and in individuals with dyslexia were employed. The tasks provided estimates of: (a) minimum speed thresholds for discrimination of shapes defined by relative motion, (b) minimum (D_{\min}) and maximum (D_{\max}) displacement thresholds for direction discrimination of moving random-dot patterns, (c) global-motion thresholds for direction discrimination of moving random-dot patterns, (d) contrast sensitivity for detection of uniform flicker and of counter-phase flickering gabor patterns, and (e) critical flicker frequency thresholds. Global-motion thresholds and grating

acuity for isoluminant stimuli were also measured. On these latter tasks, which were intended to preferentially activate the P pathway, children with dyslexia were expected to perform as well as their peers. The auditory measures of temporal processing were (a) detection of FM differences and (b) localization of DP in background noise. Both of these measures have previously revealed deficits in individuals with dyslexia.

METHOD

Participants

Twenty-one children (11 boys, 10 girls) with dyslexia and 24 children (11 boys, 13 girls) with at least average reading ability took part in the study. Fourteen other children were assessed, but were excluded because they did not fit into either the dyslexic group or the control group on the basis of their reading and intelligence test scores. Several other children were excluded because of possible attention deficits ($n = 4$), visual problems ($n = 4$), or generalized developmental delay ($n = 1$).

The children were recruited through advertisements placed in community centers, a children's hospital, and schools for children with learning disabilities. They ranged in age from 9.4 to 13.4 years, were right-handed, and had attended an English-speaking school since kindergarten. The children did not have psychiatric problems based on their parents' responses on the *Child Behavior Checklist* (CBCL). The scores for each child fell below the 95th percentile on the externalizing/internalizing scales. Attentional disorders were assessed with the *Attention Deficit Disorders Evaluation Scale—Home Version* (ADDES). Children included in this study scored higher than the 6th percentile. A neurological assessment (performed by B. Bjornson) plus parents' responses on the *Aggregate Neurobehavioral Student Health and Educational Review-Parent Questionnaire* (ANSER) were used to exclude children who had any neurological abnormalities.

An ophthalmic examination (performed by C. Lyons) established that all participants had normal or corrected-to-normal near and distance vision, as well as normal stereopsis, accommodation, visual fields, saccadic and pursuit eye movements, and color vision. Hearing was assessed using a standard audiometric technique and was normal in all children. Informed, written consent was obtained from each child and the child's parent(s) before testing commenced.

Children were assigned to the control or dyslexic group based on performance on a battery of reading tests (see Table 1). The Durrell Analysis of Reading Difficulty (Durrell) was administered as a test of oral passage reading. As the test provides only gross instructional grade norms, raw scores were expressed as z scores,

TABLE 1
 Characteristics of the Reading Disabled and Control Group Children

Measure	Dyslexic		Control		<i>t</i> (43)
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
Chronological age	11.17	1.08	11.62	0.96	1.49
Reading					
PIAT-R (recognition) ^a	75.76	8.42	116.17	7.65	16.87**
PIAT-R (comprehension)	88.90	17.12	118.00	12.60	6.55**
Durrell Accuracy (errors/minute) ^b	5.06	2.02	1.85	1.20	6.36**
Durrell Rate (words/minute) ^a	61.07	26.15	148.92	19.88	12.78**
WJ-R (identification)	91.14	8.40	128.92	12.61	11.64**
WJ-R (attack) ^{a,b}	89.10	10.61	119.83	16.76	7.44**
Intelligence (WISC-III)					
Vocabulary (Verbal IQ)	10.14	2.24	11.92	2.24	2.65*
Block design (Performance IQ)	11.95	4.06	12.17	3.14	0.20
Composite	11.05	2.74	12.04	2.14	1.36

Note. Standard scores ($M = 100$, $SD = 15$) reported for the PIAT-R and WJ-R; raw scores reported for the Durrell. PIAT-R = Peabody Individual Achievement Test-Revised; Durrell = Durrell Analysis of Reading Difficulty (3rd ed.); WJ-R = Woodcock-Johnson Tests of Achievement-Revised; WISC-III = Wechsler Intelligence Scale for Children-3rd edition.

^aTests used for selection into the study. ^bUnequal variance was assumed in computing t .

* $p < .01$. ** $p < .001$.

based on the distributions of accuracy and rate scores of the control group.² On the remaining reading measures, standardized age norms were used. To be included in the dyslexic group, a child had to score at least 1 standard deviation (SD) below the level expected on two or more of the following subtests: the *recognition* subtest of the Peabody Individual Achievement Test-Revised (PIAT-R); the *word attack* subtest of the Woodcock-Johnson Tests of Achievement-Revised (WJ-R); and the *rate* measure of the Durrell. These subtests index three aspects of reading ability,

²Each child read two pre-selected paragraphs from this test. Time and errors were recorded. In curriculum-based assessment, children in Grades 3-6 are expected to read at least 100 words per minute (wpm) to demonstrate mastery (Shapiro, 1996). The rate scores of the control group (range: 116-178 wpm) met this requirement, indicating that the control participants read the paragraphs at a rate appropriate for their grade. The reading rates of the children with reading disabilities (range: 20-122 wpm; only one child exceeded 100 wpm) were below the expected level for their grade, as well as outside the range of scores of the control group (with the one exception). The accuracy scores of most of the children with reading disabilities were also outside the range of accuracy scores of the control children; however, many of the children with reading disabilities did not exceed the number of errors expected for mastery at their grade level (6 or less errors per minute; Shapiro, 1996). This suggests that the materials were too easy, or reading slowly enabled the children with reading disabilities to compensate for decoding difficulties. Given this, the accuracy scores on the Durrell were not used for classifying the children.

namely word identification, phonological decoding, and reading speed, respectively. The children in the dyslexic group were most impaired on the measure of reading speed, with all children except one, scoring more than 1.5 *SDs* below the control group mean. The control children's scores were not more than 0.5 *SD* below the age-norm on the standardized reading measures used to select the dyslexic group, which provided a clear separation in reading ability between groups. Children in both groups had at least average intelligence, with average defined as a composite scaled score equaling or exceeding a lower cutoff of 1 *SD* below the mean for scaled scores on the WISCIII ($M = 10$, $SD = 3$), i.e., a mean scaled score of 7 or higher. The composite score was derived from one verbal and one performance subtest (see Table 1).

On each of the standardized reading measures the mean performance of the control group was at least 1 *SD* above the mean age norm. Temporal processing ability is correlated with reading skill, therefore temporal processing differences between the groups could be attributed to either poor temporal processing ability in the dyslexic group or to very good temporal processing ability in the control group. To address this problem, we contrasted the thresholds of the children with dyslexia on two of the temporal processing measures (dichotic pitch and slow global motion) with the thresholds of a second control group of strictly average readers.

The children in the second control group were participants in a large study of the development of temporal processing ability. For the developmental study, 438 children aged from 6 to 13 years were recruited from elementary schools in British Columbia. The children were assessed at school on the word attack and word identification subtests of the WJ-R, and on the vocabulary and block design subtests of the WISCIII. Their visual acuity and audiometric hearing thresholds were also measured. Children who were 9 to 13 years old, had normal hearing and visual acuity, scored between 86 and 115 on both reading subtests, and had average intelligence (as defined earlier), were included in the second control group for this study. Forty-nine children (23 boys, 26 girls) met these criteria. As shown in Table 2, the children in the second control group had significantly better reading skills than the children in the dyslexic group, but were average, rather than above average, readers for their age. Although the reading difficulties of the dyslexic children appear only moderate on the WJ-R subtests, their outcomes on the PIAT-R and Durrell measures indicate more severe difficulties (Table 1). WJ-R scores were used to compare the reading abilities of the dyslexic children and the children in the second control group because the WJ-R was administered in both studies.

Apparatus

Stimuli were generated on a Macintosh 8500 computer and were presented on a 17 in. Sony Trinitron color monitor with a resolution of 1024×768 pixels. Responses were collected with a MacGravis gamepad that was modified and placed inside a

TABLE 2
 Characteristics of the Reading Disabled and Control Group 2 Children

Measure	Dyslexic		Control		<i>t</i> (68)
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
Chronological age	11.17	1.08	10.74	1.11	1.46
Reading					
WJ-R (identification)	91.14	8.40	105.16	7.06	7.19*
WJ-R (attack) ^{a,b}	89.10	10.61	102.51	7.17	6.18*
Intelligence (WISC-III)					
Vocabulary (Verbal IQ)	10.14	2.24	10.78	2.77	0.92
Block design (Performance IQ)	11.95	4.06	11.53	3.22	0.46
Composite	11.05	2.74	11.15	2.20	0.17

Note. WJ-R = Woodcock-Johnson Tests of Achievement-Revised; WISC-III = Wechsler Intelligence Scale for Children-3rd edition.

* $p < .001$.

child-friendly response pad with cartoon character buttons. Auditory stimuli were presented through Sennheiser HD-265 headphones. The apparatus for measuring critical flicker frequency (CFF) consisted of an array of 25 high-output red light emitting diodes (LEDs) behind a frosted glass diffuser. The luminance of the LEDs was controlled at 12-bit resolution through a voltage-to-current converter by a National Instruments D/A board. The LED array was surrounded by an equiluminant white field diffusely lit by a small incandescent bulb.

Procedure

For the dyslexic and original control group, testing was conducted in the laboratory across two sessions held on separate days. The first session involved psychometric testing on a battery of cognitive and language measures, a neurological assessment and an ophthalmic exam. This session took approximately 4 hr to complete, including rest periods as required. The psychophysical tasks were completed during a separate session, which lasted 1.5-2 hr with rest periods.

The psychophysical testing was conducted in a room lit dimly with diffuse light. All tasks, except CFF, used a two-alternative, forced-choice procedure with stimulus presentation controlled by a two-down, one-up staircase. Step-size was halved after each response reversal, and the staircase ended after 10 reversals or 40 trials.

A trial began with the appearance of a traffic light on a computer screen. An amber signal prompted the child to initiate the stimulus presentation by pushing a button on a response pad. The traffic light then changed to green and disappeared, after which a beep signaled the onset of the stimulus. The stimulus presentation was

followed by a question mark indicating to the child that a response was required. Responses corresponded to cartoon characters located on the left and the right of the monitor and entailed pushing a button on the response pad marked with the matching character. For example, on the global motion task the child was instructed to press the 'tiger' button on the left of the response pad whenever most of the dots appeared to move toward the 'tiger' cartoon on the left of the screen. Visual and auditory feedback was provided. The children were practiced on each task immediately prior to beginning the experimental trials on the task.

For the second control group, all testing was completed at the child's school. The child participated in two sessions, each lasting approximately 30 min. During one session, audiometric thresholds were measured and the psychometric tests were completed. During the second session, visual acuity was measured and the psychophysical tasks were performed. For the psychophysical tasks, the physical testing conditions were matched as closely as possible to the conditions in the laboratory.

Visual Temporal Processing Tasks

For all moving-dot stimuli, the dot lifetime was equal to the stimulus duration (i.e., the same dots carried the signal throughout the display). The moving-dot tasks did not have a fixation point; the children were instructed to direct their gaze at the center of the screen.

Motion-defined form (shape discrimination). On this task the child viewed a field of random dots that contained a camouflaged arrowhead (see Figure 3a). The contours of the arrowhead were not visible when the dots were stationary or when they all moved in the same direction at one speed (Regan & Hong, 1990). The arrowhead became visible when the dots inside the contour of the arrowhead moved in one direction and the dots outside the contour of the arrowhead moved simultaneously in the opposite direction. The contour of the arrowhead was therefore defined solely by relative motion. The direction that the arrowhead pointed was varied randomly between right and left across trials, and the child was required to indicate the direction that the arrow pointed. The slowest speed at which the orientation of the arrowhead could be discriminated was determined (Regan & Hong, 1990).

The stimulus dots were single pixels that subtended 0.003 deg^2 from a viewing distance of 6.3 m. All dots were white (100 cd/m^2) on a black background (5 cd/m^2). The dot density was $12,755 \text{ dots/deg}^2$ and the dots were displayed in a 2.1 deg square region. The arrowhead was 1.6 deg high \times 0.8 deg wide. The display consisted of 4 frames of animation, each of which comprised 8 screen refreshes at 75 Hz. Each animation sequence therefore lasted 107 msec and the overall stimulus duration was 428 msec. Dot displacement was adjusted across trials to find the

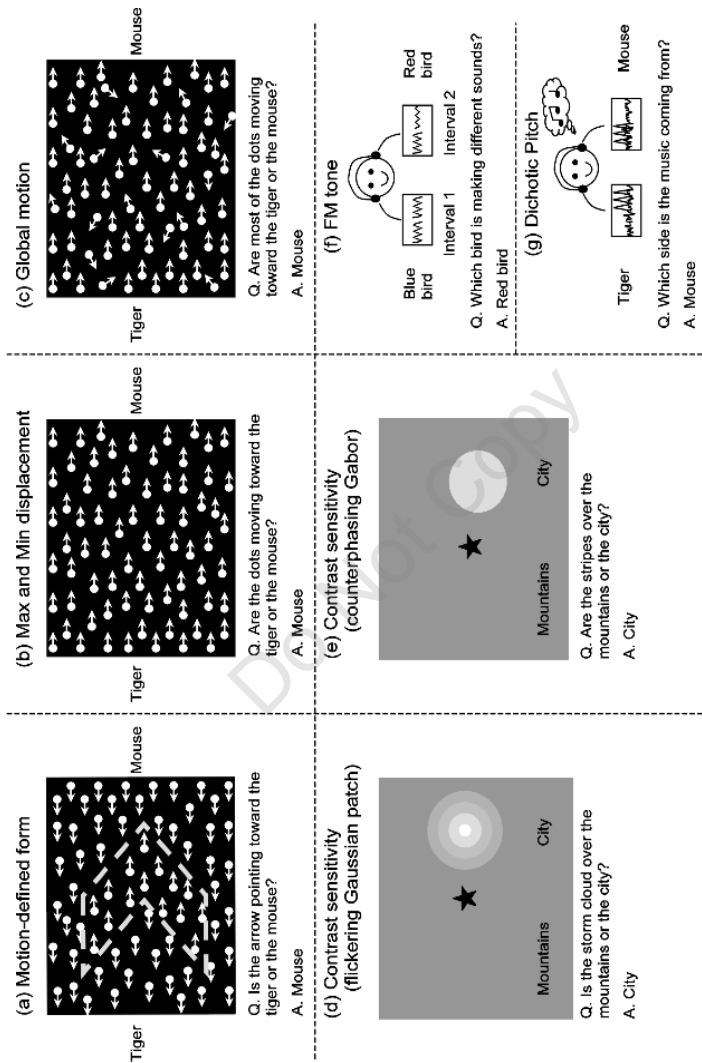


FIGURE 3 Visual and auditory temporal processing tasks. The arrows in (a) – (c) indicate the direction of motion of the dots. They were not present in the stimulus display. Images of the characters (tiger–mouse, red bird–blue bird) and landscape (mountains–city) were used rather than words as shown here.

minimum displacement (i.e., the slowest speed) required for accurate discrimination of the orientation of the arrowhead. Within a trial, all dots moved at the same speed. The starting speed of the staircase was 0.42 deg/s.

Maximum and minimum displacement thresholds. These two tests determined the slowest and fastest motion (i.e., smallest and largest dot-displacements) that could be resolved sufficiently well to determine the direction of movement of a field of dots (see Figure 3b). D_{\max} is the maximum displacement, and D_{\min} is the minimum displacement, required to accurately judge the direction of motion.

For both conditions, the stimulus was a field of white dots (100 cd/m²) on a black background (5 cd/m²). On each trial the dots moved with 100% coherence in a linear, horizontal fashion. The display area for the D_{\max} condition was a rectangle that subtended 12.8 deg horizontally and 9.6 deg vertically. At the viewing distance of 1.4 m, dot size was 0.013 deg² and dot density was 30 dots/deg². The D_{\max} stimulus consisted of 4 frames of 107 msec duration, producing a total stimulus duration of 428 msec.

The display for the D_{\min} stimulus was a 2.8 deg \times 2.1 deg rectangle with a dot density of 638 dots/deg². Dot size was 0.003 deg² viewed at a distance of 6.3 m. The D_{\min} stimulus consisted of 3 frames of 147 msec duration, producing a total duration of 441 msec.

The child was asked to indicate the direction of movement of the dots. Dot-displacement was adjusted across trials to determine a threshold for motion-direction discrimination. Separate staircases were completed for D_{\max} and D_{\min} .

Global motion thresholds with luminance dots. The global motion stimulus was a dynamic random-dot display. On each trial, a proportion of the dots in the display moved coherently either leftward or rightward. The remaining dots moved in random directions at the same speed as the dots that moved coherently (see Figure 3c). The percentage of dots carrying the correlated motion signal was varied across trials to determine the smallest proportion of coherently moving dots that a child required to accurately report the direction of the correlated motion signal.

Four versions of the task were completed: three with luminance-defined stimuli presented at slow, medium, and fast speeds, and a fourth with isoluminant stimuli presented at medium speed. The fourth version implicates the P-pathway and is described later. The display for the luminance-defined conditions comprised white dots (100 cd/m²) on a black background (5 cd/m²) with a dot density of 30 dots/deg². The entire dot field was rectangular and subtended 12.8 deg horizontally and 9.6 deg vertically. At the viewing distance of 1.4 m, dot size was 0.013 deg². The total stimulus duration was 428 msec, produced by 4 frames that each lasted

107 msec. Coherence thresholds were measured for stimulus speeds of 0.24 deg/sec, 1.21 deg/sec, and 7.29 deg/sec.

Dynamic contrast sensitivity. The following tests required children to locate grating patterns with time-averaged luminance equal to the background luminance. The stimuli were presented in one of two screen locations to the left or right of a large, black star that served as a fixation point. At one location there was a cartoon drawing of mountains and at the other location there was a cartoon drawing of a city (see Figures 3d and 3e). The child was asked to press a button indicating whether the dynamic pattern, described as a 'cloud,' appeared over the mountains or over the city. The contrast of the pattern was adjusted in log steps to determine the minimum contrast required for correct localization of the pattern.

Thresholds were obtained for two types of stimuli: a 7.5 Hz flickering Gaussian patch and a 15 Hz counterphase flickering Gabor (0.9 cycles/degree; cpd). Both formed a circular region subtending 2.8 deg and the 2D Gaussian had a full width of 2 deg at half maximum. Both stimuli had a time-averaged luminance of 30 cd/m². The stimulus duration was 2 s, which included a 500 msec half Gaussian onset and offset (full-width, half maximum of the Gaussian was 250 msec). That is, the stimuli were ramped on for 500 msec, achieved half the desired contrast after 250 msec, remained at the desired contrast for 1 s, and were then ramped off. For these tasks, higher temporal resolution was achieved by using a 120 Hz screen refresh rate. Viewing distance was 1.4 m and the stimulus pattern was presented 3.4 deg from the fixation star.

Critical flicker frequency. For this test, the flicker rate of a red light set against a white background was varied using the method of adjustment to determine each child's CFF. On half the trials, the flicker rate was increased until flicker was no longer perceived, and on the remaining trials, the flicker rate was decreased until flicker was first perceived. The average of 6 trials was taken as the CFF estimate. The task was presented as a game in which the flickering red light appeared as a candle flame held by two cartoon characters. The flickering of the light was attributed to 'windy conditions' and the child's task was to indicate when the wind 'stopped' or 'started' blowing.

The task was completed twice, once at 100% flicker modulation depth and once at 10% flicker modulation depth. The mean luminance of the display was 100 cd/m².

Visual Tasks Reliant on P-Pathway Processing

Global motion threshold with isoluminant dots. The parameters in this task were identical to those in the global motion tests using luminance-defined stimuli except that (a) the stimulus consisted of red dots (0.026 deg²) on an isoluminant green background, and (b) the velocity of the dots was 1.21 deg/sec.

Isoluminance was determined for each observer by a motion nulling technique (Cavanagh & Anstis, 1991).

Isoluminance is used to try to silence activity within the M pathway, to isolate the P pathway. The stimulus display for this task contained motion cues without luminance contrast, therefore the percept of motion was expected to be degraded. Motion perception under such circumstances is thought to reflect either motion processing within the P pathway, which is known to be poor, or residual responses within the M pathway of neurons not inactivated by the nulling technique (Derrington, Krauskopf, & Lennie, 1984; Dobkins & Albright, 1994; Lee, Martin, & Valberg, 1989; Shapley & Kaplan, 1989; see also Edwards & Badcock, 1996, for a discussion on processing of chromatic signals within the motion system in global motion perception). Elevated coherence thresholds were therefore expected on this task, without any difference between the thresholds of the two reading groups.

Grating acuity at isoluminance. This task measured a child's ability to detect fine patterns, which requires the high spatial frequency sensitivity of the P pathway. To enhance the P-pathway contribution to performance on the task, the texture to be resolved was defined by isoluminant colors (e.g., Lennie, 1993). The children viewed isoluminant red and green horizontal grating patterns presented against a yellow background. When the pattern was too fine to be resolved, the red and green blended to form yellow and could not be distinguished from the background. Similar to the contrast sensitivity tests, the child pressed a button indicating whether the red and green stripes appeared over a mountain cartoon located on one side of a fixation star, or over a city cartoon located on the other side of the star.

The eccentricity of the stimuli was 1.1 deg. The gratings were square wave with a Gaussian spatial envelope (0.8 deg full-width, half maximum) and a square wave temporal envelope. Stimulus duration was 2 sec and the viewing distance was 4.2 m. An adaptive staircase (with log steps) adjusted the spatial frequency of the pattern to find the grating acuity threshold. The starting value for the staircase was a spatial frequency of 2 cpd.

Auditory Temporal Processing Tasks

FM difference discrimination. On this task, the child listened to FM tones presented through headphones. FM tones sound like bird chirps, therefore the task was presented as a game in which the child had to decide which of two colored birds made 'different' chirping sounds. During the first interval of each trial, a red bird appeared in the left half of the screen and the stimuli were played to the child's left ear. During the second interval, a blue bird appeared in the right half of the screen and the stimuli were played to the child's right ear (see Figure 3f). The child pressed the red bird button on the left of the response pad to indicate that the first interval contained two different chirps (i.e., different FM tones), or the blue bird

button on the right of the response pad to indicate that the second interval contained two different chirps. The interval with the two different FM tones was randomly determined.

The modulation depth of the FM was fixed at 10 Hz. The carrier frequency averaged 1000 Hz and was randomly set from trial to trial to a value between 900 Hz and 1100 Hz. This made it difficult for the child to use long-term spectral cues associated with FM sounds when making the discrimination (McAnally & Stein, 1996). Each tone was 500 msec long and was ramped on and off with a 50 msec half-Gaussian. The inter-tone interval was 100 msec and the ISI was 500 msec.

Each trial contained two intervals: one interval comprised two identical 20 Hz FM tones and the other interval comprised one 20 Hz FM tone and a target tone with a variable FM frequency. A staircase algorithm adjusted the FM of the target tone across trials to find the minimum FM difference (dFM) for accurate discrimination of the two intervals. The staircase began at a maximum dFM of 20 Hz (i.e., a target tone FM of 0 Hz or 40 Hz) and adjustments were made in log units.

Localization of dichotic pitch. This task required the children to signal the side of the head on which they perceived a melody. The melody comprised four tones that were delivered to one ear slightly sooner than to the other ear on each trial. Perceptually, a single melody was heard and it was experienced on the side of the head where the tones were delivered first (see Figure 3g). The tones were embedded in background noise that was presented to both ears simultaneously, thus perceived to be in the center of the head. When the intensity of the tones was equal to or less than that of the background noise (signal to background ratio [SBR]; $SBR \leq 1$; see description that follows), the inputs to the two ears had to be fused centrally to extract the melody, as it was only present in the correlation between the sounds delivered to the two ears.

The technique used to generate the DP stimuli is described more fully by Dougherty et al. (1998). In brief, two independent, flat-amplitude noise sources were filtered to create the stimuli. One noise source was band-pass filtered to produce a signal tone and the other was notch filtered to produce background noise. The signal and background were then combined with a time delay and delivered to both ears through headphones, creating a percept of a tone embedded in noise. The pitch of the tone was determined by the peak frequency of the signal. The perceived spatial locations of the signal and background (e.g., left side, right side, or center) were manipulated by altering the ongoing interaural time difference of the sounds. The complementary band-pass and notch filters were modified to adjust the SBR from 0 (*no signal present; only background noise*) to 1 (*full dichotic signal*) and greater than 1. SBRs greater than 1 produce cues to pitch that are monaurally detectable (i.e., peaks in the amplitude spectra). These monaurally detectable pitches produced by SBR levels greater than 1 are necessary because some listeners may be insensitive to true DP. Such listeners may still have a measurable pitch

localization³ threshold; their threshold SBR will simply be above the true DP cut-off of 1.

The signal consisted of four sequential 200 msec harmonic complexes (330 & 660 Hz; 220, 440, 660 & 880 Hz; 330 & 660 Hz; 440 & 880 Hz) that formed a melody. Half-height bandwidth of the Gaussian signal frequency bands was 5% of center frequency. All stimuli were digitally low-pass filtered with a 1200 Hz cut-off before delivery and were ramped on and off with a 50 msec half-Gaussian.

An adaptive staircase adjusted the SBR using log steps to determine the minimum SBR required for correct melody localization. The staircase began with an SBR of 10 so that the tones were initially audible monaurally for all participants. All participants could easily perform the task at this initial level.

RESULTS

Weibull functions were fit to the staircase data using a maximum-likelihood minimization procedure (Watson, 1979). As staircase data contain some stimulus levels with few trials the data were forced to be monotonic before fitting the Weibull function. This monotonicity assumption facilitated the function fit by taking a weighted-average of data points that were not monotonically increasing performance with increasing stimulus level. Thus odd (non-monotonic) data points based on a few trials did not unduly bias the psychometric function fit. Both the threshold and slope parameters of the Weibull were free to vary. Thresholds were defined as the stimulus values at which participants made 82% correct responses.

The following results are based on a comparison of the data for the children with dyslexia and the children in the original control group. The mean thresholds for the two groups on the visual and auditory temporal processing tasks and the visual measures of P-pathway processing are shown in Table 3.

M Tasks

A multivariate analysis of variance (ANOVA) was performed to determine whether reading-group status (dyslexic vs. control) was associated with differences in scores on the temporal processing tasks. Before analyzing the data, group means were substituted for a small number (1.7%) of missing data points. In addition, scores on the motion-defined form task, the DP task, and the global motion task (fast speed) were log transformed, due to skew in the former two

³Determining the apparent location of a sound source within the head is more correctly termed 'lateralization' (Moore, 2001). The term localization is used here to avoid confusion with hemispheric lateralization, i.e., hemispheric specialization for different forms of information processing (Gaddes & Edgell, 1994).

TABLE 3
Mean Group Thresholds on the Temporal Processing and P-Pathway
Processing Tasks

Tasks	Dyslexic		Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Visual temporal processing				
Motion-defined form [deg/sec] ^a	0.06	0.05	0.09	0.06
D _{max} [deg] ^b	1.17	0.26	1.10	0.17
D _{min} [min] ^a	0.28	0.13	0.29	0.14
Global motion (slow) [proportion] ^a	0.59	0.22	0.43	0.20
Global motion (medium) [proportion] ^a	0.33	0.24	0.26	0.21
Global motion (fast) [proportion] ^a	0.45	0.24	0.41	0.14
Contrast sensitivity (flickering Gaussian) [llog contrast] ^b	1.88	0.14	1.98	0.29
Contrast sensitivity (counterphase flickering Gabor) [llog contrast] ^b	1.87	0.23	1.94	0.18
CFF (high) [Hz] ^b	36.61	3.92	37.04	2.31
CFF (low) [Hz] ^b	24.44	5.91	24.57	2.97
Auditory temporal processing				
FM discrimination (dFM) [Hz] ^a	3.68	1.05	3.15	0.92
Dichotic pitch (DP) [SBR] ^a	1.69	1.52	0.76	0.58
Visual P-pathway processing				
Isoluminant global motion (medium) [proportion] ^a	0.43	0.18	0.46	0.18
Isoluminant grating acuity [cpd] ^b	35.70	12.47	34.18	12.31

^aLower value indicates better performance. ^bHigher value indicates better performance.

cases and to unequal variance in the latter case. Scores on the high- and low-temporal-contrast versions of the CFF task were highly correlated ($r = 0.84$, $p < .01$) and were therefore combined into an overall CFF score for the multivariate analyses.

The Wilks' lambda indicated that performance on the M tasks differed significantly as a function of reader group, $F(11,33) = 2.10$, $p < .05$; however when univariate Fs were calculated with a Bonferroni adjustment (to maintain an overall α level of .05) the groups differed significantly on the DP measure only, $F(1,43) = 9.29$, $p_{(\text{adjusted})} = .04$). The mean DP threshold of the dyslexic group was more than twice the mean threshold of the control group and was above the true DP cut-off of 1 (see Table 3). The distributions of DP thresholds for the two groups are displayed in Figure 4. As shown by the number of thresholds above an SBR of 1, 52% of the children with dyslexia were unable to perceive the DP stimulus. By contrast, only 12% of the control children failed to demonstrate DP perception. The effect size of the group difference in DP threshold was large ($f = 0.46$; Cohen, 1992). The slopes of the psychometric functions for the DP data were not significantly different between the groups, $t(43) = 0.36$, $p > .10$.

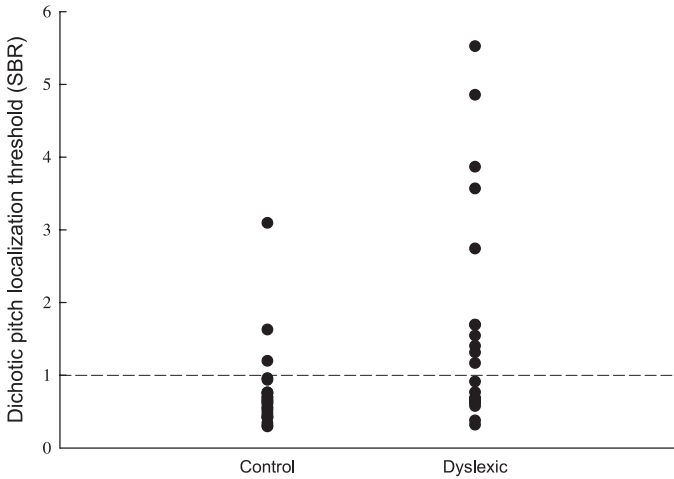


FIGURE 4 Dichotic pitch thresholds for the dyslexic and control groups. Scores below the dotted line (SBR = 1) are within the dichotic pitch range.

On the global motion task with slow moving stimuli (0.24 deg/sec) the dyslexic group tended to have higher thresholds than the control group (see Figure 5). On average, the dyslexic group required 59% of the moving dots to carry the correlated motion signal to accurately report the global motion direction, compared to 43% coherence for the control group. The difference in thresholds was not statistically significant with the corrected alpha level, $F(1,43) = 6.58$, $p_{(\text{adjusted})} = .15$, although the size of the effect was considerable ($f = 0.39$). The failure of this difference to attain significance was due to insufficient statistical power resulting from the examination of too few children. See Table 4 for effect sizes for each of the tasks. The slopes of the psychometric functions for the two groups on the slow global motion task did not differ significantly, $t(43) = 0.67$, $p > .10$.

Thresholds on the slow global motion task were weakly correlated with performance IQ when data from the groups were combined ($r = -.33$, $p = .03$), but not for either group alone. The groups were well matched on this variable, and when an ANOVA was performed while controlling for Performance IQ, the F ratio was unaffected, $F(1,42) = 6.90$, $p_{(\text{adjusted})} = .13$). None of the other tasks on which the groups differed (see discussion of effect sizes in the Discussion) were related to IQ.

A discriminant function analysis was performed to assess the usefulness of the set of temporal processing tasks for predicting children's reading status. One discriminant function was calculated with all predictors entered into the equation simultaneously (Wilks' $\lambda = 0.59$, $\chi^2(11) = 19.91$, $p < .05$). The contributions made by each measure to the discriminant function are shown in Table 4. With all vari-

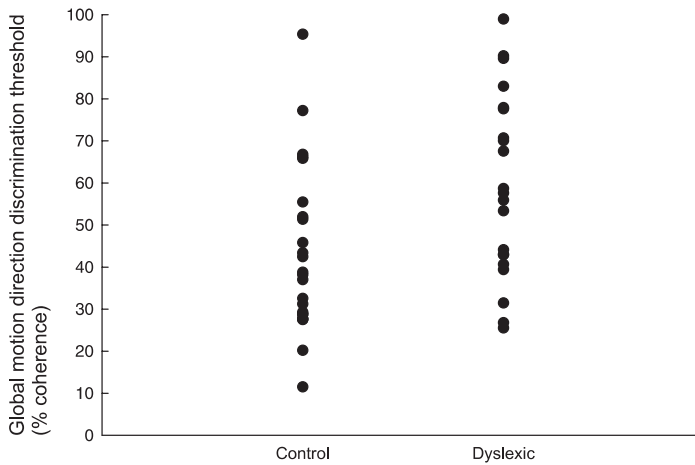


FIGURE 5 Global motion direction discrimination thresholds (slow motion) for the dyslexic and control groups.

ables contributing to the solution, 80% of the children were correctly classified: 76% in the dyslexic group and 83% in the control group. Using a stepwise procedure in which only DP and slow global motion scores entered the equation, classification fell to 71% correct in each group.

The effect size estimates, reported in Table 4, indicate large effects on the DP and slow global motion tasks and moderate effects on the motion-defined form,

TABLE 4
Correlation Coefficients and Effect Sizes of Temporal Processing Tasks
With the Discriminant Function, Ordered by Absolute Size

<i>Task</i>	<i>Correlation Coefficient (r)</i>	<i>Effect Size (f)</i>
Dichotic pitch	.56	.46
Global motion (slow)	.49	.39
Motion-defined form	-.37	.31
FM discrimination (dFM)	.33	.28
Contrast sensitivity (counterphase flickering Gabor)	-.28	.23
D_{\max}	.22	.18
Global motion (medium)	.21	.17
Contrast sensitivity (flickering Gaussian)	-.20	.17
D_{\min}	-.06	.05
CFF	-.05	.04
Global motion (fast)	-.02	.02

Note. For the effect-size index f , a value of .40 denotes a large effect; a value of .25 denotes a medium effect; and a value of .10 denotes a small effect (Cohen, 1992).

FM discrimination, and contrast sensitivity (Gabor) tasks. The motion-defined form result, which is contrary to prediction, is considered further in the Discussion. Pearson's correlation coefficients were computed separately for the two groups to examine the relationships between the tasks within each group. DP perception and FM discrimination were moderately correlated in the dyslexic group ($r = .49, p < .05$). No other bivariate correlation coefficient was significant.

The co-occurrence of auditory and visual temporal processing deficits in the children with dyslexia is shown in Figure 6, where the relationship between DP perception and slow global motion perception is plotted for each child. As a way of defining normal versus abnormal task performance, raw scores have been expressed as z scores relative to the distributions of thresholds of the control group. Using an arbitrary cut-off of 1 SD to define abnormal task performance, the profile of 2 (10%) of the children with dyslexia is consistent with a temporal processing deficit in both the auditory and visual modalities. Seven children (33%) show signs of a deficit solely in auditory temporal processing, and another seven children (33%) show signs of a deficit solely in visual temporal processing. The temporal processing ability of five (24%) of the children with dyslexia was within the normal range.

The children with dyslexia had significantly different DP and slow global motion thresholds to the children with strictly average reading scores, who formed the

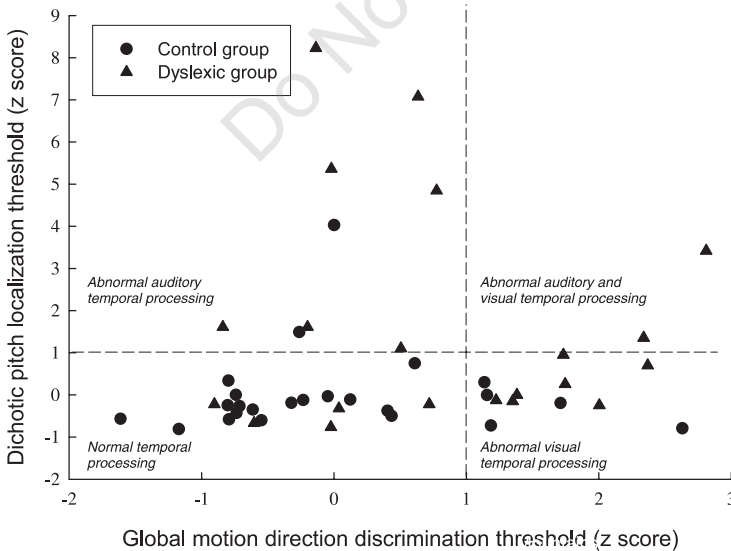


FIGURE 6 Dichotic pitch and global motion (slow) outcomes of the children in the dyslexic and control groups expressed as z scores relative to the mean performance of the control group. Dotted lines indicate an arbitrary division between normal and abnormal performance.

second control group. The DP localization thresholds ($M = 1.69$, $SD = 1.52$) of the children with dyslexia were significantly higher than the average readers' thresholds ($M = .64$, $SD = .52$), $t(22.89) = 3.07$, $p < .01$. The children with dyslexia's slow global motion thresholds ($M = .59$, $SD = .22$) were also significantly higher than the average readers' thresholds ($M = .37$, $SD = .14$), $t(30.40) = 4.21$, $p < .001$. Degrees of freedom were adjusted in these analyses because of unequal variance.

P tasks

Neither task designed to measure P-pathway function differentiated the children with dyslexia from the children making normal progress in reading. There was no difference between the thresholds of the two groups for perception of global motion with isoluminant stimuli, $F(1,43) = 0.34$, $p > .10$, nor were the group thresholds different for isoluminant grating acuity, $F(1,43) = 0.17$, $p > .10$.

DISCUSSION

There is some debate about temporal processing ability in dyslexia because of mixed empirical findings. Using a battery of tasks, 76% of the children with dyslexia in this study were found to have a temporal processing deficit in either the visual and/or auditory modalities. For most of these children, the deficit was confined to a single modality. In addition, the number of children with temporal processing deficits in each modality was the same, indicating that neither modality was more frequently affected.

Temporal processing deficits were not apparent on all of the measures employed. The different outcomes across tasks cannot be attributed to differences in sample characteristics because the same children completed every task. These outcomes show the relative sensitivity of each task to temporal processing differences between children with poor and good reading skills.

In this study, the Bonferroni adjustment set a significance level that would enable only very large effects to attain statistical significance (Cohen, 1990). It is therefore useful to consider the magnitude of the effects indicated by the effect size estimates (see Table 4). Across a range of research areas, the average size of observed effects is medium (Cohen, 1992). The large and medium effects on the two auditory tasks (DP localization and FM tone discrimination) and on three of the visual tasks (slow global motion, motion-defined form, and contrast sensitivity) in this study can therefore be considered meaningful.

As noted earlier, the above-average reading level of the original control group children confounds the interpretation of group differences on the temporal processing measures, because the differences could be driven by superior temporal processing in the control children, rather than inferior temporal processing in the

dyslexic children. However, the dyslexic children were poorer at DP and slow global motion perception than control children with strictly average reading ability, supporting an interpretation based on inferior temporal processing in dyslexic children.

Auditory Temporal Processing

The temporal processing tasks are ordered in Table 4 according to the degree to which they discriminated between the good and poor readers. The most sensitive index of weak temporal processing ability in dyslexia was the DP localization task. This is a novel task that measures the auditory system's ability to use interaural time differences (ITDs) to extract a signal from background noise and to determine the signal's spatial location. The ITD information used to extract DP and to localize low-frequency sounds is likely computed in the MSO (see the ITD sensitive stream in Figure 2). Cells in the MSO receive inputs from each ear that are phase-locked to the stimulus waveform (Moore, 2001). The ongoing time delay between the signals delivered to each ear in the DP task introduces an interaural phase difference. For complex tones, such as the tones in the DP melody, phase information of each of the component frequencies is relayed in the fine timing of the impulses that project to the MSO (Palmer, 1995). MSO cells perform a coincidence detection between the phase locked inputs from the two ears, and the output indicates sound source location along the left-right axis (head-centered; Stern & Trahiotis, 1995). This output is used by subsequent stages of auditory processing and gives rise to the perception of DP. The binaural masking level difference (MLD) is a related phenomenon that depends on interaural phase relations of signal and mask stimuli. In adults with dyslexia, a reduced binaural MLD has been found (McAnally & Stein, 1996).

The DP and MLD findings indicate that dyslexic individuals are impaired in signal processing that depends on the fine timing of auditory neural impulses. Because ITD information originates early in the auditory system—where the responses of cells are phase locked (cochlear nucleus, superior olive, and inferior colliculus) and where phase locked activity from the two ears converges (MSO)—perceptual deficits in dyslexic individuals related to the use of ITDs most likely result from abnormal physiology in these low-level mechanisms.

Higher-level cortical auditory function in dyslexic individuals has been studied with dichotic listening (DL) tests. On each trial in a DL test, two different auditory stimuli (e.g., two consonant-vowels, words, tones, or melodies) are presented simultaneously, one to the left ear and the other to the right ear. Listeners are instructed to report all the items heard (free recall) or to report items from the left or right ear only (directed recall). In the free recall condition, listeners generally report more verbal items from the right ear. Because each ear has greater neural representation in the opposite cerebral hemisphere, the right ear advantage for verbal stimuli indicates pre-

dominance of the left hemisphere for verbal processing. For tonal and melodic sequences, a left ear advantage is observed, indicating specialized processing in the right hemisphere of tonal and melodic stimuli (Kimura, 1967; Springer, 1986). From DL research there is sketchy evidence of either a lack of asymmetry or opposite asymmetry in the dyslexic group, compared to the control group. Recent findings suggest that people with dyslexia are lateralized to the same extent as the general population, but that they show a different pattern of results when attentional shifting is required, i.e., when directed to attend to the input to one or other ear (e.g., Hugdahl et al., 1998). This has been interpreted as evidence of interhemispheric transfer difficulties and of atypical cerebral organization (Bolik & Obrzut, 1995). An alternative view is that it reflects an inability to modify an inherent laterality effect through cognitive processes (Hugdahl et al., 1998).

Important to this discussion is the distinction between DP localization ability and DL performance. These tasks measure distinct aspects of auditory perception. DP perception involves fusion within the brain stem of identical, time-shifted inputs to each ear. DL, however, reflects high level processing of competing inputs presented simultaneously to the ears. The ITD information used to extract DP is computed early in the auditory system and should not be affected by higher cognitive functions such as attending to one ear or the other or by hemispheric processing biases.

In this study, both groups of children obtained thresholds at relatively low levels of modulation (~3–4 Hz) on the FM tone discrimination task. The dyslexic group, however, had a higher threshold than the control group. Poor FM discrimination has been found in adults with a history of reading difficulties (Stein & McAnally, 1995; Witton et al., 1998). Detection of FM tones at low modulation rates is based on temporal information encoded through phase locking (Moore, 2001). For the dyslexic group, performance on the FM task was moderately correlated with performance on the DP task. The mechanism common to these tasks is phase locking. These results therefore support the idea that individuals with dyslexia are impaired in low-level encoding of auditory temporal information. There was no relationship between the scores on the two auditory tasks for the control group, which was probably due to limited variance in the DP scores.

In sum, the children with dyslexia performed both auditory tasks poorly compared with children with good reading skills. Both tasks require processing of the fine temporal properties of acoustic stimuli. Similar deficits are seen in adults with a history of reading difficulties, suggesting that impairment in auditory temporal processing ability may persist in dyslexic individuals throughout life.

Visual Temporal Processing

Differences between the reading groups were evident on several measures of visual temporal processing ability. Specifically, the children with dyslexia were poorer than the control children at perceiving the direction of global motion at the

slowest speed, and at detecting a dynamic (Gabor) pattern at low contrast levels. These findings confirm earlier findings and they are consistent with the idea that processing in the M visual pathway is disrupted in dyslexic individuals.

The dyslexic group had reduced sensitivity to global motion only when the dot-motion was slow (0.24 deg/sec). Other studies have found differences between good and poor readers in global motion perception with stimulus velocities ranging from 2.5 to 15.5 deg/sec (Cornelissen et al., 1995; Richardson, 1995; Slaghuis & Ryan, 1999; Talcott et al., 2000). The absence of a difference between the groups at the faster speeds in this study (1.21 and 7.29 deg/sec) may be related to the very high density of dots in the display. Talcott and colleagues (2000) reported that differences between dyslexic individuals and normal readers in sensitivity to global motion dissipate as dot density is increased. Our findings suggest that this may only be true for medium and fast motion. Even with a very dense dot display, the dyslexic children were less sensitive than the control children to global motion at slow speed.

A sizeable between-group difference was also apparent on the motion-defined form task, although, contrary to expectation, the dyslexic children performed this task better than the children in the control group. There is evidence that motion-defined form perception is equally, or possibly more reliant on form processing than on motion processing. For example, studies of clinical groups have revealed a loss of motion-defined form perception in patients with normal speed thresholds for discriminating the direction of motion (Giaschi, Regan, Kothe, Hong, & Sharpe, 1992; Regan, Giaschi, Sharpe, & Hong, 1992). Deficits in motion-defined form perception therefore occur in cases where motion processing is intact. The perception of motion-defined form may involve a distributed system of interconnections between the M and P pathways (Regan et al., 1992), and thus is a poor test of functioning solely within the motion system. There is no obvious reason for the lower threshold of the dyslexic children on the task.

The visual measures that revealed the greatest difference between the two groups in temporal processing ability were slow global motion and contrast sensitivity. Performance of these tasks was not correlated for either group of children. Although both tasks reflect aspects of M pathway processing, these data demonstrate that motion perception is more severely affected than contrast sensitivity in children with dyslexia.

General Temporal Processing

In order of effect size, the following tasks revealed differences in temporal processing ability between the children with dyslexia and the children with good reading skills: DP localization, slow global motion perception, FM tone discrimination, and dynamic contrast sensitivity. These tasks measure perception of temporally modulated sensory inputs. The two tasks that revealed the greatest dif-

faculties for the children with dyslexia—DP and global motion—further required the sensory system to synthesize local, temporally modulated inputs into a global percept, and to then segregate the global percept from a noisy context. Increasing the demands placed on the sensory systems that encode temporal information therefore amplifies temporal processing difficulties in children with dyslexia.

The idea of a general temporal processing deficit in dyslexia is not supported by this study. For the dyslexic group, scores on the visual tasks did not correlate with scores on the auditory tasks. This can be seen in Figure 6, where DP scores are plotted against global motion scores. Unlike the finding of Witton et al. (1998) with adults, the temporal processing deficits observed in the children in this study were confined to a specific sensory modality in all but two cases.

One possibility is that the children in this study with distinct visual and auditory temporal processing deficits represent distinct subtypes of dyslexia. It has been suggested that auditory and visual temporal processing deficits are associated with failure in unique aspects of the reading process: auditory deficits with failure in phonological processing skills (e.g., Tallal et al., 1993) and visual deficits with failure in orthographic processing skills (e.g., Talcott et al., 2000; Wolf, Bowers, & Biddle, 2000). Given that most research on temporal processing ability in dyslexia has been completed within a single modality, there is insufficient evidence to establish whether the dichotomy between visual and auditory deficits observed in this study characterizes the dyslexic population at large.

CONCLUSIONS

From the comprehensive set of tasks examined, the temporal processing measures that best discriminated children with dyslexia from children who read well were DP localization and FM tone discrimination in the auditory modality, and slow global motion and dynamic contrast sensitivity in the visual modality. In both vision and audition, tasks that required complex processing within the pathways that encode temporal information resulted in the poorest outcomes for the children with dyslexia. In individual children, temporal processing difficulties were localized in either the visual or the auditory system, with few children affected in both modalities. Seventy-six percent of the children with dyslexia in this study demonstrated some form of reduced temporal processing ability.

The role played by temporal processing ability in the acquisition of reading skills is not well understood. Consistent with other reports, data from this study show that poor temporal processing ability is not always associated with reading failure. The challenge is to identify the characteristics that distinguish poor readers with temporal processing difficulties from poor readers without temporal processing difficulties. Studies are now beginning to examine temporal processing ability in light of the specific components of the reading process that are affected in indi-

viduals (e.g., phonological versus orthographic skills). This approach may lead to a better understanding of the relationship between perceptual impairments and dyslexia.

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