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Evoked Potential Measures of Interhemispheric Transfer Time in Reading Disabled and Normal Boys

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Previous research has implicated dysfunctions in interhemispheric interaction in the etiology of dyslexia. The present study was designed to examine whether dyslexics differ from matched controls on visual-evoked potential measures of interhemispheric transfer time (IHTT). Checkerboard flashes were presented hemiretinally while evoked responses were recorded from right and left side occipital scalp locations. IHTT was computed separately in response to right and left visual field presentations. Dyslexics were found to have faster IHTT from right-to-left hemisphere and slower IHTT from left-to-right hemisphere compared with controls. Evoked potential measures of IHTT accounted for significant variance in measures of reading and related cognitive skills. The implications of these data for understanding the underlying neural substrates of dyslexia are discussed.

The idea that dyslexia is associated with some problem in cerebral lateralization has been prevalent in the literature since the time of Orton (1937). Although it is likely that different subtypes of dyslexia are associated with different underlying neural dysfunctions, a growing number of investigators have proposed that at least a subgroup of disabled readers exhibit problems in interhemispheric communication. There have been numerous studies comparing dyslexics and controls on measures which putatively tap interhemispheric transfer. The nature of the measures that have been used vary widely and range from simple motor and sensory tasks, which involve either lateralized input or output (e.g., Davidson, Leslie, & Saron, 1990) to electrophysiological studies that measure features of brain activity presum-

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ably influenced by interhemispheric transfer processes (e.g., Saron & Davidson, 1989b).

Using a variety of different behavioral measures, a number of researchers have obtained a pattern of results in dyslexics that they interpret as reflecting deficits in some aspects of interhemispheric interaction. For example, in a study of asymmetries in vocal reaction time to hemiretinal presentations of stimuli, Yeni-Komshian, Isenberg, and Goldberg (1975) found that compared with normal readers, dyslexics actually had a larger right visual field advantage in response to verbal stimuli. They interpreted these data as evidence for an interhemispheric transfer deficit in dyslexics because the larger right field advantage was a function of slower vocal reaction times in response to left visual field stimuli. Presumably, vocal responses to left visual field presentations require interhemispheric transfer. A similar pattern of results has been observed in a number of studies of dichotic listening performance (Hynd, Obrzut, Weed, & Hynd, 1979; Newel & Rugel, 1981; Obrzut, Hynd, Obrzut, & Pirozzolo, 1981; see review by Kershner, 1985). In another study, Hermann, Sonnabend, and Zeevi (1986) used a novel procedure to examine the latency of eye tracking to unilateral and bilateral simple visual stimuli in dyslexics and controls. No differences were found between groups in the unilateral stimulation conditions. However, the dyslexics were significantly slower in the bilateral condition, when input was simultaneously presented to each visual field. The authors interpret their data as reflecting a deficit in interhemispheric coordination. Geiger and Lettvin (1987) found that college age former dyslexics ("residual dyslexics") were better at reading letters in the periphery compared with the fovea. Moreover, they found significant improvement in the reading of one severe dyslexic when he was taught to read with a template that exposed the written material only to the right visual field. It may be that dyslexics who learn to successfully compensate for their disorder (i.e., residual dyslexics) have learned a strategy which minimizes the degree to which information is foveally represented and hence projects to both hemispheres. In this way, problems in interhemispheric transfer can be avoided.

In a series of studies that examined different features of bimanual motor coordination, Wolff and his collaborators found that dyslexics are impaired relative to controls on those tasks likely to depend upon interhemispheric communication (Badian & Wolff, 1977; Kliepera, Wolff, & Drake, 1981; Wolff, 1977; Wolff, Cohen & Drake, 1984; see review by Gladstone & Best, 1985). Using the Purdue Pegboard (Tiffin, 1968) task, we found differences between dyslexics and controls which we interpreted as reflecting deficits in interhemispheric communication (Leslie, Davidson, & Batey, 1985). In another study, Gladstone, Best, and Davidson (1989) established deficits among dyslexics on a bimanual coordination task free of the confounding influences of timing precision.

A number of electrophysiological studies have included measures of interhemispheric EEG coherence, which have been interpreted to reflect some aspect of interhemispheric interaction. Dyslexics have been found to differ from controls on these measures both during resting conditions and in response to a variety of cognitive challenges (e.g., Sklar, Hanley, & Simmons, 1972; Leisman & Ashkenazi, 1980).

In virtually none of the aforementioned studies was a specific mechanism proposed for the problem in the interhemispheric transfer observed among the dyslexics. We have suggested interhemispheric transfer time (IHTT) as a candidate mechanism responsible for the problems in interhemispheric interaction observed among dyslexics (Davidson, Leslie, & Saron, 1990). According to our model, most attended visual input is bilaterally represented in the brain. If a stimulus is foveated, a representation of that stimulus will be produced in both hemispheres. This is because of the bilateral distribution of retinal ganglion cells from the eye that are in the foveal region. In fact, what is striking about the two hemispheres in the sensory domain is their symmetry, not asymmetry. The sensory processing regions of each hemisphere act as redundant processing modules to handle incoming sensory input. Many responses that we are required to make to visual[1] input are verbal in nature. We might be expected to name a visually presented object, or to read a visually presented word. When the processing and/or output required is verbal, the left hemisphere is presumably necessary for response execution in right-handed individuals. In this case, visual input is bilaterally represented but the left hemisphere is selectively implicated in response production. In such a situation, we argued that transfer of the redundant representation of the stimulus from the right hemisphere to the left would facilitate accurate responding. Given the documented importance of sequential operations within the left hemisphere, particularly as it executes a verbal response (e.g., Bradshaw & Nettleton, 1981), we proposed that the time at which the redundant representation arrives from the right hemisphere is critical. More specifically, we suggested that to be maximally useful, the representation of the stimulus from the right hemisphere must arrive at the left hemisphere within a relatively narrow time window. If the representation from the right hemisphere arrives outside of this window, it will interfere with the smooth execution of left hemisphere response-related processes. Thus, if the transfer time from the right hemisphere is either excessively slow or excessively fast (relative to this optimal window), left hemisphere performance should be impaired. We have suggested this to be one mechanism responsible for at least some of the cognitive anomalies which characterize some dyslexics and our behavioral data lend some support to this suggestion (Davidson et al., 1990).

Davidson, Leslie, and Saron (1990) used a simple reaction time (RT) par-

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[1] This discussion uses visual input as an example. However, a similar argument can be made about auditory input.

adigm to make inferences about interhemispheric transfer time in a group of dyslexics and matched controls. Simple RT was measured in response to unilateral presentations of simple visual and tactile stimuli during separate right and left hand response conditions. Our model predicted that dyslexics would differ from controls in those conditions which reflected transfer from right to left hemisphere (i.e., the right-hand response conditions). IHTT in these conditions is presumably reflected by the difference score between reaction time in response to left-side minus right-side stimulation (Bashore, 1981). Unfortunately, the group comparison in this study did not support our prediction. There were no reliable differences in IHTT between the dyslexics and the controls. However, when we examined the correlations between IHTT derived from the right-hand conditions (which reflect transfer from right-to-left hemisphere) and performance on measures of reading and related cognitive functions, we found, particularly among the dyslexics, that faster IHTT was associated with poorer performance. This finding was a consistent one and was apparent for IHTT measures based on responses to both visual and tactile stimuli. For example, for the dyslexics, the correlation between the visual right-hand IHTT measure and performance on the Gray Oral Reading Test (Gray, 1967) was .45; the correlation between the tactile right hand IHTT measure and performance on this test was 0.63. The correlations between the reading measures and left hand IHTT were, for the most part, reversed in sign, although none were significant.

As would be expected on the basis of extensive prior research (see Bashore, 1981), significant Side of Stimulation × Hand of Response interactions were obtained for both visual and tactile conditions in the Davidson et al. (1990) study. However, when the percentage of subjects who showed IHTT values in the direction of anatomical prediction (i.e., left-hand—left-side stimulation faster than left-hand—right-side stimulation, etc.) was examined, the highest percentage found for the visual conditions was 64% and for the tactile conditions it was 72%. The mean percentage across groups and conditions was 57%. Although there was no difference between groups in the percentage of subjects who showed IHTT effects in the direction of anatomical prediction in any of the conditions, the fact that the percentages were so low underscores a major problem with the use of reaction time measures to make inferences about IHTT.

The validity problems with reaction time measures of IHTT catalyzed our search for more acceptable alternatives. In an extensive series of parametric studies, Saron and Davidson (1989b) established both the reliability and validity of visual evoked potential measures of IHTT. The paradigm adopted consisted of recording visual evoked potentials to hemiretinal presentations of checkerboard stimuli. Subjects were required to make a simple finger-lift response to each stimulus occurrence, primarily to maintain their involvement in the task. Brain electrical activity was recorded from several electrodes on occipital scalp region and averaged evoked responses were derived in response to right and left visual field presentations. IHTT was inferred by comparing the latency difference of the P100 and N160 peaks of the evoked response recorded over each hemisphere. Using such measures in adults, Saron and Davidson (1989b) found that a larger proportion of subjects showed effects in the direction of anatomical prediction compared with simultaneously obtained reaction time measures. Across the experiments reported in Saron and Davidson (1989b), in which brain activity from lateral occipital scalp sites was recorded referenced to linked ears, the overall percentage of subjects showing IHTT effects in the direction of anatomical prediction (based on measurement of the P100 component of the evoked response) in response to left visual field stimulation was 91% and in response to right visual field stimulation the percentage was 100%. Moreover, the actual values obtained for IHTT were much more consistent with theoretical predictions based upon known axon diameters, conduction velocities and distance between the hemispheres (see Saron & Davidson, 1989b for details).

In a follow-up study, Saron and Davidson (1989a) reported that the test-retest reliability of these evoked potential measures of IHTT over a 3-week interval ranged from 0.80 to 0.93, depending upon the particular measure examined. This corpus of evidence clearly reveals the evoked potential measures to be superior to the reaction time measures for the estimation of interhemispheric transfer time.

In the present article, we present the findings from a study that utilized these visual evoked potential measures of IHTT with dyslexic and normal children. Based upon our reaction time data (Davidson et al., 1990), we predicted that dyslexics would show faster IHTT from right-to-left hemisphere (i.e., in response to left visual field presentations). We also predicted that evoked potential measures of IHTT would correlate with standardized measures of reading and cognitive performance.

METHOD

Subjects

The subjects for this experiment were a subset of the children who participated in the study described in Davidson et al. (1990). A total of 20 males were included in the current study. These subjects were selected randomly from the controls and dyslexics tested in the Davidson et al. (1990) study. Subjects were selected on the basis of a battery of neuropsychological and reading tests to participate in a laboratory study of interhemispheric transfer time. The test battery (administered during an initial psychometric test session) was designed to classify the subjects into either a reading disabled or a normal control group. The subjects were all right-handed as assessed by the Harris Test of Lateral Dominance (Harris, 1958; i.e., scoring 70% or more in the right-handed direction) and were between the ages of 9 and 12 years. Half of the subjects were reading disabled (*N* = 10, *M* age = 11.03 years; *SD* = 1.15) and half were normal (*N* = 10, *M* age = 10.84 years; *SD* = 1.32). All children were from either middle or upper middle income families.

All subjects had to obtain a full scale IQ of 90 or above on the WISC-R (Wechsler, 1974) in order to participate. In addition, all subjects were required to score 85 or above on performance IQ (PIQ) and achieve a scaled score of 7 or above on the Block Design Subtest of the WISC-R. The PIQ and Block Design criteria were established to exclude those children with perceptually based learning disabilities. Other criteria common to both groups included: (a) Scoring at or above the 17th percentile on the quiet condition of the Goldman, Fristoe, and Woodcock (1970) Test of Auditory Discrimination. This criterion served to screen out any subject with gross auditory impairment; (b) No obvious emotional or neurological problems (e.g., seizures, meningitis, encephalitis) or history of such problems; (c) No history of taking medication with known central nervous system (CNS) effects for longer than 6 months or current use of such medication; and (d) The subject was not adopted, because adoption limits adequate history information. To determine whether our dyslexics had an attentional dysfunction in addition to their reading disability, we compared the performance of each group on a measure which reflects distractibility, the noise subtest of the GFW Test of Auditory Discrimination (Goldman et al., 1970). The groups performed virtually identically on this measure. Thus, the dyslexic sample did not show any gross dysfunction in attentional performance.

In an effort to reduce the variability within our reading-disabled group, we chose to focus on a previously identified language disordered subgroup of dyslexics who have been characterized by naming deficits (Mattis, French, & Rapin, 1975). This specific subgroup was targeted for study based upon two major considerations: (a) The subgroup accounts for the largest percentage of reading disabled children compared with all other identified subgroups (Denckla, 1977; Mattis et al., 1975; Satz, 1976); and (b) We have hypothesized that this specific subgroup would exhibit deficits in interhemispheric transfer (see Davidson et al., 1990). To select our sample, we included only those dyslexics who scored more than 1 *SD* below the mean on at least one of two naming tests: The Visual Naming subtest from the Neurosensory Comprehensive Examination for Aphasia (Spreen & Benton, 1977) and/or any of the four subtests of the Rapid Automatized Naming Test (Denckla & Rudel, 1976).

A child was considered reading disabled if he scored 0.85 or below on the reading quotient proposed by Myklebust (1968): (2 × Reading Age)/(Mental Age + Chronological Age). A child qualified as a control subject if he scored 0.95 or above on the same reading quotient and if he also scored

TABLE 1
Descriptive Characteristics of the Groups

		Age	*PIQ*	*VIQ*	*FIQ*	*MQ*	*WA*	*WI*	*GO*	*GM*
Dyslexics	*M*	11.03	121.8	112.1	118.3	.71	29.4	15.1	21.8	40.3
	SD	1.15	14.3	12.2	13.6	.08	29.3	15.1	17.5	32.4
Controls	*M*	10.84	115.2	124.7	122.8	1.18	81.3	81.0	82.1	82.3
	SD	1.32	14.8	12.0	12.6	.14	16.2	9.6	12.6	8.2

Note. *N*s are 10 per group for all variables except GM (*N* = 7 for dyslexics). PIQ = performance IQ; VIQ = verbal IQ; FIQ = full scale IQ; MQ = Myklebust Quotient; WA = Woodcock Word Attack Subtest; WI = Woodcock Word Identification Subtest; GO = Gray Oral Reading Test (Gray, 1967); GM = Gates-MacGinitie Reading Test, Level D (Gates & MacGinitie, 1972).

less than 1 year below actual grade level on any of the reading tests which were administered. The mental age used in Myklebust formula was derived from the WISC-R and the reading age was derived from the Word Identification subtest from the Woodcock Reading Mastery Tests (Woodcock, 1973). In addition to the Word Identification subtest, a number of other tests of reading were administered to assess a broad range of reading related skills. Table 1 presents the descriptive data on our dyslexic and normal samples.

Design

The task we used to assess IHTT was identical to that described in Saron and Davidson (1989b). A simple RT task to unilaterally presented checkerboard flash stimuli was administered. There were four experimental conditions which represented the crossing of visual field of presentation with hand of response. Thus, the conditions included right visual field (RVF) presentations with a right-hand response (RVF–RH), RVF presentations with a left-hand response (RVF–LH), left visual field (LVF) presentations with a right-hand response (LVF–RH), and LVF presentations with a left-hand response (LVF–LH). The experiment consisted of four blocks of 100 stimuli. During each block, stimuli were presented randomly to each visual field. Within a block, only one hand was used. Hand of response was counterbalanced across blocks and counterbalance order was randomized between subjects. The mean number of trials used to derive waveform averages for each condition was 90. There were no differences between dyslexics and controls in the number of trials in the waveform average for any of the four conditions.

Procedure

Subjects were tested in a sound attenuated room separate from the recording and stimulus projection rooms. They were seated at a table that held a response push-button, snap-action switch, and a chin rest with a forehead restraint. Subjects placed both arms straight out in front of them on the table. The switch was placed at a comfortable position for the subject on the same side of the table as the response hand for that block. The height of the table and chin rest were adjusted for maximum comfort.

The table faced a 61 cm × 91 cm, rear-projection screen and was placed so that the nasion-to-screen distance was 1.23 m. A black mask covered the screen with cutouts for both visual field stimulus locations and a small fixation target.

A video camera that was mounted below the screen and focused only on the subject's eyes allowed for eye position monitoring. Two 150 W reflector spotlights directed at the wall above the projection screen provided symmetrical indirect lighting (49 cd/m^2 at the subject's eyes).

The stimuli were three-by-four check checkerboards 8.4 cm high and 6.3 cm wide (visual angle = 3.7° by 2.9°). The medial edge of the stimuli was 2.8° to the left or right of central fixation. The fixation point was a small (0.2°) circle with a cross in it. Three Kodak Ektagraphic projectors generated the stimulus and fixation images. The fixation point was visible throughout the experimental session. LVF and RVF checkerboard flashes were created with Gerbrands electromechanical shutters attached to the projector lenses and two identical stimulus slides. White noise (90 dB at 30.48 cm, A weighted) in the projection room masked the sound of the shutters in the subject room.

The background illumination of the screen was 4.0 cd/m^2. The intensity of the white checks was 19.7 cd/m^2, yielding a contrast ratio of 79.7%. Stimulus intensity was equated between visual fields with Kodak wratten neutral-density filters and a Kodak variable neutral-density glass wedge. Coulbourn digital logic controlled stimulus presentation.

The duration of each stimulus was 10 ms. A random (rectangularly distributed) interstimulus interval of 1.5 to 3.5 sec was used. All stimuli were viewed binocularly. If subjects did not respond in the 1.5-sec maximum RT epoch, the next stimulus was presented.

After a brief introduction to the nature of experiment, each subject was instructed to fixate centrally during the presentation of the stimuli and lift his index finger of the indicated hand off the button as quickly as possible following the detection of a stimulus. We chose a finger lift as the motor response for this task because we (Saron & Davidson, 1989b) and others (e.g., Milner & Lines, 1982) have used this response in other research on evoked response measures of IHTT.

Electrophysiological Data Acquisition and Analysis

EEG was recorded with an electrode cap (Electro-Cap Corp.) and Grass ear clip electrodes. A Grass Model 7 polygraph with 7P5A AC preamps amplified and displayed the EEG. Electrode impedances were below 5Kohms. Recording sites were designated 03 and 04 and were referred to linked ears. These sites were located midway between the standard EEG recording sites 01 and T5 for the left hemisphere and 02 and T6 for the right hemisphere. We recorded from these sites because our previous methodological studies indicated that these sites provided the most reliable and valid estimates of IHTT (Saron & Davidson, 1989b). These non-standard recording sites were added to the Electro-Cap. The EEG amplifier passband was 1 to 500 Hz. The output of the polygraph was low-pass filtered above 100 Hz with Rockland Model 424 dual filters (48 dB per octave) before averaging.

Two channels of electrooculography (EOG) were recorded. Miniature silver/silver chloride electrodes on the external canthi provided a horizontal eye movement signal and electrodes on the supra- and suborbit measured vertical eye movements. The EOG signals were also amplified with Grass 7P5A preamps. Eye movements greater than 1° in any direction or eyeblinks were detected with four Schmidt triggers (one per polarity per EOG channel). The Schmidt trigger outputs were combined to generate an eye movement artifact detection signal that prevented averaging of the relevant trial. Trigger thresholds were set prior to data collection for each subject.

A Teca Model TD-20 averager was used to derive the EPs from each lead for each of the four conditions. Each channel was sampled at 0.6 ms per point for 300-ms poststimulus onset. The length of the averaging epoch was determined on the basis of pilot work with subjects of this age. Before each subject's data collection, a 20-μV, 20-Hz calibration signal was used to standardize the gain for each channel. Each waveform was stored on an IBM-PC for further analysis.

Waveform Quantification and Analysis

Based on our previous methodological studies (Saron & Davidson, 1989b), we chose to compute IHTT on the basis of the latency of the P100 component. This component occurs earlier in the processing stream than the N160 component. Based on studies of the source generators of pattern-onset visual evoked potentials, it is likely that the P100 component has a single source emanating from Areas 18 or 19. In contrast, the N160 component appears to have two overlapping generators (Maier, Dagnelie, Spekreijse, & van Dijk, 1987). We thus chose to focus on the P100 component. P100 latency was defined as the latency of the greatest positivity between 82 and 145 ms. Of a total of 160 waveforms (8 Conditions × 20 Subjects), the P100 component was not identifiable in 6 (3.8%). In addition to measuring the latency of this component, we measured also its amplitude. Amplitude was measured with respect to the average of the initial three samples in the averaged waveform. The major dependent measure was formed by subtracting the latency of the P100 component in the directly stimulated hemisphere from the latency in the indirectly stimulated hemisphere, separately for each hand and visual field condition.

RESULTS

Latency and Amplitude Measures

We examined first whether there were any differences between groups in measures of P100 latency or amplitude. We found no significant main effects for group in either measure, for latency, $F(1, 13) = 0.03$, $p =$ n.s.; for amplitude, $F(1, 13) = 0.10$, $p =$ n.s., suggesting that the groups did not differ in global latency and amplitude.

Measures of IHTT

For each subject, a total of four different IHTT measures were obtained based upon the P100 latency data: right-hand–RVF, right-hand–LVF, left-hand–RVF, and left-hand–LVF. Grand average waveforms for each of these four conditions, separately for each group are presented in Figure 1. Differences between group in IHTT were assessed with an analysis of variance (ANOVA) with Group, Hand, and Visual Field as factors. Although no significant main effect for Group was present, there were significant Group × Visual Field, $F(1, 13) = 7.25$, $p = < .02$, and Group × Visual Field × Hand, $F(1, 13) = 10.35$, $p = < .01$, interactions. Table 2 presents the means and standard deviations of the IHTT values for each of the four conditions, separately by group. As can be seen from Figure 1 and Table 2, dyslexics overall show faster IHTT in response to LVF stimulus presentations compared with controls. Controls, on the other hand, show faster IHTT compared with dyslexics in response to RVF stimulus presentations, particularly in the left hand response condition. The triple order interaction was decomposed by performing separate ANOVAs for the controls and dyslexics with Visual Field and Hand as factors. These analyses revealed a significant Visual Field × Hand interaction for the controls, $F(1, 7) = 12.18$, $p = .01$; this interaction was not significant for the dyslexics, $F(1, 6) = 1.64$, $p =$ n.s. The interaction among the controls indicates that when the responding hand was contralateral to the side of stimulation, IHTT was faster compared with the ipsilateral combinations. Dyslexics failed to show this effect.

Percentage of Subjects Showing IHTT Effects in the Direction of Anatomical Prediction

Overall, the number of subjects who failed to show IHTT effects in the direction of anatomical prediction was quite low, as would be expected on the

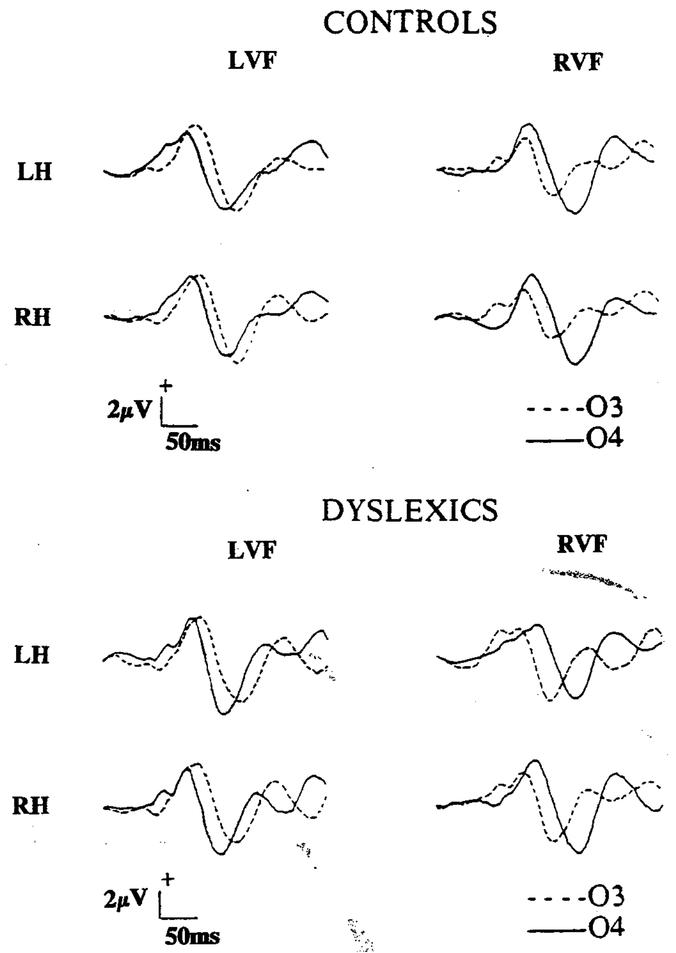

FIGURE 1 Grand average waveforms (300 ms poststimulus) for each of the four visual field-hand conditions, separately for dyslexics and controls.

basis of the data reported by Saron and Davidson (1989b). In response to LVF stimulus presentations, 100% of the controls had IHTTs in the direction of anatomical prediction, while one dyslexic did not in one condition. In response to RVF stimulus presentations, two controls and one dyslexic had an IHTT value for one condition in a direction opposite to anatomical prediction. Thus, out of a total of 80 IHTT values (20 subjects × 4 conditions), 4 were opposite to anatomical prediction (5%). This value compares quite favorably to those typical for RT estimates of IHTT (see Saron & Davidson, 1989b). We recomputed the ANOVAs with these deviant values removed and found that all of the significant effects remained significant.

TABLE 2
Evoked Potential Estimates of Interhemispheric Transfer Time (in ms) by Group and Condition

		Left Visual Field		*Right Visual Field*	
		Left Hand	*Right Hand*	*Left Hand*	*Right Hand*
Dyslexics	*M*	10.44	10.11	16.04	20.38
	SD	14.02	11.92	19.79	10.97
Controls	*M*	24.16	19.64	5.87	14.80
	SD	13.12	14.07	10.60	17.91

Note. IHTTs are based on the latency of the P100 component from the indirectly stimulated hemisphere minus the latency from the directly stimulated hemisphere. Measures are based on recordings from O3 and O4 referenced to linked ears.

Correlations Between IHTT Measures and Cognitive Performance

Given the small sample size, we computed correlations between the IHTT and cognitive performance variables across group. For the purposes of computing these correlations, a single IHTT value for each visual field (across hand) was computed for each subject. As can be seen from Table 3, faster IHTT in response to LVF stimulus presentations (presumably reflecting right-to-left hemisphere transfer) is associated with a pattern of poorer performance on the various reading measures, as well as on two of the Rapid Automatized Naming subtests. IHTT in response to RVF stimulus

TABLE 3
Pearson Correlations Between Measures of Interhemispheric Transfer Time and Performance on Tests of Reading and Other Cognitive Skills, Across Group

	LVF IHTT	*RVF IHTT*
WA	.41*	−.68***
WI	.50**	−.50**
GO	.46**	−.46**
GM	.39	−.47**
RAN-N	.45*	−.46**
RAN-L	.56***	−.33
MQ	.54**	−.48**
FIQ	.03	.28

Note. LVF IHTT refers to IHTT in response to left visual field stimulus presentations, reflecting transfer from right-to-left hemisphere. RVF IHTT refers to IHTT in response to right visual field stimulus presentations reflecting transfer from left-to-right hemisphere. Abbreviations for variable names are the same as in Table 1. RAN-N = Rapid Automatized Naming Numbers Subtest; RAN-L = Rapid Automatized Naming Letters Subtest. Positive correlations indicate that faster IHTT is associated with poorer performance; negative correlations indicate that faster IHTT is associated with better performance.

$^*p < .10$; $^{**}p < .05$; $^{***}p < .01$.

presentations (reflecting left-to-right hemisphere transfer) is associated with a pattern of better performance on the reading and naming measures. Included in Table 3 are the correlations between the IHTT variables and full scale IQ (FIQ). As can be seen, no significant relation was found between FIQ and either of the two IHTT measures.

DISCUSSION

The results of this study indicate that dyslexics could be differentiated from normal readers on the basis of visual evoked potential measures of IHTT. Dyslexics had faster IHTT from right-to-left hemisphere and slower IHTT in the reverse direction compared with controls. Moreover, IHTT was correlated with measures of reading and other cognitive functions. Faster right-to-left hemisphere transfer was associated with poorer performance on the reading and cognitive measures while faster left-to-right hemisphere transfer was associated with better performance on these measures. The pattern of results for IHTT computed on the basis of LVF stimulus presentations (presumably reflecting right-to-left hemisphere transfer) was similar to that first reported by Davidson et al. (1990). In that study, using reaction time measures of IHTT, we found that faster transfer from right-to-left hemisphere was associated with poorer performance on the same measures of reading and related cognitive functions. Although it was not significant in that study, Davidson et al. did find a trend in the opposite direction for transfer from left-to-right hemisphere.

Overall, the pattern of data we have obtained is consistent with our model, which predicts that IHTTs that fall outside of an optimal temporal window will interfere with performance. Both our previous data (Davidson et al., 1990) and the data from the current study indicate that the largest overall difference between groups is in response to stimuli initially presented to the right hemisphere. In this case, transfer time to the left hemisphere in dyslexics is faster than in controls. We have speculated that when transfer of information from the right hemisphere to the left occurs too soon (i.e., before the left hemisphere could effectively use the transferred information), it will interfere with the smooth execution of left hemisphere performance.

The significant triple order interaction of Hand × Visual Field × Group was a function of the controls, but not the dyslexics, showing a Hand × Visual Field interaction. The Hand × Visual Field interaction among the controls indicates that when stimuli are initially projected to one hemisphere, but response execution is controlled by the opposite hemisphere, transfer time is faster than in conditions where stimulus input and response output are controlled by the same hemisphere. We regard the first case as one requiring interhemispheric transfer. Thus, in the normal brain, *obligatory* interhemispheric transfer results in speeded IHTT (Saron & Davidson, 1986), while in the dyslexic brain, this task-appropriate speeding fails to occur.

Although the two groups did not differ on the noise subtest of the GFW Test of Auditory Discrimination (Goldman et al., 1970), it is possible that subtle attentional problems in the visual–perceptual domain may have been present in the dyslexic sample, despite our exclusion of subjects with poor Block Design scores. Such subtle attentional differences may have influenced the measures of IHTT in the dyslexics. However, we examined and found absolutely no evidence for any overall group difference in visual evoked potential amplitude or latency. The lack of group difference across hand, visual field and hemisphere suggests that basic visual processing did not differ between the groups.

Future research is required to examine whether a structural basis exists for the IHTT difference uncovered in this study. It would be of interest to obtain measures of callosal anatomy from MRI scans in subjects whose IHTTs have been obtained from evoked potential measures. Although some later studies have highlighted the fact that considerable variability in callosal anatomy is present, little information is currently available on possible differences in callosal anatomy in dyslexics and controls. The only report of callosal anatomy in dyslexics is the early case report by Drake (1968) who found thinning of the callosum at postmortem in a boy with reading disability.

The later anatomical studies suggest that dyslexics are more likely to show posterior symmetry in their brains compared with normal readers. For example, both Galaburda et al. (1985) and Rumsey et al. (1986) reported increased symmetry of planum temporale in dyslexics compared with controls (see review by Hynd & Semrud-Clikeman, 1989). This increased symmetry is a function of the normally smaller right planum temporale being larger in size in the dyslexics. Galaburda et al. (1985) argued that the bilaterally large plana reflect increased survival of neurons during corticogenesis. One possible mechanism of increased survival of neurons is an increased availability of synaptic targets. These synaptic targets might conceivably compete with callosal synaptic targets and thus lead to a decreased number of neurons in the callosum. This notion is supported by findings which indicate that during development, competition exists among different systems which vie for available synapses. Increased survival of neurons in one system is proportional to attrition in other systems with which it competes (e.g., Cowen, 1973). Precisely how a decrease in the number of neurons in the callosum would result in a change in IHTT is to our knowledge not known.

If IHTT is a trait marker of vulnerability to reading disabilities, it would be of interest to obtain measures of IHTT in young pre-school siblings of older dyslexics to ascertain whether IHTT differences in the direction found in this study actually predict the subsequent development of reading disabilities among subjects who have not yet learned to read. Evoked potential measures of IHTT are ideal for this purpose because they can easily be adapted for administration to such young subjects.

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