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REACTION TIME MEASURES OF INTERHEMISPHERIC TRANSFER TIME IN READING DISABLED AND NORMAL CHILDREN*

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Abstract—This experiment was designed to test whether reading disabled boys differ from matched controls on behavioral measures of interhemispheric transfer time (IHTT). Specifically, we proposed that language-disordered reading disabled children who had deficits in naming would show either faster or slower IHTTs compared with controls. From an initial group of 118 right-handed males, we selected a group of 25 disabled and 25 normal readers, matched on age. All subjects had to obtain a full scale IQ of 90 or above, a PIQ score of 85 or above, and a scaled score of 7 or above on the Block Design Subtest of the WISC-R. After meeting additional criteria for group assignment, manual reaction time (RT) measures of IHTT were obtained in response to simple visual and tactile stimuli during two laboratory testing sessions. Half the trials were conducted with the hands in an uncrossed orientation and half with the hands crossed in order to examine the effects of spatial compatibility on estimates of IHTT. The results revealed no overall group differences in IHTT for any of the conditions. However, correlations between IHTT measures and indices of cognitive performance indicated that faster IHTTs were significantly correlated with poorer performance on measures of reading and language function in the dyslexic group. These data are discussed within the context of a model of interhemispheric transfer deficits in disabled readers.

INTRODUCTION

THE BELIEF that dyslexia is associated with some problem in cerebral lateralization has been prevalent in the literature since the time of ORTON [27]. He initially proposed that dyslexics have a more diffuse or incomplete cerebral representation of language as demonstrated by a higher incidence of left-handedness and crossed hand/eye dominance (e.g., [26, 41]). However, the extent to which measures of motoric lateralization actually reflect cerebral specialization is questionable as current theory and research have shown [4, 9, 27, 29]. More recently, evidence in support of incomplete lateralization has been marshaled from perceptual laterality studies which have failed to find the typical left hemisphere advantage when processing verbal material in reading disabled children (e.g. [18, 33, 36]). However, this pattern of reduced or absent asymmetry is not consistently found. In fact, a large body of literature has found behavioral asymmetries among dyslexics that are comparable in magnitude to, or larger than, those observed in normal readers (e.g. [9, 36, 40]).

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The role of interhemispheric communication in tasks which are putative measures of hemispheric specialization has rarely been considered in the literature in this area. Differences in the contribution of interhemispheric transfer to the tasks which have been utilized to study hemispheric differences in disabled readers* may, in part, account for some of the discrepancies in the reported findings. This point is particularly important in light of recent proposals that dyslexic children may also suffer from dysfunctions in interhemispheric transfer of information. This suggestion is based upon several sources of data. WOLFF *et al.* [2, 38] have reported that dyslexic children have difficulty in inter-limb alternation which has been interpreted to reflect a deficit in interhemispheric communication. LESLIE *et al.* [19] have reported that disabled readers perform particularly poorly on the left hand condition of the Purdue Pegboard test and GLADSTONE *et al.* [15] found that dyslexics perform more poorly on certain bimanual co-ordination tasks. The tasks on which the disabled readers were found to perform more poorly than controls have been those thought to reflect interhemispheric transfer. Other investigators have reported that dyslexic children perform more poorly than controls in response to information presented directly to the right hemisphere to which a verbal response must be made [25, 40]. In this situation, interhemispheric transfer is presumably required since the input is presented to the right hemisphere and response execution (i.e. speech) is controlled by the left hemisphere.

A second source of inconsistency in current empirical and theoretical accounts of reading disability is a function of wide variations in subject selection criteria. Dyslexia is defined in very different ways from study to study. No standardized set of criteria—analogous to the DSMIII in psychiatric diagnosis—has yet been developed in the area of learning disabilities, although such a system is very much needed (see [4, 34] for a discussion of these issues). Potentially more important, however, is the fact that even with the most careful selection criteria based just upon the reading performance of subjects, the resulting group of disabled readers is bound to be heterogeneous [6, 14, 21]. This problem results from the inherent complexity of reading and the obvious fact that a disability in reading may result from many different causes. In studies of underlying hemispheric substrates of the disorder, this heterogeneity will contribute considerable variability to the findings and increase the likelihood of non-replication across different subject samples.

The following study was designed to rectify several of the design flaws present in previous research on the hemispheric substrates of dyslexia. In selecting subjects for inclusion in the group of disabled readers, we sought a more homogeneous group than has been used in similar previous studies. Secondly, we chose to focus on one very specific hypothesis concerning the nature of the hemispheric dysfunction and chose a method which we believed would directly address this hypothesis. Moreover, the group which we selected was chosen for theoretical reasons, since we expected this specific subgroup to show the targeted hemispheric dysfunction.

The literature which suggests that at least some reading disabled subjects have deficits in interhemispheric transfer is quite vague with respect to the hypothesized underlying mechanism. At least two major forms of interhemispheric transfer deficit could be operative. Information might be degraded as it crosses the cerebral commissures. This might result in poorer verbal responding to input presented to the left visual field. Alternatively, an abnormally short or long delay in interhemispheric transfer *time* could also cause at least some of the deficits which have been reported to be characteristic of dyslexic children. We

*The terms "dyslexic" and "disabled reader" are used interchangeably throughout this paper.

have developed a model for this second possible mechanism which we tested in the present study. According to this model, most attended visual input is bilaterally represented in the brain. This form of redundant representation of sensory input is likely to be of adaptive significance in minimizing errors of perception (see e.g. [20]). For example, when a verbal response is required to visual input, we propose that the left hemisphere would use, in addition to its direct input, the representation of the visual stimulus in the right hemisphere (via the corpus callosum) to provide redundant information about the stimulus and decrease the likelihood of errors in responding. This suggestion is a specific form of the more general proposal that response-relevant information in the brain is sent to those regions which are involved in response execution. Thus, for example, the presentation of an object in free vision would result in redundant representations of the stimulus in both hemispheres. If a subject is required to verbally name the object (which presumably requires the left hemisphere to respond), information about the stimulus from the right hemisphere would be sent to the relevant areas of the left hemisphere. If the transfer process occurred either too early or too late, information processing and/or response execution in the left hemisphere would be disrupted. Such disruption is based upon the notion that the left hemisphere is programmed to receive redundant information from the right hemisphere during a narrow time window in the processing sequence. If the information from the right hemisphere is received by the left hemisphere outside of this critical time window, interference will be produced. Such disruption in the left hemisphere might be expected to cause at least some of the anomalies which have frequently been associated with dyslexic children including problems in the naming of visually presented objects and problems in complex bimanual integration. According to this model, any task in which information was presented to both hemispheres would be susceptible to interference as a consequence of the hypothesized interhemispheric transfer time deficit. It would not be necessary that the task specifically demand the transfer of information between the hemispheres (i.e. where interhemispheric transfer was obligatory). It would be sufficient that the task involved the bilateral representation of input. An example of the latter would be the naming of visually presented objects. In this task, the visual information would be bilaterally represented since it is normally viewed in foveal vision. Although the task does not *require* interhemispheric transfer, such transfer is hypothesized to occur as a direct consequence of the anatomical pathways. Given that the transfer does occur, if the timing is deviant performance will be impaired.

Based upon this line of argument, we wished to assess interhemispheric transfer time (IHTT) in dyslexic and normal children. Two basic methods have been used for this purpose—reaction time (RT) indices and measure based upon the brain evoked response. Since the validity of reaction time measures has been more systematically studied [see 3, 32] and since these measures are less obtrusive and invasive than the evoked potential measures, we chose to initially explore our hypothesis using reaction time measures. The literature in this area indicates that in simple reaction time tasks, the ipsilateral hand-visual field conditions are associated with faster RT compared with the contralateral hand-visual field conditions (e.g. [5]). The mean difference in RT between the ipsilateral and contralateral conditions across studies in adults is approx 2.5 msec [3]. This difference has been taken to be an estimate of IHTT for at least certain portions of the cerebral commissures, for certain types of information. Recent studies of RT measures of IHTT have suggested that the estimate provided by these methods when a manual response is used (in contrast to a vocal response) probably reflects transfer time in the motor region, not in the visual region. This claim is based upon the fact that manual RT estimates of IHTT are not sensitive to variations in the stimulus intensity of the eliciting stimulus, while vocal RT measures of IHTT are influenced by this factor [22]. Our study investigated IHTT using a manual response measure since such measures have been found to be less variable than vocal measures [3].

The reading disabled group we chose to focus on in this study was a specific subgroup hypothesized to show deficits in interhemispheric transfer. This subgroup was a language-disordered group characterized by naming and decoding deficits. These skills require verbal responses to visually presented stimuli. Based upon the discussion above, we expect that abnormalities in interhemispheric transfer time would interfere with such a process.

In the present study, we wished to examine IHTT in response to stimuli in two different sensory modalities. We therefore compared simple RT measures in response to unilateral presentations of visual (checkerboard) and tactile (leg tap) stimuli. We ran these conditions in both right and left hand response conditions. While most previous studies of reaction time measures of IHTT have used visual stimuli [3], some have used tactile stimuli (e.g. [23]) and have obtained results in the direction of anatomical prediction.

It has been argued that spatial compatibility plays some role in the improvement in RT associated with the ipsilateral hand-visual field conditions. In order to evaluate the effects of spatial compatibility, many studies have been performed which have systematically manipulated the side of the body on which the subject is instructed to place his/her hand. Several studies involving simple visual stimuli have found that when this is done, the anatomically predicted effects are still obtained, i.e. faster RT is found for conditions during which the response is made by the hand which is normally ipsilateral to the visual field in which the stimulus occurs, irrespective of where the hand is actually placed in space (e.g. [1]). However, to date very little is known about the effects of spatial compatibility when tactile stimuli are utilized. In order to examine the possibility that spatial compatibility may differentially affect input to the visual vs tactile modalities, the task was run with the hands in both an uncrossed and a crossed condition. In the latter condition, the subjects' hands were crossed over the midline.

We know of only one additional set of studies which has examined possible differences between disabled and normal readers in IHTT [7, 8]. Unfortunately, these studies by BROMAN *et al.* have a serious methodological limitation which makes their findings difficult to interpret. In their first report, BROMAN *et al.* [7] present two studies which assess IHTT in response to simple visual and auditory stimuli. The number of stimuli presented in each condition was only 40. Forty stimuli is clearly too few to obtain stable estimates of IHTT [32]. Of most importance was that BROMAN *et al.* did not find a significant Hand × Visual Field or Hand × Ear interaction in either group, an effect which would be expected on the basis of anatomical prediction. If the controls do not show the expected longer reaction time to stimuli presented to the visual field or ear opposite to the responding hand compared with stimuli presented to the ipsilateral visual field or ear, then the comparison with dyslexics is uninterpretable. Their second study [8] examined IHTT in response to visually presented letters and suffered from the same problems. Moreover, in neither report do they present correlations between their measures of IHTT and psychometric or neuropsychological test performance, nor do they evaluate the effects of spatial compatibility on their estimates of IHTT.

The main hypothesis of this study was that the disabled readers would show differences in IHTT in conditions which required transfer of information from the right to the left hemisphere (i.e. the right hand condition). We did not have explicit hypotheses concerning differences between the visual and tactile conditions. These different conditions were included to assess IHTT in response to stimuli in two different sensory modalities. A second purpose of the study was to explore relations between RT measures of IHTT and performance on measures on reading and naming ability.

METHOD

Subjects

Fifty males from an initial group of 118 subjects were selected on the basis of their performance on a battery of neuropsychological 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. After meeting criteria for group assignment, reading disabled and normal children were tested in an additional psychometric test session during which a variety of neuropsychological measures were obtained. The subjects were all right-handed as assessed by the Harris Test of Lateral Dominance [17] (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 ($N=25$, age $=11.19$ years; SD $=1.16$) and half were normal readers ($N=25$, age $=11.18$ years; SD $=1.11$). All children were from either middle or upper middle income families. The subjects who were potentially reading disabled were drawn from classes for learning disabled children in local public and private schools. All of the subjects we included in our reading disabled group were classified as reading disabled by their schools. The normal readers were all drawn from regular classrooms at these schools.

All subjects had to obtain a full scale IQ of 90 or above on the WISC-R [35] in order to participate. In addition, all subjects were required to score 85 or above on performance IQ and achieve a scaled score of 7 or above on the Block Design subtest. The PIQ and Block Design criteria were established to exclude those children with perceptually based learning disabilities. Other criteria common to both groups included: (1) Scoring at or above the 17th percentile on the quiet condition of the Goldman *et al.* [16] Test of Auditory Discrimination. This criterion served to screen out any subject with gross auditory impairment; (2) eliminating any subject with obvious emotional or neurological problems (e.g. seizures, meningitis, encephalitis) or with a history of such problems; (3) eliminating those subjects who took medication with known CNS effects for longer than 6 months or those subjects who are currently taking such medication; and (4) eliminating any subject who was adopted due to lack of adequate history information.

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 [21]. This specific subgroup was targeted for study based upon two major considerations: (1) the subgroup accounts for the largest percentage of reading disabled children compared with all other identified subgroups [10, 21, 30]; and (2) we have hypothesized that this specific subgroup would exhibit deficits in interhemispheric transfer. 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 [31] and/or any of the four subtests of the Rapid Automatized Naming test [11, 12, 13].

A child was considered reading disabled if he scored 0.85 or below on the reading quotient proposed by Myklebust [24]: (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 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 test [39]. Table 1 presents the descriptive data on our dyslexic and normal samples.

Table 1. Psychometric characteristics of the groups

		AGE	PIQ	VIQ	FIQ	MQ	WA	WI	GO	GM
Dyslexics	*M*	11.19	117.60	110.16	115.08	0.73	32.48	17.60	19.92	36.23
	SD	1.16	12.11	11.88	11.90	0.08	24.30	15.97	13.15	27.10
Controls	*M*	11.18	114.28	124.20	121.88	1.18	81.88	77.32	81.60	82.44
	SD	1.11	14.27	11.50	12.54	0.17	14.20	13.55	12.75	14.55

N's are 25 per group for all variables except for GM ($N=22$ for dyslexics). Means for the reading tests are based on percentile scores. MQ, Myklebust Quotient; WA, Woodcock Word Attack subtest; WI, Woodcock Word Identification subtest; GO, Gray Oral Reading test; GM, Gates MacGinite Reading test—Level D.

In an effort to determine whether our dyslexics had an attentional dysfunction in addition to their reading disability, we compared the performance of each group on the noise subtest of the GOLDMAN et al. [16] Test of Auditory discrimination. This provides a measure of the degree to which auditory attention is compromised by the presence of background noise. On this test, we found that dyslexics performed similarly to controls (mean for dyslexics = 45th percentile: mean for control = 45th percentile, $t < 1$). Therefore our dyslexic sample did not show any gross dysfunction in attentional performance.

Procedure

The laboratory component of this research involved two sessions beyond those required for psychometric and neuropsychological screening. Reaction time measures of interhemispheric transfer time were obtained from the subjects during each of these sessions. In the two testing sessions, measures of IHTT were obtained from manual RTs in response to simple visual and tactile stimuli. The manual RT measures were based upon previous reports indicating that the difference in reaction time to a simple stimulus between the hand ipsilateral to the side of stimulation and the hand contralateral to the side of stimulation was a reflection of the time it took for information to cross the cerebral commissures (see 3 for review).

A total of eight conditions were run, half in response to visual stimuli and half in response to somatosensory stimuli. The four conditions within each of the two modalities included: (1) uncrossed right hand; (2) uncrossed left hand; (3) crossed right hand (the right hand is crossed in front of the body toward the subject's left side); and (4) crossed left hand (the left hand is crossed in front of the body toward the subject's right side). In the crossed hand conditions, the arms were actually crossed with the responding arm placed over the other arm. The order in which each of these four conditions were presented in each of the two sensory modalities was counterbalanced within and randomized across subjects. Half the subjects received the visual conditions during their first laboratory testing session and the remaining half received the tactile conditions.

The visual stimuli were 3.6° vertical by 3° horizontal checkerboard flashes presented 2.9° from a central fixation target for 10 msec.* The stimuli were rear-projected using Kodak Carousel projectors fitted with Gerbrands electronic shutters and controlled by Coulbourn digital logic. White noise of 90 db SPL (at one foot) was used in the projection room to mask the sound of the shutters. The subject was seated 50 in. from the rear projection screen upon which the stimuli were presented. In order to insure consistent location of stimulus presentation, subjects were required to place their heads in a chin rest, with a forehead restraint. The intensity of the visual stimuli was 4.75 ft c. The background illumination of the screen was 0.75 ft c. The ambient light at the subject's eyes was 9 ft c. Each condition consisted of the presentation of 200 trials, half randomly presented to the right visual field (RVF) and half to the left visual field (LVF). Each experimental condition was preceded by approx 25 practice trials. The inter-trial interval varied randomly between 1.5 and 3.5 sec. An experimenter was in the subject room at all times and stopped the trial presentation if the subject was not attentive. The experimenter also presented periodic breaks, dictated by subject state. The subjects were required to fixate a central point. Eye movements were monitored with a video camera which provided a close-up image of the subjects' eyes. The monitor was viewed by the experimenter in the subject room and he/she depressed a button whenever the subject was not centrally fixating. This button press automatically flagged the data from that trial (on the data acquisition computer) if the eye movement was coincident with the stimulus presentation and eliminated the trial from analysis.

The tactile stimuli were taps produced by stimulators which were made from modified phone receivers. The outer casing of the phone receiver was removed and the concave diaphram was filled with Silastic silicone adhesive to fashion a flush stimulating surface. A rubber knob (1 cm high, 1 cm dia) was attached to this surface and delivered the stimulus. Taps were generated by a single 120 Hz cosine wave produced by a Wavetek triggerable waveform generator amplified by two Exact model 170 DC amplifiers. The stimulators were placed approx 4 cm above the prominence of the lateral malleous on the right and left leg. We chose leg placements rather than hand or arm placements since the subjects were making responses with each hand and we did want the stimulators to interfere with response production. We developed a system using a calibrated velcro strap to equate the pressure on the leg of the left and right sided stimulators. Each stimulator was moved to the opposite leg following half of the trials in order to prevent slight pressure differences between stimulators from biasing the data. The leg on which each stimulator was placed at the start of the condition was randomized across subjects. Half the subjects began the tactile condition with Stimulator A on the left leg and half began with this stimulator on the right leg. The inter-trial interval was identical to that used for the visual stimuli. In order to equate the demands placed on the subjects for the visual and tactile trial conditions, subjects in the tactile conditions were required to fixate on the central point. Subjects also placed their head in the chin rest as they did for the visual trials. During the tactile conditions, subjects were required to wear sound attenuating ear cups in order to mask the slight sound of the tactile stimulators. The white noise in the projection room remained on during this condition.

Subjects were required to respond to the stimulus by lifting their index finger off a momentary contact switch. We chose a finger lift as the motor response on the basis of both our own pilot data with adults which indicated that this

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*Checkerboard stimuli were used since we planned, in the future, to collect both reaction time and visual evoked potentials simultaneously. The checkerboard stimuli are optimal for visual evoked response estimates of IHTT [28].

response produced the most valid estimates of IHTT (i.e. it yielded the largest percentage of subjects with IHTTS in the direction of anatomical prediction: see SARON and DAVIDSON, [28] and on the basis of previous research [22]. Subjects were instructed to return the button to the pressed position as soon as they made their response. The button was individually placed for each subject to accommodate a range of different arm and finger lengths. Individual placement of the button was accomplished by using a table with holes cut out every 2 cm. We determined the placement of the left and right hand buttons, separately for the uncrossed and crossed hand conditions, prior to the initiation of the experimental trials. These locations were noted so that when the subject returned for his second session these same button positions were used. The button locations for the visual and tactile conditions were the same, within hand condition. A total of 10–15 practice trials were administered prior to each condition.

An IBM PC acquired the reaction time data on-line. The computer determined the time from the stimulus presentation to the finger lift, to an accuracy of 0.1 msec. The computer stored data from each individual trial so that different combinations of trials could be averaged following the experimental session. Following the testing of each subject, the computer calculated the mean and median reaction time for each of the experimental conditions. In addition, it plotted a histogram of the response latencies so that the shape of the distribution could be easily determined. In light of the fact that the histograms were consistently positively skewed, only the median reaction times were used in the analyses. Trials on which the RT was less than 100 msec were eliminated since we considered these to be responses to have been initiated prior to actually perceiving the stimulus.

We reduced the data by computing medians of the reaction time for each hand–visual field combination for the visual tasks and for each hand–leg combination for the tactile tasks. Estimates of IHTT were derived by subtracting the RT in response to one stimulus location from the RT in response to the other stimulus location for each hand condition. We used both the median RT as well as the IHTT value as dependent measures in the analyses. We specifically chose to examine IHTT separately by hand condition since we had an *a priori* hypothesis regarding the direction of interhemispheric transfer. We predicted that group differences would be most apparent in transfer from right to left hemsiphere, i.e. the right hand condition. Computations of IHTT using the crossed–uncrossed difference score obscure potential differences between transfer in each direction since they collapse across them.

RESULTS

The data for the visual conditions will be presented first followed by the tactile RT data. Within each of these sections, the analyses on the median RT will be presented followed by the analyses on the IHTT scores.

Visual conditions

Reaction time. An analysis of variance (ANOVA) with Group (dyslexic/control) as a between subjects factor and Hand (left/right), Orientation of hand (uncrossed/crossed), and Side of stimulation (left/right) as repeated factors was performed. No main effect for Group was obtained [$F < 1$]. This indicates that there were no overall differences between groups in reaction time to the checkerboard stimuli. None of the other main effects reached significance in this analysis. The only significant effect in this analysis was the interaction of Hand × Side [$F(1, 48) = 6.07$, $P = 0.02$]. The means and SDs are presented in Table 2. As can be seen from this table, in the right hand condition, RT is faster in response to RVF presentations compared with LVF presentations. In the left hand condition, the opposite effect was obtained. Post-hoc comparisons (Newman–Keuls) revealed that the ipsilateral hand–visual field conditions were associated with significantly shorter RT compared with the contralateral conditions ($P < 0.01$ for both left and right hand conditions).

IHTT

An ANOVA on the IHTT scores was computed with Group, Hand, and Orientation as factors. Since the only reliable effect in the RT data reported above was the Hand × Side interaction, no significant effect was expected on the IHTT measure. Indeed, the analysis showed no reliable main effects or interactions. In response to the uncrossed left hand condition, 64% of the dyslexics and 64% of the controls showed IHTTs in the anatomically predicted direction. These percentages for the remaining conditions were: *uncrossed right*:

Table 2. Means and SD's (in msec) of manual reaction times for each Hand-Visual Field condition (based on within subject medians) across Group and Orientation of Hand in response to checkerboard stimuli

	Left-hand		Right-hand	
	LVF	RVF	LVF	RVF
M	321.5	324.4	321.4	319.8
SD	45.4	41.4	44.1	39.3

$N = 50$.

dyslexics—36%; controls—52%; *crossed left*: dyslexics—64%; controls—56%; *crossed right*: dyslexics—48%; controls—56%.

Tactile conditions

Reaction time. An ANOVA with Group, Hand, Orientation and Side as factors was computed on these data. This analysis revealed no significant main effects. In contrast to the visual data, the Hand × Side interaction was not significant here indicating that differences expected on the basis of anatomical prediction were not obtained. A non-significant Group × Hand interaction was obtained [$F(1, 48) = 3.83$, $P = 0.06$]. The relevant means are displayed in Table 3. The data reveal that RT for the dyslexics in these conditions was faster when the right vs left hand was responding while hand difference in RT for the controls was in the opposite direction.

Table 3. Means and SD's (in msec) of manual reaction time (based on within subject medians) to tactile stimuli presented to the right and left leg, split by Group and Hand, across Side of presentation and Orientation of Hand

		Left-hand	Right-hand
Dyslexics	*M*	367.2	358.5
	SD	57.9	57.4
Controls	*M*	344.7	348.2
	SD	62.0	73.8

$N = 25$ per group.

A significant Hand × Orientation × Side interaction was obtained [$F(1, 48) = 7.02$, $P = 0.01$]. The relevant data for this interaction are presented in Table 4. As can be seen from these means, the RT effects are in the anatomically predicted direction for the uncrossed hand conditions and in a direction opposite to anatomical prediction for the crossed hand conditions. In order to decompose this three way interaction, separate ANOVAs were computed on the uncrossed and crossed hand conditions. Although the means were in the direction consistent with anatomical prediction for the uncrossed hand condition, the ANVOA revealed no significant main effects or interactions. The ANOVA on the crossed hand conditions revealed a significant Hand × Side interaction [$F(1, 48) = 5.57$, $P = 0.02$]. As the data from Table 4 indicate, the direction of means is opposite to anatomical prediction and suggests instead that spatial compatibility was operative.

Table 4. Means and SD's (in msec) of manual reaction time (based on within subject medians) across group to tactile stimuli, split by Orientation of Hand, Side of Stimulation (L. and R. Leg) and Hand of response (L. and R. Hand)

		Straight		Crossed	
		L. Leg	R. Leg	L. Leg	R. Leg
L. Hand	*M*	354.0	359.5	355.4	354.8
	SD	60.6	60.7	62.4	61.5
R. Hand	*M*	351.4	350.1	352.0	360.1
	SD	66.5	62.3	68.7	68.6

$N = 50$.

IHTT. An ANOVA on the tactile IHTT data with Group, Hand and Orientation as factors was computed. The only reliable effect in this analysis was a significant main effect for orientation [$F\,(1, 48) = 7.03$, $P = 0.01$]. The uncrossed hand conditions were associated with a positive IHTT (i.e. in the direction consistent with anatomical prediction: $M = 3.36$ msec) while the crossed hand conditions were associated with a negative IHTT ($M = -4.37$). These findings indicate that in the crossed hand conditions the RT savings conferred by spatial compatibility override those associated with mediation through the direct anatomical pathway. There were no significant interactions with group. The percentages of subjects within each group who showed IHTTs in the anatomically predicted direction for each condition were as follows: *uncrossed left*: dyslexics—56%; controls—72%; *uncrossed right*: dyslexics—72%; controls—36%; *crossed left*: dyslexics—28%; controls—44%; *crossed right*: dyslexics—24%; controls—32%.

Correlations between measures of IHTT and psychometric test scores

For this analysis, we selected from the psychometric battery those measures which most clearly reflected language and reading processes. Given the fact that Orientation of Hand (i.e. uncrossed vs crossed) did interact with other variables in one condition (tactile), correlations between psychometric variables and IHTT measures were computed only for the uncrossed conditions. Table 5 presents the correlations across group between IHTT measures separately for the uncrossed right and left hand visual conditions and the selected group of psychometric measures. As can be seen from this table, longer IHTTs in the right hand condition are associated with better performance on several of the reading tests. Correlations between left hand measures of IHTT and performance were low and none were significant.

We next performed these correlations separately for each group. The pattern of correlations reported in Table 5 for the groups combined is replicated even more strongly among the dyslexics. As can be seen in Table 6, shorter IHTTs derived from the right hand response condition are associated with significantly worse performance on three of the four measures of reading among the disabled readers. This table also indicates that among the controls, these IHTT measures account for very little variance in psychometric test performance.

We computed correlations between tactile measures of IHTT (based on the uncrossed hand conditions) and psychometric test performance, both across group and separately for each group. The across group correlations indicated that the IHTT measures were relatively uncorrelated with performance. Only the correlation of right hand IHTT with word fluency was significant ($r = -0.29$, $P < 0.05$). When the correlations were examined separately for

Table 5. Pearson product–moment correlations between IHTT (derived from the uncrossed hand visual reaction time conditions) and reading measures, across Group

	Right-hand	Left-hand
WA	0.31†	−0.10
WI	0.26*	−0.06
GO	0.21	0.07
GM	0.06	0.03

*$P<0.10$.
†$P<0.05$.
Positive correlations indicate that longer IHTTs are associated with better performance. WA, Woodcock Word Attack subtest; WI, Woodcock Word Identification subtest; GO, Gray Oral Reading test; GM, Gates-MacGinite Reading test—Level D. $N=50$, except for the GM ($N=47$).

Table 6. Pearson product–moment correlations between IHTT (derived from the uncrossed hand visual reaction time conditions) and reading measures, separately for each Group. Positive correlations indicate that longer IHTTs are associated with better performance. Abbreviations for each test are the same as in Table 5. $N=25$ per group, except for the GM ($N=22$ for dyslexics; $N=25$ for controls)

	Dyslexics		Controls	
	R. Hand	L. Hand	R. Hand	L. Hand
WA	0.40*	−0.01	0.17	−0.36
WI	0.47*	−0.14	0.02	−0.01
GO	0.45*	0.23	−0.14	0.25
GM	−0.18	0.11	0.17	0.04

*$P<0.05$.

each group, a similar pattern emerged as was found for the visual IHTT data. For the dyslexics, shorter right hand IHTTs were associated with worse performance on a variety of different measures. These correlations are presented in Table 7. It can be seen that for the RAN measures, the direction of the correlations was negative. This indicates that shorter IHTTs are associated with longer time to complete the RAN subtests. For the reading measures, the sign of the correlations was positive indicating that short IHTTs are associated with worse performance on these measures. Significant correlations between right hand IHTT and reading performance were obtained for all reading measures with the exception of the reading comprehension measure (the Gates–MacGinite Test) where the correlation was marginally significant. For the controls, again little variance in psychometric test scores was accounted for by IHTT measures. Of all the correlations which were performed with data from this group, only one was significant.

Table 7. Pearson product-moment correlations between IHTT (derived from the uncrossed hand tactile conditions) and measures of language and reading ability for the dyslexic group only

		Right-hand	Left-hand
RAN:	colors	−0.19	0.11
	objects	−0.46†	0.10
	numbers	−0.36*	0.03
	letters	−0.25	−0.19
	WA	0.51‡	−0.07
	WI	0.48‡	−0.17
	GO	0.63‡	−0.03
	GM	0.37*	−0.19

*$P<0.10$.
†$P<0.05$.
‡$P<0.01$.
RAN = Rapid Automatized Naming test (correlations are presented for each of the four subtests separately). The remaining abbreviations are the same as in Table 6. The negative sign of the right hand correlations with the RAN indicate that faster IHTT is associated with slower (i.e. poorer) naming ability. The positive signs of the remaining correlations indicate faster right hand IHTT is associated with poorer performance. $N=25$ except for the GM ($N=22$).

Correlations among measures of IHTT

(1) *Visual measures.* Correlations among the four measures of IHTT obtained in response to visual stimuli were computed across group. The correlations ranged from −0.32 to 0.37. The correlations between the uncrossed and crossed conditions for each hand were positive and significant [$r=0.28$ for right hand conditions ($P=0.05$); $r=0.37$ for the left hand conditions ($P<0.01$)]. The correlations between the right and left hand conditions for both the uncrossed and crossed orientations were negative.

(2) *Tactile measures.* A similar pattern of correlations was obtained in response to the tactile stimuli. The correlations ranged from 0.41 to −0.30. The correlations between uncrossed and crossed conditions for each hand were positive [$r=0.25$ for right hand conditions ($P=0.08$); $r=0.41$ for left hand conditions ($P=0.03$)]. As with the visual measures of IHTT, the correlations between right and left hand conditions for both the uncrossed and crossed orientations were negative.

DISCUSSION

The data from this study did not support our original hypothesis of differences between disabled and normal readers in IHTT. No group differences were observed on any of the various measures of IHTT which were used. We retrospectively performed a power analysis on our data and determined that a group difference of 11 msec would be significant in the uncrossed visual condition with the sample size used in this study. Finding group differences much smaller than 11 msec would require a considerable increase in the sample size. For example, to resolve a difference of 8 msec would require a sample size of 43 per group. Thus, while our data suggest that normal and disabled readers do not differ on reaction time measures of IHTT, it is possible that with very large sample sizes, small group differences might be obtained.

In response to simple visual stimuli, subjects in both groups showed faster reaction time to stimuli presented ipsilateral to the responding hand compared with stimuli presented to the visual field contralateral to the responding hand. These findings on RT in response to simple visual stimuli replicate a large body of previous research on the use of reaction time to infer IHTT (e.g. [3, 5]. The mean IHTT across all subjects and visual conditions was 2.25 msec. Thus, even though a considerable number of subjects in each of the groups did not show IHTT in the direction of anatomical prediction, when the data are averaged across subjects, a highly significant Hand × Visual Field Interaction was obtained. These findings suggest that while RT measures of IHTT cannot be used on an individual subject basis for predictive purposes (at least with the number stimuli used per condition; see [28]), means across subjects provide IHTT estimates that are statistically significant and consistent with previous research.

In response to tactile stimuli, subjects in both groups showed faster responses to stimuli presented ipsilateral to the responding hand when in the uncrossed orientation. In the crossed hand condition, the opposite pattern of results was observed with faster responding occurring for the hand anatomically contralateral to the side of stimulation but placed on the same side. These findings suggest that spatial compatibility played an important role in the modulation of responses to the tactile stimuli in contrast to the relative absence of such effects in the case of visual stimuli. The mean IHTT for the uncrossed hand orientation tactile conditions across response hand and group was 3.36 msec. As was found with the IHTT measures derived from visual presentations, no group differences were observed on any measure of tactile IHTT.

Our findings thus indicate that on the two behavioral measures of IHTT which were utilized in this study, no significant differences were observed between groups. In light of the fact that considerable variability existed within each of the groups on measures of cognitive performance as well as on measures of IHTT, we examined correlations between these classes of measures. Perhaps our most important observation was the finding that individual differences in measures of IHTT were related to cognitive performance. On IHTT measures derived from responses to both visual and tactile stimuli, a consistent pattern emerged: faster IHTT's in the right hand conditions were associated with poorer performance on a variety of reading and other language measures. This pattern was found only among our group of disabled readers. These data suggest that a subgroup of disabled readers with abnormally fast IHTTs have particularly pronounced language disorders. It is important to underscore the fact that these findings were obtained only for the right hand conditions, for both visual and tactile measures. Since right hand responding is presumably controlled by the left hemisphere, IHTTs in this condition reflect transfer from the right to the left hemisphere. These findings indicate that future studies of IHTT should separately examine transfer in each direction. In our recent evoked potential studies of IHTT in normal adults [28], we have consistently found differences in speed of transfer in each direction.

It is precisely in the right hand conditions (reflecting right-to-left hemisphere transfer) where we predicted group differences to emerge. According to the model introduced earlier, transfer from the right to left hemisphere which is either abnormally fast or slow would be expected to interfere with the smooth execution of left hemisphere responding. This model holds that in situations where the left hemisphere controls response execution, representations of information in the right hemisphere are transferred to the left. This transfer is hypothesized to occur even if the task does not explicitly require interhemispheric transfer. The transfer from the right-to-left hemisphere is "expected" to occur during a relatively narrow time window. Deviations from this expected value in either direction would have a disruptive effect on left hemisphere response execution. Our findings qualify the model with which we began by the finding that deviant IHTTs (at least as assessd by RT measures) are not a general characteristic of even our relatively homogeneous group of disabled readers. Rather, they seem to be present only in a restricted subgroup characterized by particularly poor reading and language function. While the direction of the effect we observed was that faster IHTT was associated with poorer performance, we would expect that in a group where transfer time was abnormally slow, the same effect would obtain. In other words, over the entire range of right-to-left hemisphere IHTTs, from very fast to very slow, we would expect a curvilinear relation with performance measures that depend upon left hemisphere control. It would be imperative to examine a large group of subjects so that considerable range in IHTT can be obtained to evaluate the veracity of this curvilinear hypothesis.

There are features of these data which raise important questions about the validity of behavioral measures of IHTT. What is most problematic in using such procedures to estimate IHTT is the considerable number of subjects who do not show effects in the anatomically predicted direction. Precisely how to interpret such negative IHTT values is unclear at present, though it is apparent that factors other than IHTT are contributing to these effects. In a recent study [32] where subjects were tested in repeated sessions and where thousands of trails (>5000) were averaged to compute IHTT on an individual subject basis, almost every subject showed effects in the direction of anatomical prediction. Thus, reaction time measures can offer valid estimates of IHTT when very practiced subjects are administered a very large number of trials. Unfortunately, the requirement to repeatedly test each subject over multiple sessions makes a procedure impractical in studies of clinical populations. We believe that visual evoked potential procedures may yield valid estimates of IHTT which can be obtained with considerably fewer trials than is required for reaction time measures (see [28]).

Our findings indicate that spatial compatibility effects were present only in the tactile condition. The fact that such effects were significant for reaction time measures in response to tactile stimuli indicates that caution is warranted in the interpretation of the correlations between tactile IHTT measures and performance. It is possible that at least some of the variance in these relations is a function of factors associated with spatial compatibility effects (e.g. attentional biases) rather than IHTT. However, the fact that the pattern of correlations for the visual and tactile measures is the same argues against this interpretation.

The findings from this study which warrant the most attention are the reliable correlations which are obtained between measures of IHTT derived from both visual and tactile reaction times and cognitive performance. These data indicate that among our group of disabled readers, faster IHTTs are associated with poorer performance on reading and other language measures. In the future, it will be important to replicate this effect with other measures of IHTT, such as the visual evoked response method that we have found to be reliable and valid (see [28]). One of the important questions which these findings raise is whether the subgroup of disabled readers with abnormally fast IHTTs exhibit any anatomical differences in the corpus callosum compared with those who do not. We are currently exploring this question by examining MRI-scan derived measures of callosal anatomy in reading disabled subjects. Whatever the mechanism, the findings underscore the importance of examining interhemispheric communication in disabled readers.

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