

Anomalous Bimanual Coordination Among Dyslexic Boys

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Dyslexia has been associated with left-hemisphere dysfunctions; however, recent studies also suggest interhemispheric difficulties. To test this, we assessed bimanual coordination in dyslexic and nondyslexic boys using an Etch-a-Sketch-like task. Group performance was equivalent for parallel hand movements (both clockwise). However, the dyslexics showed significant impairments on mirror movements, particularly in their left hands, and often unknowingly reverted to parallel movements when visual feedback was removed. Although these difficulties generally suggest impaired interhemispheric coordination, specific mirror movement deficits have never before been observed in any population. We propose that deficient interhemispheric collaboration combined with anomalous ipsilateral manual control may account for the dyslexics' performance.

Recent theoretical proposals suggest that efficient interhemispheric integration is important in reading development (Gladstone & Best, 1985; Kershner, 1985a) and that dyslexic children may have deficits in interhemispheric collaboration (Davidson, Leslie, & Saron, 1988; Denckla, 1986; Gladstone & Best, 1985; Kershner, 1985b). A number of empirical investigations lend support to this proposal. Compared with normal readers, reading impaired children show less interhemispheric electroencephalogram (EEG) coherence (Sklar, Hanley, & Simmons, 1973). Anatomical measures of the corpus callosum, the major neocortical commissure, have been reported for two dyslexic brains; both showed abnormal thinning (Drake, 1968; Witelson in McGuinness, 1985). Behaviorally, certain tachistoscopic (Gross-Glenn & Rothberg, 1984; Yeni-Komshian, Isenberg, & Goldberg, 1974) and dichotic (Kershner, Henninger, & Cooke, 1984; Obrzut, Obrzut, Hynd, & Pirozzolo, 1981) studies of reading disabled children have also suggested abnormal inter-

hemispheric sharing of sensory information. Whereas normal age-matched children display a stable right-ear advantage on verbal dichotic tests, reading disabled children switch the direction of ear advantage as a function of which ear is attended to (Obrzut et al., 1981) and whether the response mode is oral or written (Kershner et al., 1984). This "attentional switching," a phenomenon usually seen only among younger normal children, has been attributed to the inadequate regulation of attentional resources between the hemispheres (Hiscock & Kinsbourne, 1980).

Thus, although contemporary views of dyslexia have more commonly attributed reading failure to left-hemisphere impairment (Rudel, 1985), recent evidence has also implicated deficient interhemispheric attentional regulation and sensory integration. However, a number of questions about interhemispheric coordination among disabled readers remain unanswered. For example, relatively little is known about the role of interhemispheric processes in the bilateral motor anomalies that have been clinically observed for many years in reading disordered children (Denckla, 1985; Tomaino, in press). Recently, Denckla (1985) has stated that "Orton's [1937] concept of mixed dominance may be important not in terms of 'competing engrams' in the visual field, but rather in terms of [interhemispherically] competing motor coordination systems in the anterior portions of the brain" (p. 193). In light of the theory and data suggesting impaired interhemispheric communication among dyslexics, it would be important to determine whether their atypical motor performance is also indicative of anomalous interhemispheric processes.

The motor anomalies of "pure dyslexic" children (i.e., children with primary reading impairment but without other significant language, neurodevelopmental, or emotional disorders) appear to be largely confined to fine or repetitive movements of the distal musculature of the fingers and hands. For example, impairment in rapid alternating finger movements was the only

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distinguishing motor characteristic found in one group of dyslexics (Owen, Adams, Forrest, Stolz, & Fisher, 1971). Similarly, dyslexic children have shown difficulties in a sequential finger-to-thumb opposition task (Denckla, 1985). Of particular importance to the issue of interhemispheric collaboration are findings that indicate poor coordination between the hands. Notably, certain types of motor imprecision among dyslexics appear only when bilateral coordination is required (Badian & Wolff, 1977; Denckla, 1985; Wolff, Cohen, & Drake, 1984). When unilateral movement is required, synkinetic or mirror movements may occur in the opposite hand (Denckla, 1985). Moreover, there is often a large left-right asymmetry, with poorer than normal left-hand performance among right-handed dyslexics (Leslie, Davidson, & Batey, 1985).

Any of these motoric findings may implicate disturbances in interhemispheric coordination or left-hemisphere processes. Manual performance in dextral brain-damaged populations has suggested that the left hemisphere is dominant for fine motor control of *both* hands, influencing the left hand via callosal connections to the right-hemisphere motor centers (Geschwind, 1975). Thus, deficits in left-hand performance have been found in both left-hemisphere-damaged individuals (Wyke, 1971a) and commissurotomy patients (Kreuter, Kinsbourne, & Trevarthen, 1972). The impaired left-hand performance of dextral dyslexics suggests the possibility of poor collaboration between the hemispheres (Denckla, 1986; Leslie et al., 1985) or impaired left-hemisphere function (Rudel, 1985).

When the motor deficits of reading disabled children are exclusive to conditions requiring bimanual coordination, interhemispheric processes are implicated. Specifically, deficits on an alternating bimanual tapping task have been interpreted as evidence of impaired interhemispheric coordination (Badian & Wolff, 1977; Klicpera, Wolff, & Drake, 1981). The general relation between intermanual coordination and interhemispheric collaboration has been most clearly demonstrated by Preilowski (1972, 1975). In this study, epileptic adults whose anterior neocommissures had been sectioned were compared with normal and unoperated epileptic adults. The subjects were required to learn a bimanual coordination task similar to Etch-a-Sketch. While seated in front of a screen, participants were required to turn two cranks in order to guide a stylus along a prescribed pathway. Control subjects learned to coordinate their hands to produce a relatively straight line within the required diagonal pathway. In contrast, the commissurotomy patients failed to develop the smooth intermanual motor control seen among other subjects. Rather, they appeared to rely on visual feedback mechanisms to correct their movement errors. Moreover, when visual feedback was removed, the control subjects were able to retain their learned pattern of intermanual coordination. In contrast, the commissurotomy patients were largely unable to do so, indicating their reliance on inefficient visual feedback. Furthermore, they demonstrated particular difficulty in controlling their left hands. Preilowski's findings indicate the specific role of the anterior portion of the corpus callosum in left-hand control and the acquisition of intermanual coordination.

Impaired intermanual coordination, however, has also been associated with specific left-hemisphere damage. Left-hemisphere-damaged patients produced more errors on a bimanual pantograph task than did normals or right-hemisphere-dam-

aged patients (Wyke, 1971b). Although Wyke's task did not assess individual hand contributions to overall bimanual ability, because a pantograph links the two hands to control a single stylus, her data nonetheless suggest a left-hemisphere contribution to bimanual ability.

In light of the evidence for both left-hemisphere and interhemispheric contributions to manual and intermanual coordination, it is not clear to what extent the manual coordination deficits of dyslexics may derive from left-hemispheric or interhemispheric anomalies (or from both). Wolff and his coworkers have attempted to address this issue (Badian & Wolff, 1977; Klicpera et al., 1981; Wolff et al., 1984). They assessed "reading retarded" boys on a tapping task that required them to maintain various metronome-entrained tapping rates. Unimanual, synchronous bimanual, and alternating bimanual modes of this timed tapping precision task were used. This procedure permitted the measurement of individual hand contributions to various modes of manual coordination. Specific left-hand deficits appeared only in the bimanual alternating mode, which the authors interpreted as evidence of impairment in rapid communication between the hemispheres (Badian & Wolff, 1977; Klicpera et al., 1981). Because the bimanual condition alone revealed deficits, the results seem analogous to Preilowski's (1972) findings with partial commissurotomy patients. A later report by Wolff and colleagues (Wolff et al., 1984), however, failed to support their earlier conclusion. That study found that when the absolute *rate* of motor production was measured on a variety of speeded motor tasks, including some unrelated to bimanual coordination, the performance of the reading impaired children was better characterized by the rate at which motor timing broke down, rather than by intermanual ability *per se*. It appeared that the rapid motor timing ability of the dyslexics was impaired, and that this had been most evident in the bimanual alternating tapping task. Consequently, their use of a rapid timing precision task confounded intermanual coordination ability and rapid motor timing control. Given the evidence that the left hemisphere is specialized for rapid motor sequencing ability (Kimura, 1977), the Wolff et al. (1984) report suggested that the earlier observed intermanual anomalies of poor readers may not be due specifically to interhemispheric collaboration deficits. It should be noted that Davidson and his colleagues (Davidson et al., 1988) have proposed that problems in the timing of interhemispheric transfer in dyslexics may actually interfere with left-hemisphere response processes and, thus, reveal themselves as left-hemisphere deficits. No study to date has shown the differences in intermanual coordination between normal and impaired readers to be independent of rapid motor sequencing ability. Clarification of this issue might shed some light on the role of interhemispheric processes in developmental dyslexia. Consequently, in the study reported here, the performance of dyslexic and nondyslexic boys was compared on a bimanual fine motor coordination task designed to measure manual abilities independent of absolute timing precision. Following Preilowski (1972), we used a task similar to Etch-a-Sketch to assess bimanual performance, but designed our apparatus to measure the independent contributions of left and right hands. Also following Preilowski, both visual feedback and no visual feedback conditions were used to evaluate the role of visual guidance in the performance of this bimanual task.

Table 1
Scores for Criterion Measures and Reading Tests

Measure or test	Dyslexic		Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Wechsler Intelligence Scale for Children—Revised				
Verbal IQ	111.68	12.86	126.84	11.69
Performance IQ	119.74	11.95	116.79	13.87
Full Scale IQ	117.21	12.50	124.84	12.28
Woodcock Reading Mastery Word Identification	17.89	16.94	81.79	10.79
Harris Laterality	96.11	8.50	97.22	4.61
Rapid Automatized Naming: Colors	43.94	35.88	80.39	15.19
Rapid Automatized Naming: Objects	33.11	23.60	72.50	14.04
Rapid Automatized Naming: Numbers	18.44	26.44	77.50	21.54
Rapid Automatized Naming: Letters	10.11	21.22	82.78	16.29
NCCEA Visual Naming	61.78	29.53	75.29	11.14
GFW Auditory Discrimination: Quiet	92.00	16.26	73.39	24.40
Myklebust Reading Quotient	.72	.09	1.21	.17

Note. IQ test is expressed in standard score units ($M = 100$, $SD = 15$); all other tests except Myklebust quotient are expressed as percentiles. NCCEA = Neurosensory Center Comprehensive Examination for Aphasia. GFW = Goldman-Fristoe-Woodcock (Woodcock, 1976).

Method

Subjects

Eighteen impaired (M age = 12.08 years; range = 10.0 to 14.10 years) and 18 nonimpaired readers (M age = 12.31 years; range = 9.8 to 14.7 years) were selected from schools in Westchester County, New York. All children were right-handed boys (as assessed using the Harris Test of Lateral Dominance; Harris, 1958) and had participated in a previously published study of dyslexia (Leslie et al., 1985). Each child was paid \$10 per research session. Children with histories of head trauma, seizures, psychiatric illness, recent use of psychotropic medication or uncorrected visual or auditory acuity deficits were excluded from the study. Subjects were of at least average intelligence (i.e., their Wechsler Intelligence Scale for Children—Revised [WISC-R; Wechsler, 1974] scores were greater than 90, and their Block Design subtest scores were greater than 7). Reading level was measured by word recognition (Woodcock Reading Mastery Test; Woodcock, 1973). Reading impairment was determined by the Myklebust Quotient (see Myklebust, 1968): $(2 \times \text{reading age}) / (\text{mental age} + \text{chronological age})$. Impaired readers had Myklebust quotients below .85, whereas controls scored above .95. Additionally, all impaired readers were deficient in object naming as assessed using the Neurosensory Center Comprehensive Examination for Aphasia (NCCEA; Spreen & Benton, 1977) or using Rapid Automatized Naming (Denckla & Rudel, 1976). None of the control subjects had naming deficits.

Table 1 lists the group differences on tests related to the inclusion criteria.

Apparatus

A Hewlett-Packard model 7035B x-y plotter was used to assess bimanual coordination. The plotter pen was controlled by two small, remote 10-turn hand-manipulated potentiometers, with one knob controlling the x-axis and the other controlling the y-axis. The apparatus functioned much like the children's game Etch-A-Sketch. The position of the potentiometers was counterbalanced so that the left hand controlled the x-axis for half of the subjects in each group, but controlled the y-axis for the other half. The movement of the two knobs allowed the subject to steer the plotter pen through various predetermined pathways. Addi-

tionally, an opaque screen was hinged to the base of the plotter to occlude the subject's view of the pen and plotter during the no visual feedback trials.

Potentiometer movement was monitored using optical counters mounted below the potentiometers. The counters were triggered by movement of the gear teeth on the knobs and fed two decade counters (Thornton Model DEC 110). Knob movement of approximately 12° rotation, in either direction, registered as a single count on the LED readout of the decade counter. At the end of a trial, the readout value was recorded by hand.

To assess memory for line orientation, as a control measure for the no visual feedback condition (see *Procedure*), a simple apparatus was used. It consisted of a 11 × 14 in. (280 × 350 mm) Masonite board, onto which a 8½ × 11 in. (243 × 280 mm) lucite frame had been glued to hold a sheet of paper of the same size. A clear lucite pointer with a black line scribed in it was attached so as to pivot from the midpoint of the base of the frame.

Stimuli

Each stimulus for the Etch-a-Sketch-like task consisted of a "path," defined by parallel straight lines drawn 5 mm apart on 8½ × 11 in. (243 × 280 mm) white paper, which was positioned on the plotter screen. The subject was to guide the plotter pen between the two lines. There were two test conditions: Visual Feedback (VF) and No Visual Feedback (NVF).

In the VF Condition the paths were 180 mm in length, varying only in the angle of line orientation on the page. Six trials were presented: a 26.5° angle and its supplementary and complementary angles (63.5°, 116.5°, and 153.5°) as well as a 45° angle and its supplement (135°). The 26.5° angle required a bimanual ratio of 2:1 for left- to right-hand (or right- to left-hand) movement of the potentiometer knobs. At 26.5°, both hands moved in a clockwise direction. At 63.5°, the hand ratio for each subject was reversed (1:2), with both hands moving in a clockwise direction. At 116.5° and 153.5°, the left- to right-hand ratios were also 1:2 and 2:1, but one hand turned clockwise while the other turned counterclockwise. At 45°, the two hands turned clockwise at the same rate (1:1 ratio). At 135° the 1:1 ratio was retained, but the hands turned in opposite directions (clockwise and counterclockwise). The six angles

thus assessed equal and unequal rates of left- and right-hand movement as well as unidirectional (clockwise) and bidirectional (clockwise and counterclockwise) movements. In the analyses, the former factor is designated as *movement* ratio, and the latter as *direction*.

The stimuli for the NVF Condition were identical with those for the VF Condition, except that a line had been drawn perpendicular to the pathway, 60 mm from the start of the 180-mm pathway, in order to mark the beginning of the NVF portion of the trial.

Procedure

Thus, the two bimanual tasks consisted of a total of 12 trials presented to each subject. The two conditions were presented to all subjects in the same order: VF followed by NVF. Both conditions were preceded by a single practice trial. Within both the VF and NVF conditions, presentation order of pathway orientations was randomized across subjects. At the conclusion of all trials, the memory of line orientation task was administered.

At the beginning of the session, the subject was seated in front of the plotter screen and situated so that each potentiometer knob could be controlled with the thumb and index finger of the assigned hand. All subjects were allowed approximately 1 min of practice with the apparatus to familiarize themselves with the movement of the plotter pen. The counters were set to zero prior to the start of each trial. Verbal encouragement was given freely during each bimanual trial, but no assistance with the task or feedback about performance was provided until the trial ended. Subjects were instructed to steer the plotter pen through different pathways quickly, with an emphasis on accuracy in staying between the lines. They were told that if they strayed outside the lines, they should try to reenter the pathway at the point where they had exited it. Time and individual left- and right-hand scores were recorded at the conclusion of each trial.

VF condition. For this condition, the subjects steered the plotter pen through the six straight pathways in free viewing. At the beginning of each trial, the examiner placed the sheet containing one of the blank pathways on the plotter screen and moved the pen to the beginning of the pathway. Time was recorded by stopwatch to the nearest .1 s, beginning from when the subject began steering the pen. Left- and right-hand potentiometer readings were recorded from the decade counters for each trial.

NVF condition. At the conclusion of the VF trials, subjects were given a brief rest and were then given the six NVF trials, preceded by a practice trial. They were instructed to begin as in the VF trials but to stop moving the pen momentarily when it reached the small perpendicular line drawn across the path, so that the experimenter could lower the screen that occluded the subject's subsequent view of the plotter. This screen was marked with an X in the center as a visual fixation point, approximately at eye level, to keep the subjects from watching their hands as they completed the path without visual feedback. Time and potentiometer output scores were recorded separately for the first 60-mm (VF) and the last 120-mm (NVF) portions of each trial. When the subjects reached either the end of the path or a point 120 mm from the start of the NVF portion of the trial (determined by an arc drawn 120 mm from the origin of that segment of the path), the subjects were stopped and the time and potentiometer readings were recorded. Subjects were permitted to see their performance at the conclusion of each trial, but no cues about performance were given during the trial.

Memory for line orientation. To assess the effect of visual memory for line orientation on performance in the NVF condition, a separate line orientation memory task was administered at the conclusion of the session. Subjects were presented with a sheet of paper, which was placed in the apparatus described earlier, onto which was drawn a line segment starting from the midline of the bottom of the page and oriented at one of the six stimulus angles. Subjects were instructed to remember the

orientation of the line. Following a 15-s presentation and a 10-s delay, subjects were presented with a blank sheet of paper in the same apparatus. They were asked to reproduce the orientation of the line segment by pivoting the lucite pointer to the correct angle. The subjects' response in angular degrees was recorded for each of the six trials. Presentation order for the six line segments was randomized across subjects.

Results

VF Condition

Error scores. For each trial, in each condition, an ideal score (mm) was computed to reflect the minimum *x*- and *y*-axis inputs necessary to complete the path without deviation from the center. The subject's obtained scores were compared with these ideal scores on each trial: Error scores for each hand were calculated as obtained score minus ideal score for the *x*- and the *y*-axis.

A $2 \times 2 \times 3 \times 2$ analysis of variance (ANOVA) was computed for error scores in the VF Condition, with Group as a between-subjects factor and Hand, Movement Ratio, and Direction as within-subjects factors. *Direction* refers to the direction of bimanual movement required for the trial (unidirectional vs. bidirectional), and *Movement Ratio* refers to the ratio of right- to left-hand movement required (1:1, 1:2, or 2:1) (see *Stimuli*).

There were no main effects for Group, Movement Ratio, Hand, or Direction. However, the interaction of Group \times Direction, $F(1, 34) = 4.88, p < .04$, and of Group \times Direction \times Hand, $F(1, 34) = 4.1, p = .05$, were both significant. Figure 1 suggests that the Group \times Direction interaction was attributable to a greater error rate by dyslexics in the bidirectional trials and greater error rate by controls in the unidirectional trials. However, the simple effects tests for this two-way interaction were nonsignificant.

In contrast, the simple effects tests were significant for the Group \times Direction \times Hand interaction, which was attributable to Group \times Direction differences in left-hand performance. The control subjects showed significantly greater left-hand errors in the unidirectional trials than in the bidirectional trials, $F(1, 34) = 5.99, p < .02$. The reverse effect for the dyslexics (see Figure 1) was not significant, but they did show significantly greater errors for the left hand than for the right hand in the bidirectional trials, $F(1, 34) = 5.15, p < .03$. There was no group difference in left-hand performance, however, on either the bidirectional or the unidirectional trials.

Completion time scores. The analysis of completion time also indicated group differences (see Figure 2). A $2 \times 3 \times 2$ ANOVA, with Group, Movement Ratio, and Direction as factors, failed to find a significant main effect for Group. There was a significant effect for Direction, $F(1, 34) = 5.14, p < .03$, and for the Group \times Direction interaction, $F(1, 34) = 5.09, p < .03$. Although Movement Ratio was also significant, $F(2, 68) = 12.69, p < .001$, with longer completion times associated with equal rather than unequal hand movement ratios, this did not interact with either Group or Direction \times Group.

Simple effects tests of the Group \times Direction interaction indicated that dyslexics were slower than controls only in the bidirectional trials, $F(1, 34) = 4.07, p = .05$. Whereas the dyslexics showed no completion time differences between directions, the controls were faster in the bidirectional than the unidirectional

VISUAL FEEDBACK CONDITION

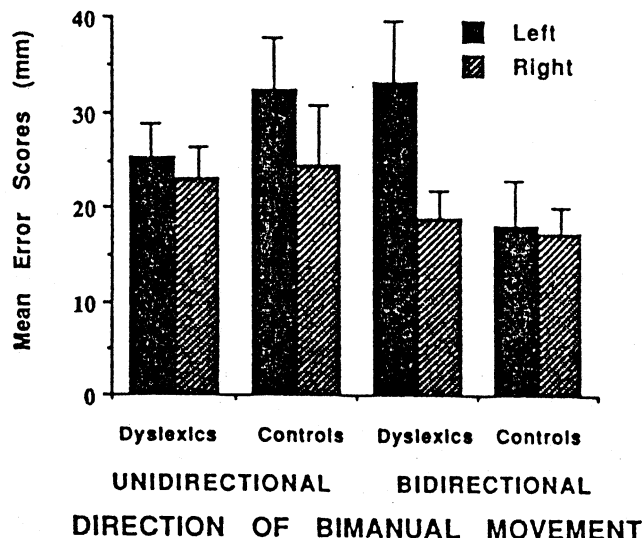


Figure 1. Mean error scores in the Visual Feedback condition. (Error bars represent standard error of the mean.)

trials, $F(1, 34) = 10.23$, $p = .003$. Thus, in the VF trials, the dyslexics were slower than controls only on trials requiring opposing hand movements.

NVF Condition

Error scores. In the NVF trials, the last 120 mm of the pathway was performed without visual feedback and, therefore, relied primarily on memory of performance during the first 60 mm. Subjects' error scores on this last 120 mm were analyzed using a $2 \times 2 \times 3 \times 2$ ANOVA, with Group as a between-subject factor, and Hand, Movement Ratio, and Direction as within-subject factors, as in the VF condition. There were no main effects for Group or Direction, but Movement Ratio, $F(2, 68) = 14.96$, $p < .001$, and Hand, $F(1, 34) = 5.09$, $p < .04$, were both significant. Overall, the right hand produced fewer errors than the left, and trials requiring a 1:1 ratio of input from the two hands (45° and 135°) produced fewer errors than 1:2 or 2:1 ratios. The latter effects did not, however, significantly interact with Group and, thus, were not specific to the dyslexics.

Although this analysis failed to indicate any significant Group differences, we noticed that some subjects completely reversed the direction of rotation of one or both hands after visual feedback was removed, and that this pattern appeared strikingly different for the dyslexic compared with the control subjects (see Figure 3). Because the hand error scores were computed from the amount of hand input to the potentiometers, regardless of direction, such reversals could yield a near-zero error score by a turn of the potentiometer knob of the correct magnitude, but completely in the wrong direction. These directional reversals can be treated in two different ways, which led

us to develop two new measures of error. First, we computed the arc degrees of difference between the subject's response line and the center of the prescribed path (see Figure 3), referred to as *arc error* scores. Second, we noted that directional reversals placed the response line in the spatial quadrant opposite to the stimulus path. For example, if the stimulus path was at 135° , which is in the negative- x , positive- y quadrant, and the response line was in the positive- x , positive- y quadrant, the subject had reversed the direction of rotation of the hand controlling the x -axis. Therefore, *reversal frequency* served as another dependent measure.

Arc error scores. Arc error scores were analyzed in a $2 \times 3 \times 2$ ANOVA, with Group as a between-subject factor, and Movement Ratio and Direction as within-subject factors. There was a significant main effect for Group, $F(1, 34) = 14.61$, $p < .005$, but not for Movement Ratio or Direction. The Group \times Direction interaction was significant, $F(1, 34) = 8.96$, $p = .005$. Simple effects tests on this interaction revealed that the dyslexics had a greater error magnitude on the bidirectional trials in comparison to the controls, $F(1, 34) = 15.09$, $p < .0005$, and in comparison to their own unidirectional performance, $F(1, 34) = 12.17$, $p < .002$ (see Figure 4).

Reversal frequency scores. Reversal frequency scores were submitted to binomial probability tests, which yielded no group differences for any of the unidirectional trials. For each of the bidirectional trials, however, dyslexics produced significantly more reversals than did controls (see Table 2).

This finding, in conjunction with the nonsignificant Group effect in the hand error scores, indicates that the group differences in arc error were largely a function of reversal frequency on bidirectional trials. Group differences attributable to this combination of large arc error scores and low hand error scores are possible only when the errors are caused by complete reversals in the direction of hand rotation.

VISUAL FEEDBACK CONDITION

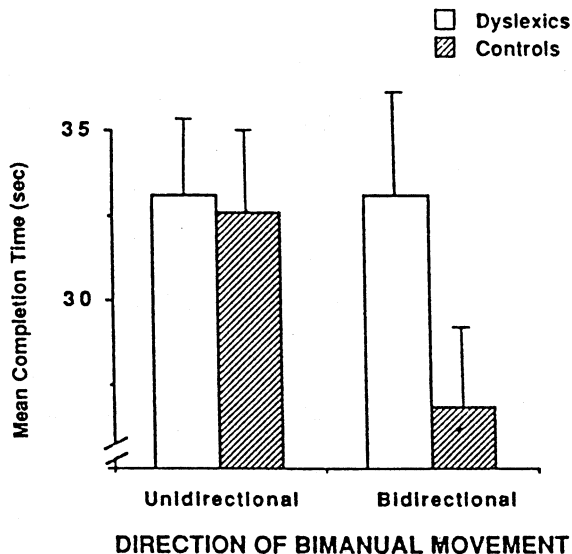


Figure 2. Mean completion times for the Visual Feedback condition.

NO VISUAL FEEDBACK CONDITION

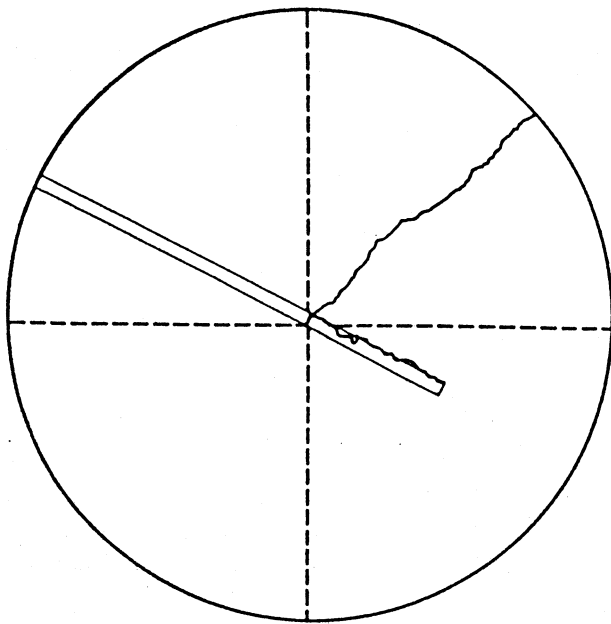
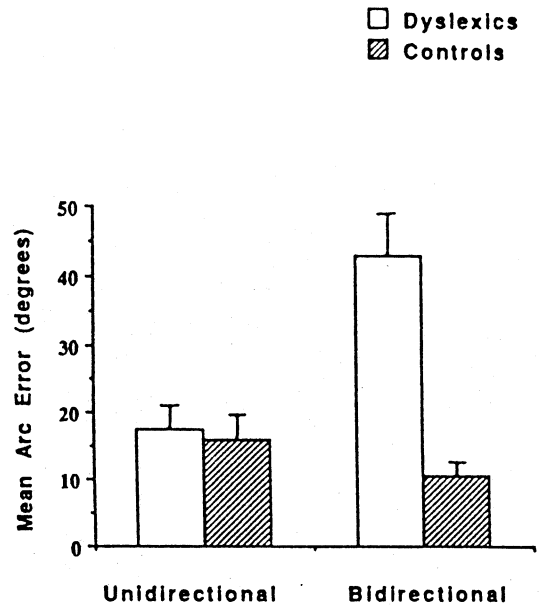


Figure 3. Tracing of a reversal error produced by a dyslexic subject on one of the bidirectional No Visual Feedback trials.



DIRECTION OF BIMANUAL MOVEMENT

Figure 4. Mean arc error scores for the No Visual Feedback condition.

To assess whether the reversals were preferentially influenced by one hand or by one direction of movement (clockwise vs. counterclockwise), we examined the quadrant of actual response on each trial for which a reversal occurred (Figure 3). Among the 24 reversals found in the dyslexic group (20 in the bidirectional trials and 4 in the unidirectional trials), 13 were attributable to the left hand alone (11 on bidirectional trials, 8 of which involved a switch from counterclockwise to clockwise motion), 10 to the right hand (8 on bidirectional trials, 5 of which involved a counterclockwise to clockwise switch), and 1 to both hands (bidirectional trial). According to binomial tests, neither the hand difference nor the difference in direction of switching was significant. Nor was there a significant association between hand and switching direction, as assessed using a Fischer's Exact Probabilities test. However, the dyslexics were more likely to revert to unidirectional (parallel) movement of the two hands (19 instances) than to revert to bidirectional (mirror) movements (5 instances), $p < .003$ (binomial test). Moreover, reversals to unidirectional (parallel) movement were more likely to result in clockwise motion of both hands (13 instances) than in counterclockwise motion (6 instances), $p = .05$ (binomial test). Only three reversal errors occurred among the control subjects, all in unidirectional trials (i.e., reverting to mirror movement).

It is notable that 15 of the 18 dyslexic subjects produced reversals at least once, whereas only 2 of the 18 controls did so. Seven of the dyslexics and 1 control reversed on more than one trial, even though they had been shown their errors at the end of each trial. Thus, awareness of their reversal errors did not stop a number of dyslexics from reversing on subsequent trials.

Completion time scores. Trial completion times were also analyzed using a $2 \times 3 \times 2$ ANOVA, with Group as a between-subject factor and Movement Ratio and Direction as within-

subject factors. Results indicated no significant main effects. Although the dyslexics appear to have performed somewhat more slowly than the controls on the bidirectional trials (36.62 s vs. 28.54 s) and on the unidirectional trials (33.02 s vs. 29.7 s), the effect was not significant. The Group \times Movement Ratio interaction, however, was significant, $F(2, 62) = 3.72, p < .04$. This effect was the result of the dyslexics' slower performance on the 45° (unidirectional and 1:1 ratio of hand inputs), 135° (bidirectional and 1:1 ratio), and 153.5° (bidirectional and 2:1 ratio) trials. No other completion time effects were significant.

Thus, several findings in the NVF condition paralleled those found in the VF Condition. Dyslexics were slower and less accurate on bidirectional trials and showed a bias toward greater left-hand errors. In contrast to the VF condition, however, hand error scores did not reveal significant Group \times Direction differences for the NVF condition. The lack of group differences in NVF hand errors can be accounted for by the incidence of reversals among dyslexics, which were evident in arc error scores and reversal frequencies.

Table 2
Number of Reversals in Bidirectional Trials of the No Visual Feedback Condition

Trial angle	Dyslexics	Controls	Binomial probability
116.5°	7	0	.008
135°	8	0	.004
153.5°	5	0	.031

Counterbalancing of Hand and Plotter Axis

The effect of counterbalancing hand of control with plotter axis was examined using an ANOVA for the VF and NVF trials. There were no significant effects in any condition.

Memory for Line Orientation

For the line memory task, error scores were computed as the average difference in angular degrees between the target lines and the subjects' responses on the six trials. Scores among the dyslexics appeared to contain several extreme values, so group scores were tested for homogeneity of variance. Because the group variances were significantly different, $F(1, 34) = 5.62, p = .023$, a *t* test for unpooled variances was conducted to compare group means. There was no significant group difference in memory for line orientation.

Age as a Factor

To assess the influence of age on group performance, age at time of testing was entered as a covariate with the dependent measures of time and left- and right-hand error scores in the VF condition and arc error scores in the NVF condition. The analysis of covariance (ANCOVA) indicated no significant effect for age in any condition.

Discussion

In this study, the performance of dyslexic children on an intermanual coordination task unrelated to the reading process was consistent with the well-accepted position that they have atypical functional cerebral organization. The disabled readers showed impairments in bimanual coordination, relative to their nondisabled controls, under several conditions. Group differences were evident on both speed and accuracy measures; impaired readers performed more slowly and less accurately with visual feedback, particularly with their left hands during bidirectional trials, and performed less accurately without visual feedback. A primary difference between the two conditions was that under visual feedback monitoring, the dyslexics were able to correct the direction of their left-hand movement. Their high error scores, however, reflect the inefficiency of this approach. In contrast, without visual feedback these subjects were unable to monitor their hand movements visually and unknowingly reverted to unidirectional bimanual movement. This was demonstrated in both their arc error and frequency of reversal scores.

Most striking was the tendency of nearly all the dyslexics, but none of the control subjects, to revert unknowingly to unidirectional (parallel) movements of the two hands under requirements of bidirectional (mirror) movements without visual feedback. This pattern of reversals more often resulted in clockwise, rather than counterclockwise, movements of both hands. Thus, the dyslexics had difficulty maintaining mirror-image movements or they showed a strong preference for unidirectional bimanual movements, usually clockwise.

At a general level, the impaired intermanual coordination of our dyslexic subjects coincides with Preilowski's (1972, 1975) report of intermanual deficits among partial commissurotomy patients. Both the commissurotomy patients and our disabled

readers showed greater left- than right-hand impairment, which Preilowski attributed to a failure in the interhemispheric coordination of motor commands from the dominant left hemisphere in his subjects. In addition, both these groups had difficulty maintaining certain preestablished bimanual movements without visual guidance and unknowingly reverted to movement patterns that were presumably less demanding for them. Preilowski explained this behavior in his commissurotomy patients as a failure to develop efficient motor feedforward, a putative function of the anterior portion of the corpus callosum. The parallels in the two sets of findings suggest that there may be similar interhemispheric deficiencies among dyslexics.

The present results are also consistent with other reports of impairments among poor readers on intermanual (Badian & Wolff, 1977; Klicpera et al., 1981) and left-hand (Leslie et al., 1985) performance, which were interpreted as evidence of deficient interhemispheric processes. As we noted earlier, however, Wolff et al. (1984) found that impaired readers differed from normal controls in timing precision on a variety of speeded motor tasks, and not only on bimanual coordination. Thus, the tapping task used in the earlier Wolff studies had confounded intermanual coordination with timing precision, which is dependent on specialized left-hemisphere processes (Kimura, 1977; Vaughn & Costa, 1962; Wyke, 1971a). These considerations suggest the possibility that the poor readers' bimanual tapping deficit reflected a left-hemisphere rather than an interhemispheric dysfunction, thus limiting comparisons between Wolff's and Preilowski's findings.

In contrast, the present study assessed intermanual coordination independent of absolute timing precision. Therefore, the bimanual impairments that we found in reading disabled boys cannot be ascribed solely to deficits in left-hemisphere control of rapid sequential motor output. However, it is premature to draw the alternative conclusion that interhemispheric processes alone are responsible.

A primary limitation in interpreting our findings is that there are no previous reports of impaired performance on bidirectional, or mirror-like, movements in any population. Thus, there is no precedent for relating the bidirectional movement deficits to hemispheric or interhemispheric function. No such deficits are present in Preilowski's studies with commissurotomy patients; in fact, both his patients and normal control subjects showed *better* performance on bidirectional, mirror movements than on unidirectional, parallel ones (see also Sperry, Gazzaniga, & Bogen, 1969). It should be noted, however, that Preilowski's task required movements of the lower arms (proximal musculature) to turn cranks, whereas ours required fine movements of the thumb and forefinger (distal musculature) to turn small knobs. Therefore, differences in the pattern and degree of cortical control over the distal versus proximal musculature (Brinkman & Kuypers, 1972) might seem to suggest an explanation for the disparity between our findings and those of Preilowski.

Two observations, however, mitigate against the possibility that our findings completely depend on the requirement for distal motor control. First, our control subjects, like Preilowski's control and commissurotomy subjects, demonstrated clear preferences for mirror movements. They were faster and more accurate on bidirectional (mirror movement) than unidirec-

tional (parallel movement) trials with visual feedback, and the few reversals that they produced without visual feedback all occurred on unidirectional trials (parallel movement requirement) and resulted in mirror movement of the hands. Second, using unimanual finger-thumb apposition tasks, Denckla (1985) found overflow of mirror movements in the contralateral hand among "pure" dyslexics. The difference between our finding and Denckla's needs explanation, given that both involved distal motor control. In this regard, it should be noted that her study used a unimanual rather than bimanual coordination task to examine mirror-movement preferences. On the basis of these two considerations, our findings with dyslexics appear to be specific to the *relationship* between their distal motor coordination abilities and our bimanual task requirements.

Can the anomalous parallel bimanual movement tendencies observed among our dyslexics be explained by existing neural models of the more commonly observed mirror-movement patterns? Current theory argues that both commissural action and the distribution of ipsilateral (uncrossed), as opposed to contralateral (crossed), pathways from motor cortex in each hemisphere to each hand contribute to the appearance or inhibition of mirror movement (Haerer & Currier, 1966; Nass, 1985; Preilowski, 1975). Evidence from unilateral brain-damaged and hemispherectomy patients suggests that the ipsilateral motor pathway from each hemisphere contains a mirror representation of the movement pattern projected via the larger contralateral pathway. This would lead to an underlying preference for mirror movements, which is normally suppressed because the ipsilateral message is overridden by the contralateral message transmitted by means of the corpus callosum from the opposite hemisphere. Increased mirror movement tendencies in congenital acallosals (Dennis, 1976) and in commissurotomy patients (Preilowski, 1975) indicate that the corpus callosum plays an important role in this suppression of mirror movements.

Figure 5 (Panel A) illustrates the neural model proposed by Preilowski (1975) to account for the mirror-movement preference in normal subjects. In our diagram, the solid black lines descending from the left hemisphere to the right hand (crossed or contralateral pathway) and to the left hand (uncrossed or ipsilateral pathway) represent the dominant influence of the left hemisphere on bimanual performance. The dark gray bridge between the hemispheres represents the corpus callosum; the arrow within the corpus callosum indicates that the left hemisphere has a dominant influence over the right hemisphere for manual control by means of the corpus callosum. The greater thickness of the contralateral than of the ipsilateral pathways illustrates the greater degree of contralateral influence over manual control. To illustrate left-hemisphere dominance in manual control, the pathways emanating from the left hemisphere are darker and thicker than those emanating from the right hemisphere. The arrows within the circles represent commands for the direction of hand rotation. Note that, following Preilowski (1975), the ipsilateral pathway from each hemisphere is assumed to represent the mirror-image motion of that specified by the contralateral pathway from the same hemisphere.

Thus, Figure 5 (Panel A) illustrates that for normal subjects bidirectional (mirror) movements of the hands should be relatively easy, because each hand receives identical movement

commands through its contralateral and ipsilateral pathways. Unidirectional (parallel) movements should be more difficult, however, because of the conflicting commands to each hand through the contralateral versus the ipsilateral pathways. In the latter case, there is greater conflict for the left hand than for the right hand, because there is greater ipsilateral influence from the dominant left hemisphere to the left hand than there is from the nondominant right hemisphere to the right hand.

This model of mirror-movement tendencies, exemplified in Preilowski (1975) and Nass (1985), characterizes the performance of various clinical populations as well as normal children and adults under certain task demands quite well. It cannot, however, account for our dyslexic subjects' reversals to unidirectional, parallel action of the hands without some modification. A general hypothesis of poor interhemispheric coordination would be consistent with the unwanted appearance of an underlying movement preference under increased task demands, such as removal of visual feedback, which would indicate deficient inhibition of the ipsilateral messages. Moreover, it is in line with other suggestions of abnormal interhemispheric functions in disabled readers (e.g., Davidson et al., 1988; Gladstone & Best, 1985; Kershner, 1985a, 1985b; Obrzut et al., 1981). Yet the *direction* of the dyslexics' underlying movement preference is obviously incompatible with Preilowski's (1975) neural model of mirror movements as it stands. If, however, we modify the model by hypothesizing anomalous organization of the ipsilateral motor pathways in our disabled readers, in addition to interhemispheric deficiency, it may extend to our findings.¹ That is, parallel movements could occur if the ipsilateral pathway in dyslexics represents a *spatial match* of the movement direction projected in the contralateral pathway rather than the mirror-image representation proposed by Preilowski (1975).

Figure 5 (Panel B) illustrates our modified neural model of the unidirectional (parallel) bimanual movement preferences of our dyslexic subjects. As with the normal subjects, the left hemisphere is assumed to dominate in control of both hands, as illustrated by the darker pathways emanating from the left hemisphere than from the right hemisphere. Likewise, the contralateral pathways are assumed to be more influential than the ipsilateral pathways, as shown by their greater thickness. However, it is proposed that dyslexic children have deficient corpus callosum function, as illustrated by the lightly stippled corpus callosum and by the absence of callosally mediated influence of the left hemisphere over the right hemisphere. Furthermore, the ipsilateral pathways are presumed to convey a movement pattern that is spatially identical (rather than a mirror image, as in normals) with that conveyed by the contralateral pathway from the same hemisphere.

Thus, Figure 5 (Panel B) indicates that, unlike normal subjects, dyslexics have greater difficulty with bidirectional (mirror) bimanual movements than with unidirectional (parallel) movements. In the former situation, conflicting commands would arrive at each hand from the contralateral versus the ipsi-

¹ Our proposal assumes both inhibitory and facilitative interhemispheric influences during the performance of bimanual coordination tasks.

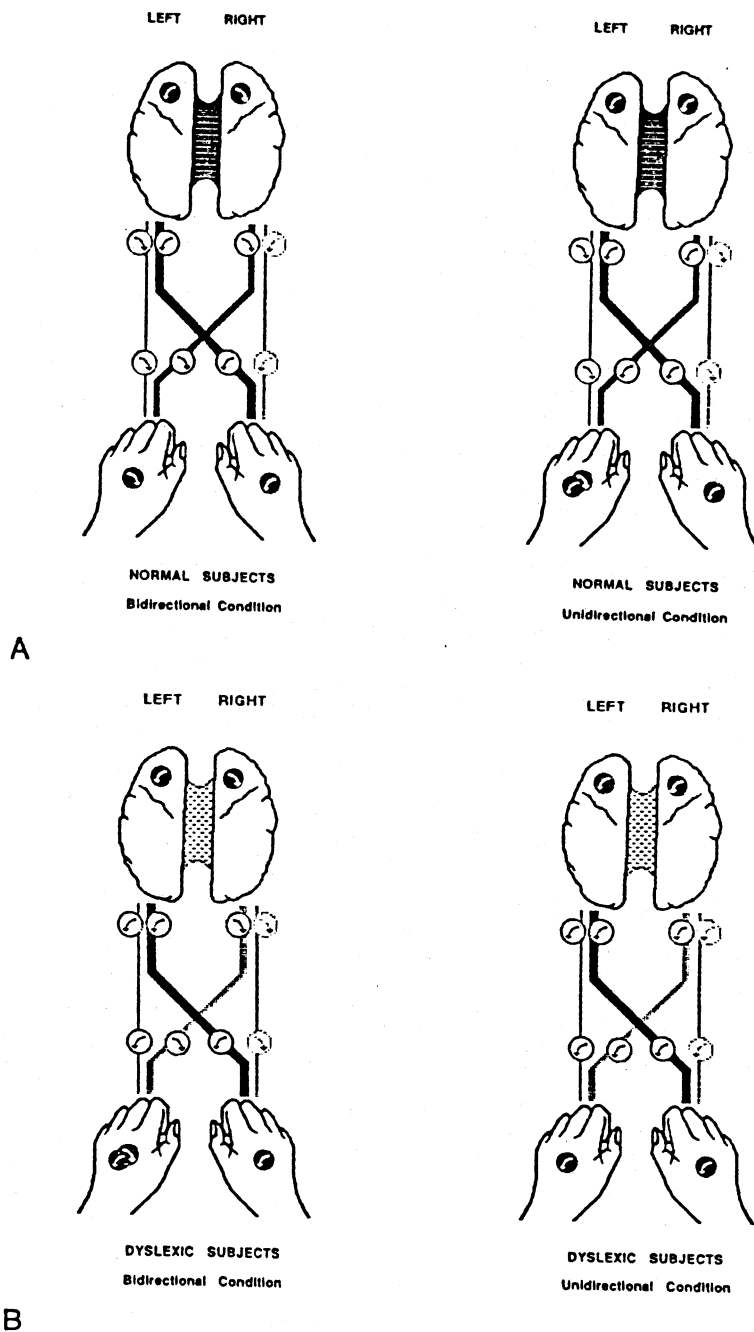


Figure 5. (A) Diagram of proposed influences from each hemisphere during bimanual performance by normal subjects (redrawn from Preilowski, 1975). (B) Diagram of deficits in interhemispheric coordination and anomalous ipsilateral influences during bimanual performance by dyslexics.

lateral pathways. This would lead to left-hand performance deficits in particular, resulting from conflict between the contralateral pathway from the nondominant right hemisphere to the left hand as opposed to the ipsilateral pathway from the dominant left hemisphere to the left hand. Unidirectional bimanual movements should be easier, because each hand would receive spatially identical movement commands from its contralateral and ipsilateral pathways.

Furthermore, the combination of poor interhemispheric

communication, anomalous ipsilateral representation, and left-hemisphere dominance for bimanual control (e.g., Kreuter et al., 1972; Wyke, 1971a, 1971b) could account for specific deficits in left-hand performance, especially when bidirectional (mirror) movements are required of dyslexics. This deviates from the pattern that Preilowski's model would predict for normal subjects—poor left-hand performance under requirements for unidirectional (parallel) bimanual movements (Figure 5, Panel A).

The possibility of a parallel-movement preference in some subpopulations, as opposed to the more typical mirror-movement preference, is supported by a study of bimanual drawing patterns in normal right- and left-handed children (Reed & Smith, 1961). Although most children chose to draw in the rungs for two side-by-side "ladders" with simultaneous extensor (mirror) movements of the hands, a subset of the right-handers instead produced simultaneous left-to-right movements (parallel). Thus, the mirror preference does not appear to be universal, even in normal right-handed children. The proposal of anomalous ipsilateral representation of movement as an explanation of either our findings or those of Reed and Smith is, of course, post hoc and quite speculative. As discussed earlier, however, no other existing model can account for a parallel-movement preference. The present hypothesis would need to be tested in clinical populations known to have abnormal organization of both callosal and pyramidal pathways, such as callosal agenetics.

A number of additional questions remain to be addressed in future research. For example, the assumption that the bimanual pattern seen among the impaired readers is specific to that population, and not simply a phenomenon characteristic of general cerebral impairment, should be tested. Also unanswered is whether the observed bimanual (bilateral) deficits reflect a general characteristic of interlimb coordination among dyslexics, which might be found even for movements of ipsilateral limbs.² Systematic developmental studies of bimanual coordination would also be useful. Although the ANCOVA attempted to determine the effect of age on bimanual performance, the issue would be more adequately addressed through the inclusion of a younger control group. Our bimanual task presumably tapped interhemispheric coordination of frontal motor functions. It would be of interest to assess for anomalous interhemispheric coordination of cortical functions in other regions. Finally, although this task demonstrates deficits among dyslexics on a task that presumably requires interhemispheric interaction, the precise mechanism of the interhemispheric transfer anomaly remains to be determined. Recent research (Davidson et al., 1988) suggests that one such mechanism may be a deficit in the timing of interhemispheric transfer. The examination of the relation between interhemispheric transfer time and performance on the bimanual coordination task used in this study would provide valuable information on one possible mechanism for the interhemispheric transfer deficit.

There are also methodological limitations in our design that may warrant further study. Following Preilowski (1972, 1975) we had predicted that dyslexics would have difficulty under bimanual conditions requiring different ratios of hand movements. Because we had not expected that the direction of hand movement would show group differences, we did not assess bimanual movement in all directions. The condition omitted would have required counterclockwise movement of both hands. Inclusion of this condition might further clarify the observed bias for parallel clockwise action of the hands. It should be noted, however, that parallel counterclockwise movements do not seem to pose a particular problem for dyslexics, given that several of them spontaneously produced such movements during reversals. A further design limitation was present in the

no visual feedback condition. Although the apparatus occluded the subjects' view of the plotter screen, it did allow them to monitor their own hand movements visually. The elimination of all visual feedback in the no visual feedback condition would provide a more adequate control condition.

In summary, our findings support the hypothesis that dyslexics manifest intermanual coordination deficits. The specific pattern of deficits that we found, however, was neither predicted nor previously reported. As a result, it is not readily explained by current models of interhemispheric collaboration. As an attempt to explain the observed pattern, we hypothesized that dyslexics may show both deficient interhemispheric processes and anomalous organization of the ipsilateral motor pathways. The novelty of these findings, however, indicates the need for further research.

² Our thanks to Paula Tallal for making this point to us.

References

- Badian, N. A., & Wolff, P. H. (1977). Manual asymmetries of motor sequencing in reading disability. *Cortex*, *13*, 343-349.
- Brinkman, J., & Kuypers, H. G. J. M. (1972). Split brain monkeys: Cerebral control of ipsilateral and contralateral arm, hand and finger movements. *Science*, *176*, 536-539.
- Davidson, R. J., Leslie, S. C., & Saron, C. (1988). *Reaction time measures of interhemispheric transfer time in reading disabled and normal children*. Manuscript submitted for publication.
- Denckla, M. B. (1985). Motor coordination in dyslexic children: Theoretical and clinical implications. In F. Duffy & N. Geschwind (Eds.), *Dyslexia: A neuroscientific approach to clinical evaluation* (pp. 187-196). Boston: Little, Brown.
- Denckla, M. B. (1986, November). *Application of disconnection concepts to developmental dyslexia*. The Norman Geschwind Memorial Lecture delivered at the Annual Orton Society Meeting, Philadelphia, PA.
- Denckla, M. B., & Rudel, R. (1976). Rapid "automatized" naming (R.A.N.): Dyslexia differentiated from other learning disabilities. *Neuropsychologia*, *14*, 471-479.
- Dennis, M. (1976). Impaired sensory and motor differentiation with corpus callosum agenesis: A lack of callosal inhibition during ontogeny? *Neuropsychologia*, *14*, 455-469.
- Drake, W. E. (1968). Clinical and pathological findings in a child with a developmental learning disability. *Journal of Learning Disabilities*, *1*, 486-502.
- Geschwind, N. (1975). The apraxias: Neural mechanisms of disorders of learned movement. *American Scientist*, *63*, 188-195.
- Gladstone, M., & Best, C. T. (1985). Developmental dyslexia: The potential role of interhemispheric collaboration in reading acquisition. In C. T. Best (Ed.), *Hemispheric function and collaboration in the child* (pp. 87-118). San Francisco: Academic Press.
- Gross-Glenn, K., & Rothberg, S. (1984). Interhemispheric tactile transfer in dyslexics. *International Journal of Neuroscience*, *24*, 23-35.
- Haerer, A. F., & Currier, R. D. (1966). Mirror movements. *Neurology*, *16*, 757-765.
- Harris, A. J. (1958). *The Harris tests of lateral dominance*. New York: Psychological Corporation.
- Hiscock, M., & Kinsbourne, M. (1980). Asymmetries of selective listening and attention switching in children. *Developmental Psychology*, *16*, 70-82.
- Kershner, J. R. (1985a). Ontogeny of hemispheric specialization and relationship of developmental patterns to complex reasoning skills

- and academic achievement. In C. T. Best (Ed.), *Hemispheric function and collaboration in the child* (pp. 327-360). San Francisco: Academic Press.
- Kershner, J. R. (1985b, May). *Dual processing models of learning disability*. Paper presented at the conference on the Developmental Implications of Brain Lateralization, St. Catharines, Ontario, Canada.
- Kershner, J. R., Henninger, P., & Cooke, W. (1984). Written recall induces a right hemisphere linguistic advantage for digits in dyslexic children. *Brain and Language*, *21*, 105-122.
- Kimura, D. (1977). Acquisition of a motor skill after left hemisphere damage. *Brain*, *100*, 527-542.
- Klicpera, C., Wolff, P. H., & Drake, C. (1981). Bimanual coordination in adolescent boys with reading retardation. *Developmental Medicine and Child Neurology*, *23*, 617-625.
- Kreuter, C., Kinsbourne, M., & Trevarthen, C. (1972). Are the disconnected hemispheres independent channels? A preliminary study of the effects of unilateral loading on bilateral finger tapping. *Neuropsychologia*, *10*, 453-461.
- Leslie, S. C., Davidson, R. J., & Batey, O. B. (1985). Purdue pegboard performance of disabled and normal readers: Unimanual versus bimanual differences. *Brain and Language*, *24*, 359-369.
- McGuinness, D. (1985). *When children don't learn*. New York: Basic Books.
- Myklebust, H. R. (1968). Learning disabilities: Definition and overview. In H. R. Myklebust (Ed.), *Progress in learning disabilities* (Vol. 1, pp. 1-16). New York: Grune & Stratton.
- Nass, R. (1985). Mirror movement asymmetries in congenital hemiparesis: The inhibition hypotheses revisited. *Neurology*, *35*, 1059-1062.
- Obrzut, J., Obrzut, A., Hynd, G., & Pirozzolo, F. (1981). Effect of directed attention on cerebral asymmetries on normal and learning-disabled children. *Developmental Psychology*, *17*, 118-125.
- Orton, S. (1937). *Reading, writing and speech problems in children*. New York: Norton.
- Owen, F., Adams, P. A., Forrest, T., Stolz, L. M., & Fisher, S. (1971). Learning disorders in children sibling studies. *Monographs of the Society for Research in Child Development*, *36* (Serial No. 144).
- Preilowski, B. (1972). Possible contributions of the anterior forebrain commissures to bilateral motor coordination. *Neuropsychologia*, *10*, 267-277.
- Preilowski, B. (1975). Bilateral motor interaction: Perceptual motor performance of partial and complete "split brain" patients. In K. J. Zulch, O. Creutzfeldt, & G. C. Galbraith (Eds.), *Cerebral localization* (pp. 115-132). Berlin: Springer.
- Reed, G. F., & Smith, A. C. (1961). Laterality and directional preference in a simple perceptual motor task. *Quarterly Journal of Experimental Psychology*, *13*, 122-124.
- Rudel, R. G. (1985). Hemispheric asymmetry and learning disabilities: Left, right or in between? In C. T. Best (Ed.), *Hemispheric function and collaboration in the child* (pp. 275-308). San Francisco: Academic Press.
- Sklar, B., Hanley, J., & Simmons, W. W. (1973). A computer analysis of EEG spectral signatures from normal and dyslexic children. *IEEE Transactions on Biomedical Engineering*, *20*, 20-26.
- Sperry, R. W., Gazzaniga, M. S., & Bogen, J. E. (1969). Interhemispheric relationships: The neocortical commissures. Syndromes of hemisphere disconnection. In P. J. Vinken & G. W. Bruyn (Eds.), *Handbook of clinical neurology* (Vol. 4., pp. 273-290). Amsterdam: North-Holland.
- Spreen, O., & Benton, A. L. (1977). *Neurosensory center comprehensive examination for aphasia*. Neuropsychology Laboratory, Department of Psychology, University of Victoria, British Columbia, Canada.
- Tomaino, C. A. (in press). Dyslexia and abnormal motor movements: A review of the literature. *Journal of Educational Neuropsychology*.
- Vaughn, H. G., & Costa, L. D. (1962). Performance of patients with lateralized cerebral lesions: 2. Sensory and motor tests. *Journal of Nervous and Mental Disease*, *134*, 237-243.
- Wechsler, D. (1974). *Manual for the Wechsler Intelligence Test for Children—Revised*. New York: Psychological Corporation.
- Wolff, P. H., Cohen, C., & Drake, C. (1984). Impaired motor timing control in specific reading retardation. *Neuropsychologia*, *22*, 587-600.
- Woodcock, R. W. (1973). *Woodcock Reading Mastery Tests*. Circle Pines, MN: American Guidance Service.
- Woodcock, R. W. (1976). *Goldman-Fristoe-Woodcock Auditory Skills Battery*. Circle Pines, MN: American Guidance Services.
- Wyke, M. (1971a). The effect of brain lesions on the performance of bilateral arm movements. *Neuropsychologia*, *9*, 33-42.
- Wyke, M. (1971b). The effect of brain lesions on the learning performance of a bi-manual coordination task. *Cortex*, *7*, 59-72.
- Yeni-Komshian, G. H., Isenberg, D., & Goldberg, H. (1974). Cerebral dominance and reading disability: Left visual field deficit in poor readers. *Neuropsychologia*, *12*, 131-139.

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