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Cognitive Processing Deficits in Reading Disabilities: A Prefrontal Cortical Hypothesis

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Much research investigating the neuropsychological underpinnings of reading disabilities has emphasized posterior brain regions. However, recent evidence indicates that prefrontal cortex may also play a role. This study investigated cognitive processes that are associated with prefrontal and posterior brain functions. Subjects were 12-year-old reading disabled and nondisabled boys. Discriminant analysis procedures indicated that measures of prefrontal functions distinguished between the two groups better than measures of posterior functions. The results suggest that reading disabled boys have difficulty with cognitive processes involving selective and sustained attention, inhibition of routinized responses, set maintenance, flexibility in generating and testing alternative hypotheses, and phonemically based language production. © 1989 Academic Press, Inc.

Research that attempts to identify the neuropsychological underpinnings of developmental reading disabilities has focused almost exclusively on functions associated with posterior cortical regions. These studies have demonstrated a variety of language dysfunctions and other information processing problems associated with posterior cortical mechanisms in adults. These symptoms include rapid and confrontational

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naming deficits (Aaron, Baker, & Hickox, 1982; Denckla, 1978, 1979; Denckla & Rudel, 1976a, 1976b; Denckla, Rudel, & Broman, 1981; Mattis, French, & Rapin, 1975; Vellutino, 1976, 1977, 1983; Vellutino, Smith, Steger, & Kamen, 1975; Vellutino, Steger, & Kandel, 1972), difficulty maintaining serial order (Bakker, 1972; Corkin, 1974; Denckla, et al., 1981; Rudel & Denckla, 1974; Symmes & Rapoport, 1972), deficits in intersensory integration (Birch & Belmont, 1964, 1965), difficulties in visual discrimination and visual analysis (Mattis et al., 1975; Pirozzolo, 1979; Satz & Friel, 1973, 1974), and finger agnosia (Aaron et al., 1982; Fletcher, Taylor, Morris, & Satz, 1982; Satz & Friel, 1973, 1974; Satz, Taylor, Friel, & Fletcher, 1978).

Despite its compelling contributions to the field of reading disabilities, the hypothesis that posterior cortical deficits alone are responsible for reading disabilities fails to account for the totality of symptoms found in the dyslexic population. In the language domain, for example, many reading disabled youngsters exhibit language difficulties that are associated with damage to areas other than left posterior cortex, including verbal dysfluency (Levin, 1983; Wolf, 1984), insensitivity to syntax and grammatical markers (Rudel, 1985; Waller, 1976; Wiig, Semel, & Crouse, 1973), and difficulties in phonemic processing (Denckla, 1978, 1979; Downing, 1973; Liberman, Shankweiler, Liberman, Fowler, & Fischer, 1976; Shankweiler & Liberman, 1976).

Attentional disorders, which are not accounted for by posterior cortical deficits, are also frequent concomitants of reading and other learning disabilities (Gardner, 1979; Rudel, 1985). Reading disabled youngsters exhibit deficits in the ability to attend selectively to appropriate aspects of tasks (Rudel, 1985) and have difficulty with tasks requiring sustained attention (McManis, Figley, Richert, & Fabre, 1978; Symmes & Rapoport, 1972).

Finally, failure to solve complex problems, both verbal and nonverbal in nature, and to abstract or generalize information are also characteristics of reading disabled children, but are not accounted for by posterior cortical deficits. Deficits have been noted in their ability to plan ahead, to switch among various components of a task, to inhibit routinized responses, and to use feedback appropriately (Jordan, Birch, & Schumsky, 1981; McManis et al., 1978; Levin, 1983; Rudel, 1980; Torgesen, 1977).

These nonposterior deficits have been associated with prefrontal brain damage in adults. Prefrontal cortex appears to subservise particular language functions including speech initiation (Stuss & Benson, 1984), the appreciation of the phonemic aspects of words (Benton, 1968; Borkowski, Benton, & Spreen, 1967; Coslett, Bowers, Verfaellie, & Heilman, 1984; Milner, 1964; Newcombe, 1969; Pendleton, Heaton, Lehman, & Hulihan, 1982; Perret, 1974; Zangwill, 1966), and the comprehension and use of

syntactical rules and grammatical markers (Luria, 1980; Samuels & Benson, 1979; Stuss & Benson, 1984; Zurif, Caramazza, & Myerson, 1972). One of the most striking characteristics of prefrontal cortical damage is its effect on verbal fluency. In particular, prefrontal patients have great difficulty generating word lists based on initial letters while their ability to generate lists based on semantic categories remains intact (Coslett et al., 1984; Newcombe, 1969).

Focal prefrontal damage may also impair the ability to attend selectively to specific aspects of stimuli and the ability to sustain focused attention. Patients with prefrontal damage have difficulty focusing selectively on information in an effort to inhibit irrelevant information and are very subject to interference effects (Luria, 1980; Perret, 1974; Stuss, Benson, Kaplan, Weir, & Della Malva, 1981; Stuss, Kaplan, Benson, Weir, Naesser, & Levine, 1981).

Problem solving tasks present special difficulty to prefrontal patients. They fail to analyze the general situations created by a task (especially a complex task), to make a preliminary investigation of the problem, to form a plan to solve the problem, and to generate hypotheses regarding the problem (Luria, 1980). Studies of sorting or categorization abilities have demonstrated that prefrontal patients have difficulty inhibiting routinized responses and thus tend to exhibit perseverative behaviors, have difficulty switching among various task components, and are unable to use "right-wrong" feedback to eliminate irrelevant hypotheses (Cicerone, Lazar, & Shapiro, 1983; Drewe, 1974; Luria, 1980; Milner, 1963, 1964; Robinson, Heaton, Lehman, & Stilson, 1980; Teuber, 1971).

The cognitive abilities that appear to be uniquely associated with prefrontal cortex include developing and shifting sets, maintaining a course of action despite interference, utilizing feedback to facilitate problem solving, producing language with fluency and automaticity, and exploiting the phonemic aspects of words.¹ These abilities are relevant to the task of learning new information and to the application of that knowledge to new situations, and therefore to learning to read. The acquisition of reading ability, both basic skills and comprehension, rests in part on linguistic competencies associated with prefrontal lobe functions such as the ability to focus on and exploit the phonemic aspects of language, to produce fluent speech, and to grasp syntactical relations.

Learning to read, however, also depends on "learning-to-learn" capacities that are not limited to language processes (Denckla, 1983). These include capacities associated with prefrontal lobe functions, such as the ability to generate hypotheses to solve problems and to test those hy-

¹ Prefrontal functions also include certain motor organization and personality-emotional characteristics that are not addressed in the discussion that follows because this study focused upon cognitive processes related to learning.

potheses in an organized fashion, the ability to appreciate and utilize relations among various parts placed within a particular framework, and the ability to inhibit salient visual cues while focusing attention selectively on meaning. Disruptions of any of these processes could result in difficulties in learning to read.

Recent electrophysiological and anatomical research has suggested that prefrontal cortex may play a role in disorders of learning to read (Denckla, 1983). While Brain Electrical Activity Mapping (BEAM) (Duffy, Denckla, Bartels, & Sandini, 1980) revealed electrophysiological differences between dyslexic and nondyslexic boys that suggest a left posterior deficit in dyslexics, differences were also found that suggest dysfunction in *prefrontal* cortical regions. Differences in prefrontal alpha activity were noted when the children listened to a story and answered questions about it, when they were at rest, when they took a paired-associate test, when they read silently, and when they were tested on the recognition of nonsense figures. Alpha activity characterizes the "idling" state of the brain and is seen when individuals are awake but at rest, implying lowered cognitive activity (Denckla, 1983). The BEAM studies revealed higher mean alpha values for dyslexic boys than for normal boys, indicating prefrontal regions were underactivated when they were engaged in cognitive tasks. Higher mean theta values, which are often associated with drowsiness and thus also imply lowered cognitive activity, were obtained for the dyslexics in the left anterolateral frontal regions during a silent reading task. Anatomical evidence (Galaburda, 1983, 1984, 1986; Galaburda & Kemper, 1979) reveals a pattern of results compatible with those of the BEAM studies. The brains of five young men who had been diagnosed as dyslexic when they were children showed evidence of structural abnormalities at the cellular level. In one case, the cellular abnormalities were restricted to the left hemisphere. In the other cases the anomalies were found bilaterally, with a greater preponderance in left hemisphere compared to right. In each case ectopic neurons were located in the most superficial cortical layer and in the subcortical white matter, which normally are devoid of neurons, suggesting abnormal prenatal development of those regions in dyslexics. As would be hypothesized from a posterior brain model of dyslexia, these abnormalities were evident in posterior left hemisphere regions thought to subservise language functions, including temporoparietal cortex. However, abnormalities were also found in Broca's area in premotor cortex, and these architectonic abnormalities extended into the more anterior left dorsolateral prefrontal region.

In summary, consideration of the cognitive processes associated with prefrontal cortex may shed light on why theories of reading disabilities that emerge from an emphasis on posterior cortical functions are not completely adequate. Posterior cortical deficits associated with reading

disabilities appear to account for some symptoms of reading disabilities, including the reversal and sequence errors noted in the oral reading and spelling of some reading disabled youngsters, the reduced speed of linguistic processing, and some aspects of the verbal dysfluency and verbal memory deficits noted in the disorder. Clinical, educational, and empirical approaches have revealed, however, that posterior cortical deficits are not adequate to account for other aspects of the symptom complex (see, for example, Rudel, 1980). They fail to account for symptoms such as the high incidence of attentional problems (McManis et al., 1978; Obrzut, Obrzut, Hynd, & Pirozzolo, 1981; Symmes & Rapoport, 1972), the insufficient development or generalization of problem solving strategies (Rudel, 1980; Torgesen, 1982), nonverbal problem solving deficits (Jordan et al., 1981; McManis et al., 1978; Levin, 1983), and some aspects of verbal fluency deficits, particularly deficits noted in the ability to generate word lists based on initial letters (Wolf, 1984).

Without dismissing the possibility that the difficulties of some reading disabled children derive from posterior cortical dysfunctions, this study examined one alternative conceptualization of difficulties in learning to read: a prefrontal deficit hypothesis. This study examined functions associated with prefrontal cortex, and functions associated with posterior cortex, in 12-year-old boys with deficits in basic reading skills (i.e., each of the subjects had extreme difficulty in decoding and word recognition), as well as in normal readers. Both anterior and posterior cortical functions were investigated in both groups of youngsters to determine which were best able to distinguish between the two groups. The specific measures were selected to sample broadly within these two brain regions, and from both left and right hemispheres. Specifically, this study examined the abilities attributable to prefrontal functions: generating word lists based on initial sounds, attending selectively to stimuli, maintaining attention, inhibiting routinized responses, and generating and testing hypotheses. Abilities attributable to posterior cortical functions including visual discrimination, facial recognition, naming, and finger gnosis were also tested.

METHOD

Subjects

The original subject sample for the study included 25 nondisabled and 24 reading disabled 12-year-old boys. Subject characteristics are summarized in Table 1. The nondisabled group (ND) comprised seventh-graders who had scored within an average to above average range on recent academic achievement tests. All but 2 boys in this group were Caucasian: 1 was Black and 1 Asian. All came from middle-class families.

The reading disabled (RD) subjects were all Caucasian boys who had been identified as having special educational needs. School records indicated that either the boys were unable to attempt a standardized test of reading achievement or they were reading at least 1½ years below their expected grade level on individual oral reading tests administered within the year prior to this study.

TABLE I
SUBJECT CHARACTERISTICS

| Group | Age | | IQ | | Handedness | |
|-------|------|-------|--------------------|------|------------|--------|
| | Mean | (SD) | Mean | (SD) | n Right | n Left |
| ND | 12-4 | (3.4) | 114.5 ^a | (10) | 21 | 4 |
| RD | 12-3 | (7.3) | 101.7 ^a | (12) | 24 | 0 |
| | | | 101.6 ^b | (13) | | |

^a Test of Cognitive Skills

^b WISC-R

The 7.5 grade level passage (Form R) from Diagnostic Reading Scales (Spache, 1981), an individually administered test of oral reading skills, was used as a final selection criterion to verify the reading achievement of the members of each group.

After administration of the measures for the study, several exclusions from the subject pool had to be made. Three ND youngsters made more than the mean number of errors expected on the Diagnostic Reading Scales passage (10 ± 2) and thus were eliminated from the final sample. Six RD boys made fewer than the mean number of expected errors on that test. They were also eliminated. Four ND youngsters who read below the level that would be predicted by their IQ scores and 1 RD boy who read above his IQ predicted level were also eliminated.² Thus, 18 ND and 17 RD boys remained in the final sample.

Procedures

Four published measures of prefrontal, and four of posterior, brain functions were administered individually in hour-long testing sessions.³ The concept of double dissociation first defined by Teuber (1959) guided the selection of the neuropsychological instruments. All testing was done in the subjects' schools during school hours. The boys were tested during study periods, recess, or nonacademic classes (e.g., gym) so as not to interfere with their academic classes.

Measures of Prefrontal Functions

Verbal fluency (VF). This task requires attention to phonemic and orthographic aspects of words rather than semantic aspects. Poor performance on this task is most often associated with left prefrontal or bilateral prefrontal damage (Benton, 1968; Milner, 1964; Newcombe, 1969). In contrast, patients with posterior lesions show verbal fluency deficits when word lists must be generated on the basis of semantic categories but perform adequately on this phonemic task (Newcombe, 1969). Subjects are required to supply as many words as possible that begin with the letter F, then with the letter A, and finally with the letter S. One minute is allowed for each letter. The VF score is the total number of words produced that conform to the rules presented by Spreen and Benton (1977). Proper names

² IQ and oral reading scores were converted to Z scores. Reading Z scores were subtracted from IQ Z scores. ND boys were excluded on the basis of Z-score differences of -1.0 or greater (reading score $<$ IQ). The RD boy was excluded on the basis of a Z-score difference greater than 1.0 (reading score $>$ IQ).

³ The Rey-Osterreith Complex Figure and a second oral reading measure were also administered to all subjects. These data were collected for another study and will not be reported here.

or repetitions of a given stem word with different morphemic endings are not counted in the total score.

Stroop Color-Word Interference Test (Stroop). The Stroop (Stroop, 1935) was selected as a measure of left prefrontal function. It was administered and scored according to the procedures described by Golden (1978). Subjects first read color words printed in black uppercase letters. Then, they identify a series of color patches (red, blue, and green). Finally, they are presented with color names printed in colored inks that differ from the color names. The task is to identify the color of the ink while ignoring the color name. Each of the subtests is printed on a single sheet of paper with the stimuli arranged in columns. Scores for each of the three sections are the number of correct responses given in a 45-sec time limit. In order to control for group differences in speed of verbal retrieval, which is particularly important in the present research because reading disabled youngsters exhibit impairment on rapid naming tasks (Denckla & Rudel, 1976a, 1976b), an interference score was computed according to the formula presented by Golden (1978). This interference score represents the ability to inhibit a more salient response, unconfounded by rapidity of verbal output. Perret (1974) demonstrated that left prefrontal patients are severely impaired in the ability to complete the interference section of the Stroop. Patients with right prefrontal lesions or with posterior lesions tend to complete the three Stroop sections more slowly than normal controls, but do not show greater interference effects (Nehemkis & Lewisohn, 1972).

Wisconsin Card Sorting Test (WCST). This measure was employed to assess left dorso-lateral prefrontal brain function (Milner, 1963, 1964; Robinson et al., 1980). Right prefrontal lesions can also affect WCST performance, but smaller left hemisphere lesions result in larger performance deficits. Damage to orbitofrontal, temporal, parietal, or occipital cortex does not have an effect on performance on the WCST (Milner, 1963, 1964). It was administered and scored according to criteria established by Heaton (1981). Subjects are required to sort cards printed with geometric symbols according to color, form, and number of symbols, which vary orthogonally. These categories are "discovered" independently, with the examiner providing only "right" or "wrong" feedback for each card sorted. Once a category is "discovered" it must be maintained over 10 trials. Then the examiner switches to reinforcing another category, without advance warning to the subject. The test continues until six categories are achieved (color, form, number, color, form, number) or until 128 responses are made. Heaton (1981) developed a total of nine scores that can be derived from WCST performance. Two of these scores distinguish patients with prefrontal damage from normal subjects. Only these two scores were used for the current study: (1) the total number of categories achieved; and (2) the percentage of perseverative errors (perseverative errors/total trials \times 100). Perseverative errors are those responses which would have been correct in the previous stage of testing; for example, the examinee continues to respond by sorting to color even though the examiner is reinforcing responses to form.

Necker Cube. This perceptual illusion was used to assess prefrontal lobe function. Performance on this task is affected by both left and right prefrontal lesions, whereas performance is unaffected by a variety of posterior lesions (Cohen, 1959; Teuber, 1964). The subjects look at a two-dimensional drawing of a transparent cube and report each time the perspective appears to alternate. Scores for this task are the number of changes in perspective reported during a 90-sec interval.⁴

⁴ Unfortunately, validity was doubtful for the Necker Cube task. After completing the testing some boys reported seeing the cube "jump around" the page or reverse in more than two ways. Because it was unclear what these boys were actually seeing, the Necker Cube findings were excluded.

Measures of Posterior Functions

Boston Naming Test—Revised (BNT). This confrontational naming task was used to assess posterior brain language functions, particularly left temporal lobe functions. Prefrontal damage does not usually result in difficulties in object naming (Luria, 1980). The BNT (Kaplan, Goodglass, & Weintraub, 1980) consists of cards with black on white line drawings depicting various objects to be named, in order of increasing difficulty. If no naming response is given within 20 sec a phonemic cue (the first few sounds of the word) is given. Total scores are based on the number of items named correctly within the 20-sec time limit (prior to presentation of the phonemic cue) until a ceiling of six consecutive errors is reached. For this study administration began with Item 13, because a previous study had shown that the first 12 items are very easy for 12-year-olds (Kirk & Kelly, 1986) and do not need to be administered to find a basal level of eight consecutive correct responses. Only two subjects, both boys from the ND group, were unable to reach the basal level with the items beginning at number 13. In those cases, testing proceeded backward from Item 12 until the basal level was reached.

Reversals Frequency Test—Recognition (RF). This subtest of the Reversals Frequency Test (Gardner, 1978) was used to measure left and right parietal and occipitoparietal brain functions (Albert, 1979; Luria, 1980). Prefrontal lesions are not associated with disturbances of letter identification or discrimination. A series of numbers and lowercase letters in both correct and incorrect orientation are printed in black in evenly spaced rows on white paper. The subjects are asked to cross out each instance of an incorrectly oriented symbol. No time limits are imposed. Total score is the number of errors (both of omission and of commission).

Test of Facial Recognition (FR). Performance on this task (Benton, Hamsher, Varney, & Spreen, 1983) is associated with right parietal lobe functions rather than prefrontal regions (Dricker, Butters, Berman, Samuels, & Carey, 1978; Lezak, 1983; Warrington & James, 1967) and can also be affected by left posterior lesions that result in language comprehension deficits (Hamsher, Levin, & Benton, 1979). The subjects are asked to match photographs of identical full facial views, different full facial views, and full facial with profile views taken under various lighting conditions. A total of 27 matches are made. Scores are based on the number of correct matches. No time limits are imposed. Because the short form of this test was administered the total was converted into a long form score based on a table presented by the test authors (Benton et al., 1983).

Finger Localization (FL). Difficulties in finger recognition, identification, or orientation are associated with lesions of either the right or left parietal lobes (as well as bilateral parietal lesions) but are not associated with prefrontal lesions (Benton et al., 1983; Gerstmann, 1940; Head, 1920). According to the procedures recommended by Reitan (undated) the subject closes his eyes while each finger is touched just below the fingernail with the eraser end of a pencil in a pseudorandom order (neither the same finger nor adjoining fingers are touched consecutively). Subjects respond by naming the touched finger (in a fashion agreed upon prior to administration of the test). Each finger is touched a total of four times, yielding a sample of 20 trials on each hand. Scores are the total number of correct identifications made.

The tests were given in the following order:

1. Finger Localization
2. Test of Facial Recognition
3. Wisconsin Card Sorting Test
4. Reversals Frequency—Recognition
5. Verbal Fluency
6. Necker Cube
7. Boston Naming Test

Because the eighth test, the Stroop, requires great effort in terms of concentration, it was administered at either the beginning, the middle, or the end of the battery in order to allow us to assess for the influence of fatigue on performance.

RESULTS

Order Effects of Stroop Administration

Analysis of variance indicated no effect of order of administration within the total battery on the color subtest ($F(2, 46) = .30$, ns), the word subtest ($F(2, 45) = .47$, ns), or the color-word subtest ($F(2, 46) = .44$, ns).

Discriminant Analysis I

Discriminant analysis was used to evaluate how well the dependent measures discriminated between the ND and the RD groups. Although examination of means and standard deviations as well as univariate analyses can assist in identifying variables that differ between groups, these methods do not take into account the interrelationships among the variables or how well those interrelationships predict group membership of individual subjects. Discriminant analysis identifies the variables that are the most powerful discriminators or separators between groups. The variables that provide separation are weighted and an equation is derived. The scores of individual subjects are entered into this equation which produces individual discriminant function scores. These scores are used to classify the individual into the group which s/he most closely resembles (Klecka, 1980). Stepwise discriminant analysis procedures were used in the present study to eliminate variables that did not contribute to separation between the groups. The statistic Rao's V was employed during the stepwise elimination of variables, because it provides for the greatest statistical separation between groups.

Eight test scores from each of the 35 final-sample subjects were entered into the analysis, compatible with Tatsuoka's (1970) recommendation that the sample size used for discriminant analysis be at least two to three times the number of variables. The test scores used were WCST categories achieved and percentage of perseverative errors, Stroop interference score, total VF score, total BNT score, total RF errors, total FR score, and total FL score.

Three of the measures, all of which were tests of prefrontal brain functions (Stroop interference, VF total, and WCST categories achieved), produced a significant degree of separation between the groups according to the discriminant function analysis (Wilks' $\Lambda = .61$, $p < .002$; canonical correlation = .62—see Table 2 for discriminant function coefficients and group centroids). Thus, the prefrontal measures provided the best discrimination between ND and RD boys, clearly better than the discrimination provided by the posterior measures.

TABLE 2
RESULTS OF DISCRIMINANT ANALYSIS I: DISCRIMINANT FUNCTION COEFFICIENTS
AND GROUP CENTROIDS

| | |
|---|-------|
| Standardized canonical discriminant function coefficients | |
| Verbal Fluency total score | .627 |
| Stroop interference score | .568 |
| WCST categories achieved | .343 |
| Group centroids | |
| ND | 0.76 |
| RD | -0.80 |

Classification results showed that 100% of the ND subjects and 76.5% of the RD subjects (13 of 17) were correctly assigned to their respective groups by the discriminant function that was defined by Stroop interference score, VF total score, and number of WCST categories achieved (see Fig. 1). Overall, 88.57% (31 of 35) of the subjects were correctly classified. When compared to their normally achieving peers, 6 RD boys had difficulty on measures of prefrontal functions but performed well on all measures of posterior functions. In contrast, only 1 RD boy had difficulty with one measure of posterior function while performing well on all measures of prefrontal functions. The remaining 10 RD subjects had difficulty with one or more measures of both prefrontal and posterior functions.

None of the nondisabled boys were misclassified, suggesting good performance by all these youngsters on the three measures of prefrontal functions. In contrast, four reading disabled boys were misclassified, suggesting that their reading difficulties do not derive completely from deficits in cognitive processes associated with prefrontal cortex.

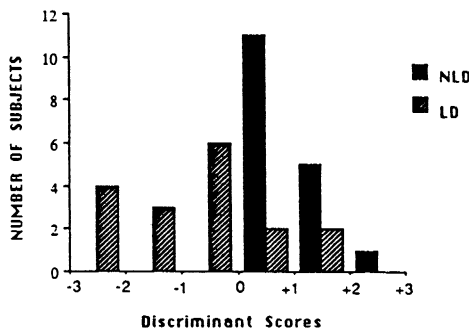


FIG. 1. Frequency histogram to the results of Discriminant Function Analysis I. In a discriminant function, 0 is treated as the category boundary.

Discriminant Analysis II

A second discriminant analysis was carried out with IQ scores entered as well as the scores from each of the neuropsychological measures in order to assess the influence of group differences in IQ. VF total, Stroop interference score, and IQ scores produced a significant degree of separation between the groups (Wilks' $\Lambda = .60$, $p < .01$; canonical correlation = .63). The classification results varied only slightly from the first discriminant analysis (see Fig. 2). Two ND boys were misclassified, presumably on the basis of IQ scores. Three of the four RD boys misclassified in the first analysis were also misclassified in the second. This suggests that although IQ scores can contribute to discriminating between disabled and nondisabled readers, they do not provide any information additional to that derived from the analysis with only the neuropsychological instruments utilized. Indeed, this analysis introduced some misclassification of the ND boys.

Post hoc Analyses

Post hoc analyses of the individual neuropsychological measures, which utilized t tests, were undertaken to assess between-groups differences on individual tests further. First, an omnibus F ratio was computed using a multiple regression equation into which the scores from the three measures of prefrontal functions (WCST categories achieved and percentage of perseverative errors, Stroop interference score, and VF total) and scores from the four measures of posterior functions (BNT total, RF errors, FR total, and FL total) were entered. A significant F statistic was derived ($F(8, 26) = 2.33$, $p < .05$). Like the results of the discriminant analysis, this F statistic indicates significant differences between the groups on these measures, while controlling for Type I error. It indicates that the results of the t tests, reported next, are reliable.

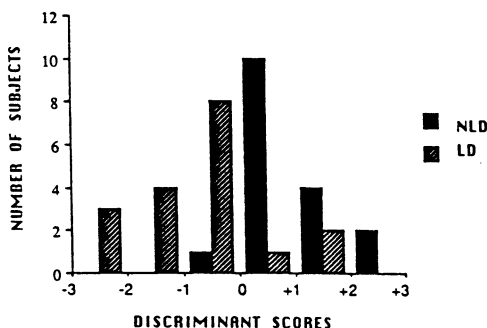


FIG. 2. Frequency histogram of Discriminant Function Analysis 2 which included IQ score as one of the variables considered.

As indicated in Table 3, the performance of the ND and RD boys differed on the three measures of prefrontal functions. Significant differences between the groups were also found on two measures of posterior brain functions, RF and FL.

Correlational analyses were used to estimate the relationship between oral reading ability and each of the neuropsychological measures. In each case, reading *Z* scores were correlated with neuropsychological test scores. As examination of Table 4 indicates, significant correlations were obtained between reading scores and two prefrontal measures: WCST categories achieved and VF total scores, both of which produced highly reliable group differences. Interestingly, WCST perseverative error score also showed a significant relationship with reading performance, even though the groups did not differ significantly on this measure. Significant correlations were also found between reading scores and functions attributed to posterior cortex as measured by RF error score and FL scores (which produced differences between the groups) and BNT scores (which did not differentiate between the groups). Two measures, FR and Stroop interference score, failed to correlate with reading scores, although the Stroop had produced highly reliable group differences.

DISCUSSION

Whereas the currently accepted and most widely utilized neuropsychological investigations of reading disabilities focus upon posterior cortical mechanisms, particularly those pertaining to language functions, the present results indicate that functions attributed to prefrontal cortex may

TABLE 3
MEANS, STANDARD DEVIATIONS, DIFFERENCE SCORES, AND EFFECT SIZES FOR ND AND RD GROUPS ON MEASURES OF PREFRONTAL AND POSTERIOR BRAIN FUNCTIONS

| Variables | Groups | | | | <i>t</i> |
|----------------------------|---------------------|---------------|---------------------|---------------|----------|
| | ND (<i>n</i> = 18) | | RD (<i>n</i> = 17) | | |
| | Mean | (<i>SD</i>) | Mean | (<i>SD</i>) | |
| Prefrontal tests | | | | | |
| WCST categories achieved | 5.11 | (1.68) | 3.41 | (2.18) | 2.59** |
| WCST % perseverative error | 15.32 | (5.56) | 21.53 | (16.88) | -1.48 |
| Stroop interference | .48 | (3.94) | -3.91 | (5.01) | 2.89** |
| Verbal Fluency | 33.33 | (6.70) | 24.06 | (9.75) | 3.30** |
| Posterior measures | | | | | |
| Finger Localization | 38.22 | (2.60) | 35.86 | (4.73) | 2.19* |
| Facial Recognition | 44.33 | (3.69) | 42.23 | (5.53) | 1.30 |
| Boston Naming | 45.67 | (6.23) | 44.24 | (5.76) | .70 |
| Reversals Frequency | 1.61 | (1.38) | 4.29 | (3.62) | -2.93** |

* *p* < .05.

** *p* < .01.

TABLE 4
CORRELATIONS OF READING Z-SCORES^a WITH
SCORES ON NEUROPSYCHOLOGICAL MEASURES

| | |
|--|--------|
| WCST categories achieved ^b | .43** |
| WCST percent perseverative errors ^c | -.57** |
| Verbal Fluency total ^b | .49** |
| Stroop interference score ^b | .21 |
| Finger Localization total ^b | .58** |
| Boston Naming Test ^b | .41** |
| Reversals Frequency Test ^c | -.58** |
| Facial Recognition ^b | .11 |

^a High reading Z scores indicate good performance.

^b High scores indicate good performance.

^c Error scores. high scores indicate poor performance.

** $p < .01$.

also be of importance to reading ability. Thus, consideration of prefrontal processes should play a role in evolving theories of reading and learning disabilities.

In this study, the majority of 12-year-old boys with severe decoding difficulties performed poorly on three measures of prefrontal lobe functions, in comparison to their nondisabled peers: the WCST (hypothesis generation and testing), the Stroop (verbal inhibition and set maintenance), and a verbal fluency task (word generation based upon initial letters). While significant differences between the groups were also found on two posterior brain measures (the Reversals Frequency Test and a finger localization task), no differences were found on the other measures of posterior functions (facial recognition and object naming). Discriminant analysis, however, showed that the overwhelming majority of the reading disabled boys (77%) were distinguished from their nondisabled peers on the basis of their performance on the three measures of prefrontal functions, rather than by their performance on the posterior measures.

The reading disabled boys had particular difficulty with the WCST. Like adults with prefrontal damage, they failed to use feedback consistently to change their hypotheses. In addition, many tended to persevere on previous responses, although the differences between the groups on the WCST percentage of perseverative errors did not reach statistical significance, owing to the high variability found within the reading disabled group. Correlational analysis indicated, however, that the number of perseverative errors made by the subjects was significantly related to their reading competence. The reading disabled boys also performed like adult prefrontal patients on the Stroop interference task:

they were unable to maintain selective attention to the color of the ink and to inhibit responses to the color words themselves. Similarly, on the VF task they had difficulty maintaining selective focus on the phonemic aspects of words, i.e., the first letter or sound.

Blank (1976) and others have pointed out the importance of the ability to ignore the purely visual aspects of words in an effort to focus selectively on the phonemic aspects as reading skills are acquired. The measures that distinguished between the disabled and nondisabled groups all depend, in part, on the identification and maintenance of a particular set; that is, they require selective attention to task-relevant information and inhibition of responses to irrelevant information. In each case it is necessary to "step back" from salient but irrelevant aspects of the stimuli and focus upon other, task-relevant aspects. It appears that these processes of selective attention and inhibition of irrelevant responses were disrupted in the majority of the RD boys examined in this study.

Although this study and discussion focused on problem solving and attentional process mediated by prefrontal regions, we do not mean to imply that language processes have no role in these functions or in reading disabilities. In part, earlier findings demonstrating the importance of linguistic factors in reading and learning disabilities were supported by the present study. The reading disabled boys who participated in this study had difficulty with two language-based measures: the Stroop test and the VF task. Further refinement of a linguistic deficit hypothesis can, however, be made. As Denckla (1983) and Rudel (1980) point out, a context is needed for placing language within the framework of reading and learning disabilities. The findings of this study help to explain cognitive processing deficits left unaddressed by a linguistic deficit hypothesis of reading disabilities and add an important dimension to understanding the relationship between language and reading. The results suggest that another important language factor, the use of verbalization to regulate behavior, may pertain to the acquisition of basic reading skills. There is evidence to suggest that verbal mediation plays an important role in the development and use of problem solving strategies (Luria, 1961; White, 1965, 1970; Vygotsky, 1962), such as those tested by our prefrontal tasks. The difficulties experienced by the RD subjects of this study appear to result from deficits in higher cognitive processes (selective attention, and acquisition, automatization, and fluent utilization of novel information) that are regulated by what Vygotsky (1962) terms "inner language." This aspect of verbal regulation is mediated by prefrontal regions in adults (Luria & Homskaya, 1964). Additional studies are needed to examine thoroughly the role of verbal mediation in reading and reading disabilities.

Two additional considerations need to be addressed. First, the age of the children tested may be expected to affect the pattern of group dif-

ferences on test of prefrontal and posterior cortical functions. This investigation assessed 12-year-olds, an age by which prefrontal abilities should be functional in normal children. However, prefrontal functions are relatively immature prior to about 10 years of age, even in normal youngsters. Thus, performance on prefrontal tasks may not differentiate between younger nondisabled and reading disabled children as clearly as was the case in our 12-year-old subjects. Tests of posterior functions may indeed provide better discrimination when younger subjects are tested.

Second, the subjects of this study were restricted to two groups: normal readers and readers with deficits in basic reading skills. Although correlational analyses suggested that reading performance is related to hypothesis generating and testing abilities, verbal fluency, letter and number discrimination ability, and finger gnosis, the ability to attend selectively to stimuli appears to be a nonspecific marker of cognitive difficulty. There is no reason to assume that the cognitive processing difficulties exhibited by the RD subjects of this study would not be present in other cases of developmental disorders. Investigations of other developmentally disabled groups, including groups with behavioral and/or emotional difficulties as well as groups with other academic difficulties (e.g., mathematics, reading comprehension), need to be undertaken.

CONCLUSION

This study suggests that, like adults with damage in prefrontal cortex, many reading disabled youngsters have difficulty with cognitive processes involving sustained attention, inhibition, set maintenance, and flexibility in generating alternative hypotheses. The finding that these boys also exhibit difficulties with some posterior brain processes suggests that a prefrontal cortical model of reading disabilities cannot *replace* a posterior cortical model. Consideration of prefrontal processes, however, clearly provides an important adjunct to models based purely on posterior functions. Prefrontal measures may help to elucidate the neuropsychological dysfunctions exhibited by reading disabled students and appear to explain more fully the widely varying symptoms associated with dyslexia.

REFERENCES

- Aaron, P. G., Baker, C., & Hickox, G. L. 1982. In search of the third dyslexia. *Neuropsychologia*, 20, 203-208.
- Albert, M. L. 1979. Alexia. In K. Heilman & E. Valenstein (Eds.), *Clinical neuropsychology*. New York: Oxford. Pp. 59-91.
- Bakker, D. J. 1972. *Temporal order in disturbed reading*. Rotterdam: Rotterdam Univ. Press.
- Benton, A. L. 1968. Differential behavioral effects in frontal lobe disease. *Neuropsychologia*, 6, 53-60.
- Benton, A. L., Hamsher, K. deS., Varney, N. R., & Spreen, O. 1983. *Contributions to neuropsychological assessment*. New York: Oxford.

- Birch, H. G., & Belmont, L. 1964. Auditory-visual integration in normal and retarded readers. *American Journal of Orthopsychiatry*, **34**, 852-861.
- Birch, H. G., & Belmont, L. 1965. Auditory-visual integration, intelligence, and reading ability in school children. *Perceptual and Motor Skills*, **20**, 295-305.
- Blank, M. 1976. Review of "Toward an understanding of dyslexia": Psychological factors in specific reading disability. In A. L. Benton & D. Pearl (Eds.), *Dyslexia: An appraisal of current knowledge*. New York: Oxford. Pp. 115-122.
- Borkowski, J. G., Benton, A. L., & Spreen, O. 1967. Word fluency and brain damage. *Neuropsychologia*, **5**, 135-140.
- Cicerone, K. D., Lazar, R. M., & Shapiro, W. R. 1983. Effects of frontal lobe lesions on hypothesis sampling during concept formation. *Neuropsychologia*, **21**, 513-524.
- Cohen, L. 1959. Perception of reversible figures after brain injury. *Archives of Neurology and Psychiatry*, **81**, 765-775.
- Corkin, S. 1974. Serial ordering deficits in inferior readers. *Neuropsychologia*, **12**, 347-354.
- Coslett, H. B., Bowers, D., Verfaellie, M., & Heilman, K. 1984. February. *Phonological memory deficits with "minor" Broca's aphasia*. Paper presented at the Twelfth Annual International Neuropsychological Society Meeting, Houston, TX.
- Denckla, M. B. 1979. Childhood learning disabilities. In K. Heilman & E. Valenstein (Eds.), *Clinical neuropsychology* (pp. 535-573). New York: Oxford.
- Denckla, M. B. 1978. Minimal brain dysfunction. In J. S. Chall & A. F. Mirsky (Eds.), *Education and the brain*. The seventy-seventh yearbook for the National Society of the Study of Education. Pp. 223-268.
- Denckla, M. B. 1983. Learning for language and language for learning. In U. Kirk (Ed.), *The neuropsychology of language, reading, and spelling*. New York: Academic Press. Pp. 33-44.
- Denckla, M. B., & Rudel, R. G. 1976a. Naming of object drawings by dyslexic and other learning disabled children. *Brain and Language*, **3**, 1-15.
- Denckla, M. B., & Rudel, R. G. 1976b. Rapid automatized naming (R.A.N.): Dyslexia differentiated from other learning disabilities. *Neuropsychologia*, **14**, 471-479.
- Denckla, M. B., Rudel, R. G., & Broman, M. 1981. Tests that discriminate between dyslexic and other learning-disabled boys. *Brain and Language*, **13**, 118-129.
- Downing, J. 1973. *Comparative reading*. New York: Macmillan Co.
- Drewe, E. A. 1974. The effect of type and area of brain lesion on Wisconsin Card Sorting Test performance. *Cortex*, **10**, 159-170.
- Dricker, J., Butters, N., Berman, G., Samuels, I., & Carey, S. 1978. The recognition and encoding of faces by alcoholic Korsakoff and right hemisphere patients. *Neuropsychologia*, **16**, 683-695.
- Duffy, F., Denckla, M. B., Bartels, P. H., & Sandini, G. S. 1980. Dyslexia: Regional differences in brain electrical activity by topographic mapping. *Annals of Neurology*, **7**, 412-419.
- Fletcher, J. M., Taylor, H. G., Morris, R., & Satz, P. 1982. Finger recognition and reading achievement: A developmental neuropsychological perspective. *Developmental Psychology*, **18**, 124-132.
- Galaburda, A. M. 1983. Developmental dyslexia: Current anatomical research. *Annals of Dyslexia*, **33**, 31-54.
- Galaburda, A. M. 1984. May. *Developmental dyslexia. Ontogeny of asymmetry and deviation*. Paper presented at the Eighth Annual Conference of the Program in Neurosciences and Education, Teacher College, New York, NY.
- Galaburda, A. M. 1986. Developmental dyslexia: A review of biological interactions. *Annals of Dyslexia*, **35**, 21-34.
- Galaburda, A. M., & Kemper, T. L. 1979. Cytoarchitectonic left-right asymmetries in the temporal speech region. *Archives of Neurology*, **35**, 812-817.

- Gardner, R. A. 1978. *Reversals Frequency Test*. Cresskill, NJ: Creative Therapeutics.
- Gardner, R. A. 1979. *The objective diagnosis of minimal brain dysfunction*. Cresskill, NJ: Creative Therapeutics.
- Gerstmann, J. 1940. Syndrome of finger agnosia, disorientation for right and left, agraphia and acalulia. *Archives of Neurology and Psychiatry*, **44**, 398-408.
- Golden, C. J. 1978. *Stoop Color and Word Test: A manual for clinical and experimental uses*. Chicago: Stoelting.
- Hamsher, K. deS., Levin, H. S., & Benton, A. L. 1979. Facial recognition in patients with focal brain lesions. *Archives of Neurology*, **36**, 837-839.
- Head, H. 1920. *Studies in neurology*. London: Oxford.
- Heaton, R. K. 1981. *Wisconsin Card Sorting Test manual*. Odessa, FL: Psychological Assessment Resources.
- Jordan, M. K., Birch, D. B., & Schumsky, D. A. 1981, May. *Hypothesis testing in learning disabled children*. Paper presented at the Biennial Meeting of the Society for Research in Child Development, Boston, MA.
- Kaplan, E., Goodglass, H., & Weintraub, S. 1982. *Boston Naming Test*. Philadelphia: Lea & Febiger.
- Kirk, U., & Kelly, M. S. 1986, February. *Children's differential performance on selected dorsolateral prefrontal and posterior cortical functions: A developmental perspective*. Paper presented at the Fourteenth Annual International Neuropsychological Society Meeting, Denver, CO.
- Klecka, W. S. 1980. *Discriminant analysis*. Beverly Hills: Sage.
- Levin, B. 1983, February. *Organizational deficits among dyslexic children*. Paper presented at the Eleventh Annual International Neuropsychological Society Meeting, Mexico City, Mexico.
- Levin, H. S., Hamsher, K. deS., & Benton, A. L. 1975. A short form of the Test of Facial Recognition for clinical use. *Journal of Psychology*, **91**, 223-228.
- Lezak, M. 1983. *Neuropsychological assessment*. New York: Oxford, 2nd ed.
- Liberman, I. Y., Shankweiler, D., Liberman, A. M., Fowler, C., & Fisher, F. W. 1976. Phonetic segmentation and recording in the beginning reader. In A. S. Reber & D. Scarborough (Eds.), *Reading: Theory and practice*. Hillsdale, NJ: Erlbaum.
- Luria, A. R. 1961. *The role of speech in the regulation of normal and abnormal behavior*. New York: Boni & Liveright.
- Luria, A. R. 1980. *Higher cortical functions in man*. New York: Basic Books.
- Luria, A. R., & Homskaya, E. D. 1964. Disturbance in the regulative role of speech with frontal lobe lesions. In J. M. Warren & K. Akert (Eds.), *The frontal granular cortex and behavior*. New York: McGraw-Hill.
- Mattis, S., French, J. H., & Rapin, I. 1975. Dyslexia in children and young adults: Three independent neuropsychological syndromes. *Developmental Medicine and Child Neurology*, **17**, 150-163.
- McManis, D. L., Figley, C., Richert, M., & Fabre, T. 1978. Memory-for-Designs, Bender-Gestalt, Trail Making Test, and WISC-R performance of retarded readers and adequate readers. *Perceptual and Motor Skills*, **46**, 443-450.
- Milner, B. 1963. Effects of different brain lesions on card sorting: The role of the frontal lobes. *Archives of Neurology*, **9**, 100-110.
- Milner, B. 1964. Some effects of frontal lobectomy in man. In J. M. Warren & K. Akert (Eds.), *The frontal granular cortex and behavior*. New York: McGraw-Hill. Pp. 313-334.
- Nehemkis, A. M., & Lewisohn, P. M. 1972. Effects of left and right cerebral lesions in the naming process. *Perceptual and Motor Skills*, **35**, 787-798.
- Newcombe, F. 1969. *Missile wounds of the brain: A study of psychological deficits*. London: Oxford.

- Obrzut, J., Obrzut, A., Hynd, G., & Pirozzolo, F. 1981. Effect of directed attention on cerebral asymmetries in normal and learning disabled children. *Developmental Psychology*, 17, 117-125.
- Pendleton, M. G., Heaton, R. K., Lehman, R. A. W., & Hulihan, D. 1982. Diagnostic utility of the Thurstone Word Fluency Test in neuropsychological evaluations. *Journal of Clinical Neuropsychology*, 4, 307-317.
- Perret, E. 1974. The left frontal lobe of man and the suppression of habitual responses in verbal categorical behavior. *Neuropsychologia*, 12, 323-330.
- Pirozzolo, F. J. 1979. *The neuropsychology of developmental reading disorders*. New York: Praeger.
- Reitan, R. M. (undated). *Instructions and procedures for administering the Neuropsychological Test Battery used at the Neurological Laboratory, Indiana University Medical Center*. Unpublished manuscript.
- Robinson, A. L., Heaton, R. K., Lehman, R. A. W., & Stilson, D. W. 1980. The utility of the Wisconsin Card Sorting Test in detecting and localizing frontal lobe lesions. *Journal of Consulting and Clinical Psychology*, 48, 605-614.
- Rudel, R. G. 1980. Learning disability: Diagnosis by exclusion and discrepancy. *Journal of the American Academy of Child Psychiatry*, 19, 547-569.
- 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*. New York: Academic Press. Pp. 275-308.
- Rudel, R. G., & Denckla, M. B. 1974. Relation of forward and backward digit repetition to neurological impairment in children with learning disabilities. *Neuropsychologia*, 12, 109-118.
- Samuels, J. A., & Benson, D. F. 1979. Some aspects of language comprehension in anterior aphasia. *Brain and Language*, 8, 275-286.
- Satz, P., & Friel, J. 1973. Some predictive antecedents of specific learning disability. In P. Satz & J. Ross (Eds.), *The disabled learner*. Rotterdam: Rotterdam Univ. Press.
- Satz, P., & Friel, J. 1974. Some predictive antecedents of specific learning disabilities: A preliminary two-year follow-up. *Journal of Learning Disabilities*, 7, 437-444.
- Satz, P., Taylor, H. G., Friel, J., & Fletcher, J. 1978. Some developmental and predictive precursors of reading disabilities: A six-year follow-up. In A. L. Benton & D. Pearl (Eds.), *Dyslexia: An appraisal of current knowledge*. New York: Oxford.
- Shankweiler, D., & Liberman, I. Y. 1976. Exploring relationships between reading and speech. In R. M. Knights & D. J. Bakker (Eds.), *The neuropsychology of learning disorders: Theoretical approaches. Proceedings of the NATO conference*. Baltimore: University Park Press. Pp. 279-313.
- Spache, G. 1981. *Diagnostic Reading Scales*. Monterey, CA: CTB/McGraw-Hill.
- Spreen, O., & Benton, A. L. 1977. *Neurosensory Center Comprehensive Examination for Aphasia*. Victoria: University of Victoria.
- Stroop, J. R. 1935. Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18, 643-661.
- Stuss, D. T., & Benson, D. F. 1984. Neuropsychological studies of the frontal lobes. *Psychological Bulletin*, 95, 3-28.
- Stuss, D. T., Benson, D. F., Kaplan, E. F., Weir, W. S., & Della Malva, C. 1981. Leucotomized and nonleucotomized schizophrenics: Comparisons on tests of attention. *Biological Psychology*, 16, 1085-1100.
- Stuss, D. T., Kaplan, E. F., Benson, D. F., Weir, W. S., Naesser, M. A., & Levine, H. 1981. Long-term effects of prefrontal leukotomy: An overview of neuropsychological residuals. *Journal of Clinical Neuropsychology*, 3, 13-32.
- Symmes, J. S., & Rapoport, J. L. 1972. Unexpected reading failure. *American Journal of Orthopsychiatry*, 42, 82-91.

- Tatsuoka, M. M. 1970. *Discriminant analysis: The study of group differences*. Champaign, IL: Institute for Personality and Ability Testing.
- Teuber, H. L. (1959). Some alterations in behavior after cerebral lesions in man. In A. D. Bass (Ed.), *Nervous control from primitive organisms to man*. Washington, DC: American Association for the Advancement of Science. Pp. 157-194.
- Teuber, H. L. 1964. The riddle of frontal lobe function in man. In J. M. Warren & K. Akert (Eds.), *The frontal granular cortex and behavior*. New York: McGraw-Hill. Pp. 410-477.
- Teuber, H. L. 1971. Unity and diversity of frontal lobe function. *Acta Neurobiologica Experimentalis*, 32, 615-656.
- Torgesen, J. K. 1977. The role of non-specific factors in the task performance of learning disabled children: A theoretical assessment. *Journal of Learning Disabilities*, 10, 27-33.
- Torgesen, J. K. 1982. The study of short-term memory in learning disabled children: Goals, methods, and conclusions. In K. D. Gadow & I. Bailor (Eds.), *Advances in learning and behavioral disorders*. Greenwich, CT: JAI Press. Pp. 2-34.
- Vellutino, F. 1977. Alternative conceptualization of dyslexia: Evidence in support of a verbal deficit hypothesis. *Harvard Educational Review*, 47, 334-354.
- Vellutino, F. 1976. Toward an understanding of dyslexia: Psychological factors in specific reading disability. In A. L. Benton & D. Pearl (Eds.), *Dyslexia: An appraisal of current knowledge*. New York: Oxford. Pp. 61-111.
- Vellutino, F. 1983. Childhood dyslexia: A language disorder. *Progress in Learning Disabilities*, 5, 135-173.
- Vellutino, F., Smith, H., Steger, J. A., & Kamen, M. 1975. Reading disability: Age differences in the perceptual deficit hypothesis. *Child Development*, 46, 487-493.
- Vellutino, F., Steger, J. A., & Kandel, G. 1972. Reading disability: An investigation of the perceptual deficit hypothesis. *Cortex*, 8, 106-118.
- Vygotsky, L. S. 1962. *Thought and language*. Cambridge, MA: MIT Press.
- Waller, T. G. 1976. Children's recognition memory for written sentences: A comparison of good and poor readers. *Child Development*, 46, 90-95.
- Warrington, E. K., & James, M. 1967. An experimental investigation of facial recognition in patients with unilateral cerebral lesions. *Cortex*, 3, 317-326.
- Wiig, E. H., Semel, M. S., & Crouse, M. B. 1973. The use of English morphology by high-risk and learning disabled children. *Journal of Learning Disabilities*, 6, 457-465.
- White, S. H. 1965. Evidence for a hierarchical arrangement of learning processes. In Lipsitt & Spiker (Eds.), *Advances in child development and behavior*. New York: Academic Press. Vol. 2.
- White, S. H. 1970. Some general outlines of a matrix of developmental changes between 5 and 7 years. *Bulletin of the Orton Society*, 20, 41-57.
- Wolf, M. 1984. Naming, reading, and the dyslexias: A longitudinal overview. *Annals of Dyslexia*, 34, 87-115.
- Zangwill, O. L. 1966. Psychological deficits associated with frontal lobe lesions. *International Journal of Neurology*, 5, 395-402.
- Zuriff, E. B., Caramazza, A., & Myerson, R. 1972. Grammatical judgments of agrammatic aphasics. *Neuropsychologia*, 10, 405-417.