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Event-related potentials and behavioral assessment: A 20 year follow-up of adults who were diagnosed as reading disabled in childhood

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EVENT-RELATED POTENTIALS AND BEHAVIORAL ASSESSMENT:

A 20 YEAR FOLLOW-UP OF ADULTS WHO WERE

DIAGNOSED AS READING DISABLED

IN CHILDHOOD

by

Cecile Edith Naylor

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The purpose of this study was twofold: (a) to identify physiological correlates of reading disability in adults based on childhood studies by Harter et al. (in press); and (b) to identify physiological correlates of reading improvement from childhood to adulthood. The subjects were 38 males, 32 of whom had been tested in childhood. Of those 32, 24 met the criteria of specific reading disability in childhood. All subjects scored in the normal range in childhood and adulthood on intelligence measures.

Subjects with reading disability (RD) in childhood were fairly successful in terms of educational and vocational attainment. All had finished high school and were gainfully employed at the time of the study. Subjects with RD tended to be in slightly lower socioeconomic strata (SES) compared to their fathers. No behavioral or historical variables were found to predict adult reading scores or reading improvement. These included SES in childhood, family history of reading disability, and presence of symptoms of attention deficit disorder.

Event-related potentials were recorded over O1, O2, C3, C4, F3, and F4 to letter and color stimuli using a single stimulus presentation paradigm. Subjects with RD showed a general reduction in positivity starting at 150 msec. Reduced positivity at 240 and 420 msec over central regions replicated the findings of Harter et al. with children. Also consistent with Harter et al., subjects with RD showed reduced selective attention to relevant compared to irrelevant stimuli at 330 and 420 msec over occipital and often central regions. Subjects with RD

showed an enhancement of the negativity to irrelevant stimuli at 290 msec which was interpreted as representing a compensatory mechanism.

Adult RD, compared to children, showed more diffuse reduction in electrophysiological response to both color and letter stimuli. Unlike children who showed greater left hemisphere deficits, the deficit in adults with RD was bilateral in nature. Childhood deficit was often predictive of the amplitude of the ERP component. Independent of childhood deficit, reading improvement was related to an enhancement of the negativity to irrelevant stimuli at 290 msec. Changes in ERP's related to improvement were typically in a normal direction.

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CHAPTER I

INTRODUCTION

Reading is a skill that most individuals learn with relative facility. However, for some children, the acquisition of reading skills is a challenging if not seemingly impossible task. These children are often bright and healthy, yet reading poses a major obstacle in their educational career. Soon, they may be labeled as underachievers, "slow," or even generally handicapped. The impact of this selective reading disability on a child's emotional adjustment as well as his/her educational advancement is far reaching. They generally fall behind in other academic subjects and develop a poor attitude toward school (Spreen, 1982). Adults may chastise the child for being lazy and soon lose patience with him/her. The child may respond by withdrawing or rebelling which in turn impacts his social adjustment (Spreen, 1982). A "negative and defeatist attitude about life in general" is often prevalent (Balow & Blomquist, 1965). Spreen (1982) summarizes the social and economic importance of the disorder based on his findings as follows:

> Not only do these youngsters suffer through a miserable and usually foreshortened school career and live a discouraging social life full of disappointments and failures; they also have a relatively poor chance for advanced training and skilled employment. The need for early educational intervention and appropriate job counseling and training is obvious. (p 490)

Satz and colleagues (Satz, Taylor, Friel & Fletcher, 1978) also emphasize the common occurrence of secondary emotional and behavioral disturbances as well as the need for early detection. The objective is to initiate treatment "at a time when the central nervous system may be more plastic and responsive to change and when the child is less subject to the shattering effects of repeated academic failure (p. 316)".

Early intervention depends on early identification. However, the diagnosis of specific reading disability (RD) is generally based on behavioral criteria of delayed reading skills in the absence of other explanatory factors. The Diagnostic and Statistical Manual of Mental Disorders (DSM-III) classifies specific reading disability under developmental disorders of childhood, coded on Axis II. The diagnosis is made when a child shows significant impairment in the development of reading given the child's chronological age, mental age, and intellectual capacity determined by formal IQ testing. The diagnosis is exclusionary in nature, that is, one reads poorly yet does not have a number of other features such as generally low intelligence or mental retardation, impaired vision, and/or a history of inadequate schooling. One would also be reluctant to make the diagnosis if the child evidences serious emotional problems or is poorly motivated. Thus, a psychologist, teacher, or parent may hesitate to identify a child as having RD if the child is very quiet, making it difficult to assess the effort the child is expending, or if a child is very rebellious and thus seemingly resistant to instruction. Once identified, the child is labeled by the school system. While this then enables a child to be eligible for special services, it also carries all the negative ramifications of labeling the child as different or "disabled" (Cromwell, Blashfield, & Strauss, 1975; Hobbs, 1974).

Unfortunately, if we rely on a diagnosis based on behavioral identification of reading problems, early intervention is limited by the developmental progress in the acquisition of reading skills. Methods which identify markers of RD which are not contingent on the development of reading would provide a means of early identification and thus early intervention.

In summary, RD, also often referred to as dyslexia, poses a serious problem for many children, and therefore understanding the underlying mechanisms and taking steps toward adequate remediation become crucial issues. While successful remediation may not depend on a full understanding of the "markers" found to identify the disorder, such knowledge could have implications for the remedial technique that would best be implemented. In the search for knowledge about the underlying mechanism(s) of RD, an important theoretical consideration involves the debate as to whether this disorder represents a mere delay in the aquisition of otherwise normally developing skills versus the presence or absence of an underlying deficit in brain function.

Developmental Lag versus Deficit?

The search for possible underlying mechanisms of RD in children has been the focus of considerable research, especially in recent years. Although some have proposed that structural abnormalities underly RD, particularly in the left hemisphere (Galaburda, 1986), attempts to identify specific lesions resulting in precise syndromes have been inconclusive (For reviews, see Benton & Pearl, 1978; Sobotowicz & Evans, 1982). Many of the theories postulating possible structural damage in dyslexic children have been based on adult models of acquired alexia (Benson, Brown, & Tomlinson, 1971; Benson & Geschwind, 1975).

In adults with acquired RD or alexia as opposed to dyslexia, specific pathological damage has been identified in various areas of the left hemisphere, primarily those involved in language processing (Benton & Pearl, 1978). These areas include the medial occipital lobe impinging upon the corpus collosum, the temporal lobe, "Wernicke's area", the angular gyrus, and the frontal lobes. Each type of lesion typically results in a different cluster of "hard" neurological signs evident on neurological exam as well as impacting an individual's ability to read. If different lesions can result in a similar behavioral outcome (poor reading), the implication is that reading is multifaceted and can be disrupted by interfering with any one of a number of stages in the process.

While adults with acquired alexia show obvious signs of neurological impairment, dyslexics whose RD is developmental by history do not show consistent deficits on neurological exam (Ludlam, 1981). Studies attempting to identify neuroanatomical differences via autopsy or computerized tomography (CAT Scan) of dyslexic individuals (Thompson, Ross, & Horowitz, 1980) or abnormalities on clinical neurological examination have yielded inconclusive results (Golden, 1982). Perhaps the neural abnormalities are too subtle to show up on static imaging of the brain or gross pathological studies. Galaburda, Geschwind and colleagues (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1986) have been more successful in locating subtle neuropathological differences in brains of dyslexics. These differences are in the form of polymicrogyria in portions of the brain, primarily temporal regions. Often, these findings are bilateral in nature. It is likely that neurological tests which assess structure (CAT or MRI) may not be sensitive to these subtle anomalies. A test which measures brain function in an active stage of processing may be more sensitive to subtle differences between children with RD and those who read normally.

Some researchers have challenged the notion that neurological impairment causes RD. An alternative explanation for RD has been postulated by Satz and colleagues (Satz & Fletcher, 1980; Satz, Friel, & Rudegeair, 1974; Satz & Van Nostrand, 1973) which is based on a developmental model as opposed to a disease model. They proposed an underlying lag in brain maturation which results in a delay in the acquisition of certain skills, an hypothesis first proposed by Money (1966). Satz and colleagues extended the theory of Money by focusing on left hemisphere integration and relating developmental disorders to acquired left hemisphere loss of function. The difference in the reading disorders of children and adults can be explained by the fact that in the former group, the delay in the maturation of the left hemisphere interrupts the acquisition phase whereas adults suffer a loss of that function after acquisition has been completed.

Satz and colleagues further propose several stages of acquisition as a function of the chronological age of the child, with each stage depending on the preceding stage. Thus, younger children often show a delay in perceptual-spatial and cross-modal integration, whereas older children show a delayed acquisition of language skills and formal operations. The implicit assumption behind the maturational lag theory is that children will eventually "catch up" behaviorally on these developmentally earlier skills but may continue to show cognitive-linguistic deficits which involve a later stage of development. As long as differences in behavior are evident, corresponding physiological differences may be present. However, if an individual "catches up" behaviorally, any neural differences should no longer be evident. Improved readers should be "caught up" in all respects.

These contrasting theories (developmental lag versus deficit) would predict different outcomes in adulthood. The deficit hypothesis postulates sustained underlying neurological dysfunction that should remain present in adulthood. Therefore, any measure which specifically taps this neurological dysfunction should remain constant through the years, even if the individual has learned to compensate for his/her deficit at the behavioral level.

Alternatively, if one accepts the developmental lag theory, once an individual has "caught up" behaviorally, any neurophysiological abnormalities detected during the stage of behavioral dysfunction should disappear once the behavior is remediated. Thus, adults who have improved their reading skills should have neurophysiological measures more like normal readers. In order to address this issue, a longitudinal study which follows children with RD into adulthood is required.

There have been several behaviorally-oriented follow-up studies presented in the literature which are summarized in several review articles (Finucci, 1986; Horn, O'Donnell, & Vitulano, 1983; Schonhaut & Satz, 1983; Spreen, 1982). Although many of the follow-up studies are fraught with methodological problems such as small sample size, unclear diagnostic criteri, or too short a follow-up period, one is left with the impression that individuals with RD do not "catch up" in their reading skills by adulthood, that is, they have an unfavorable adult outcome. Schonhaut and Satz (1983) reviewed 18 follow-up studies and concluded that the more methodologically sound the study, the less favorable the outcome for reading ability in terms of reading and spelling skills. Spreen (1982) stated that individuals with RD often become worse with time, and remediation does not appear to improve their prognosis. Horn et al. (1983) also in general reported an enduring basic skills deficits, some people actually showing a deterioration in skills.

The follow-up of 20 dyslexic boys by Rawson (1968) was an exception to the generally unfavorable adult academic outcomes reported in most studies. These children attended a private school that used the Orton-Gillingham approach to remediation. Rawson reported favorable adult outcomes in both academic and occupational pursuits for dyslexic boys compared to nondyslexic students. However, Schonhaut and Satz

(1983) found that even the adults who were ultimately successful in terms of academic achievement and occupation continued to be slow readers and poor spellers.

When favorable adult occupational and educational outcomes have been reported, it has often been linked to socioeconomic status (SES). That is, individuals from upper SES backgrounds are more successful (Spreen, 1982). Schonhaut and Satz (1983) reported that SES was "a powerful variable moderating the reading potential of children." (p. 555) However, in a follow-up study of 500 graduates of the Gow School for dyslexic boys, Finucci, Gottfredson and Childs (1985) failed to find SES to be predictive of adult educational, occupational, or attitudinal status compared to those in the general population. The failure to find SES to be predictive may have been related to the generally high SES and IQ of these subjects with RD.

The Role of Attention Deficit Disorder in Dyslexia

The study of reading disability is complicated by the presence of attention deficit disorder (ADD). In that symptoms of ADD, such as hyperactivity, are considered to be "soft" neurological signs on clinical exam, the presence of ADD in children with RD has been well documented. Many of the cognitive deficits present in RD may actually be related to the presence of ADD (Kinsbourne, 1982). This is particulary evident when a child is placed on methylphenidate and then shows a marked improvement in attentional control and cognitive processing in general (Aman, 1982). The relevance of ADD has been documented by

Ackerman, Dykman, and Peters (1977). They found that children with both RD and ADD had an poorer outcome than children with only RD, although this latter group was still impaired when compared to normal controls. ADD has an additive effect on behavioral deficits manifested by children with RD. This is supported by recent behavioral and electrophysiological findings. Felton, Wood, Harter, Brown and Campbell (in press) found more severe naming and memory problems in children with both RD and ADD. Harter, Wood, and Diering (in press) and Harter, Wood, and Marvin-Schroeder (in press) reported RD and ADD are associated with distinct changes in event-related potentials (ERP's). The follow-up studies further indicate that the ramification of this deficit may extend into adulthood (Ackerman et al., 1977).

The identification of ADD is crucial in studying RD. Although severe ADD is fairly easily identified by teachers or clinicians, more subtle attentional problems, especially those without obvious hyperactivity, may go unnoticed. Such subtle attentional problems may have a similar impact on overall cognitive skills. Thus, a sensitive measure of selective attention could help to identify even subtle attentional disorders. Children with ADD may have difficulty on any task demanding sustained attentional control and fine discriminations. Thus, while children with RD may have more difficulty on tasks requiring the discrimination of language stimuli in particular, children with ADD may show poor performance on any paradigm requiring good attentional control.

Unfortunately, it is often difficult to assess the presence or absence of ADD retrospectively. Even during childhood, the score on questionnaires to identify ADD depends on the rater, yielding poor interrater reliability. Adults are typically poor historians regarding childhood behavior. Given these obstacles, it is important to assess the contribution of ADD whenever possible.

Event-Related Potential (ERP) Studies of Dyslexia

In past years, numerous researchers have used various electrophysiological techniques to study children with RD. These range from the neurometric approach of John (John, 1981; John, Prichep, Ahn, Easton, Fridman, & Kaye, 1983; John, 1981) and the BEAM analysis of Duffy and his colleagues (Duffy, Bartels, Bartels, Sandini, & Kiessling, 1980; Duffy, Denckla, Bartels, & Sandini, 1980) to more standard measures of amplitude or latency shifts in the evoked potential waveforms (e.g., Connors, 1970; Preston, Guthrie, & Childs, 1974; Sobotka & May, 1977). In that children with RD versus those without RD may indeed show differences in neural processing, electrophysiological measures offer a possible means of assessing these differences.

Research using event-related potentials (ERP's) to measure neural processing in reading disabled children as compared to normal readers has yielded two important findings: (a) longer latencies in the ERP's of children with RD; and (b) reduced amplitude of ERP waveforms at a number of latencies. One of the first investigations to demonstrate such differences was a series of studies conducted by Conners (1970) who reported that children with RD showed an attenuation of a positive component at 140 msec and a negative component at 200 msec over left parietal leads. Visual evoked potentials were collected in response to simple light flashes, and the subjects were not required to engage in an active processing of language stimuli, per se. His study, however, has been criticized for using Cz as a reference (Kooi, 1972), for having an insufficient number of subjects, and for having no control groups (Preston, 1979). These findings were encouraging, however, and stimulated a surge of research on ERP's in children with RD.

Using an improved test procedure, attempting to avoid problems of subject selection and/or choice of reference, both Sobotka and May (1977) and Weber and Omenn (1977) failed to replicate Connors' findings. They found either no differences in amplitude or greater amplitudes to light flashes in RD. Sobotka and May also found increased amplitude of the ERP to irrelevant stimuli in children with RD. Both groups of researchers, therefore, concluded that the results could be explained by attentional factors alone. They failed, however, to exclude children with ADD, and this factor may have confounded their results. Harter, Wood, and Marvin-Schroeder (in press) have found that ADD may lead to enhanced task-relevant ERP's. Also, in that Sobotka and May reported effects to irrelevant stimuli alone, the relevance effects of RD would not have been evident.

A number of investigators have recognized the necessity of employing linguistic stimuli requiring an active processing of language information. Symann-Louett, Gascon, Matsumiya, and Lombroso (1977) recorded ERP's to words and found differences (less waves in the RD group) in the early portion of the waveform (less than 200 msec) over left parietal leads. Unfortunately, this measure (number of waves) is difficult to interpret in relationship to information processing. Preston and colleagues conducted a series of studies (Preston, Guthrie, & Childs, 1974; Preston, Guthrie, Kirsch, Gertman, & Childs, 1977) using both light flashes and words. They found reduced amplitude ERP's in disabled subjects over left parietal regions in the negative component at 180 msec. A later study with adults further identified a difference in the amplitudes of the positive components at 200 msec. and a late positive component (LPC) defined as a composite of amplitudes for latencies at 250, 350, 450 and 550 msec between normal and RD subjects. The normal group showed a larger difference in the ERP waveform to words versus flashes than the RD group. Subjects were engaged in a task requiring active processing. They were required to count words which they were tested on after the run was completed. However, the ISI was over two seconds which would not have been very demanding in terms of time constraint.

This later study by Preston and colleagues (1977) is particularly relevant to the present one in that the subjects were adult dyslexics (mean age = 40). This suggests that RD continues to be associated with physiological differences in adulthood. They also found a positive correlation (.71) between reading scores and discriminant ERP measures based on P200 and LPC scores. While one may be tempted to conclude that this supports a deficit model, we have no way of knowing premorbid reading skills. It is possible that some or all of these individuals improved in reading ability, and physiological changes may have followed a similar course, though still remaining attenuated when compared to controls. Thus, a developmental model is not disconfirmed by this study. One would need to compare the physiological results to reading scores in childhood as well as adulthood and look for any dissociations between behavioral and physiological indices.

The factor of task complexity has been shown to be important in differentiating children with and without RD in several studies employing visual evoked potentials. Dainer, Klorman, Salzman, Hess, Davidson, and Michael (1981) reported reduced amplitude of the late positive component in subjects with RD compared to normal readers on a more difficult version of a continuous performance task. Johnstone, Galen, Fein, Yingling, Herron, and Marcus (1984) further demonstrated an attenuation on the amplitude of the waveform in RD. The reduction in amplitude for RD was found in response to an irrelevant visual probe stimulus (checkerboard) in the 250-350 msec range while reading difficult as opposed to easy reading materials.

Several researchers have reported hemispheric differences between normal and disabled readers depending on the type of stimulus and its degree of complexity. Bakker, Licht, Kok, and Bouma (1980) recorded ERP's to word stimuli and found interactions between ear dominance and hemisphere. They interpreted their findings as evidence that word memory is mediated by the hemisphere opposite to the dominant ear. Word processing was not found to be hemispheric specific in subjects with RD.

Fried, Tanguay, Boder, Doubleday, and Greensite (1981) reported that dyslexics with auditory-verbal processing deficits failed to show the typical asymmetry of greater amplitude ERP's to word versus musical chord stimuli over the left hemisphere. A study by Ornstein, Herron, Johnstone, and Swencionis (1979) suggested that the right hemisphere may play a greater role in some reading skills. They reported greater right hemisphere activation (measuring EEG alpha) in normal subjects while reading technical material. Taken together, these findings would suggest that a linguistic task which demands active processing of the materials may be a more sensitive measure to detect differences in neural processing between normal and disabled readers.

An earlier study by Musso and Harter (1975) offers preliminary evidence that a stringent selective attention paradigm may indeed yield valuable information. They compared children with RD involving either visual or auditory perceptual problems to normals on a task requiring the discrimination between two colors, orientations, letters, or words using a warning stimulus. They concluded that word problems were indeed more difficult and arousing for children, yielding smaller differences in the ERP's to relevant vs. irrelevant stimuli, yet larger contingent negative variation (CNV). The children with RD showed enhanced ERP's to relevant stimuli compared to normals which the authors related to greater selective attention as a means of compensating for their deficit. It should be noted, however, that these authors like Sobotka and May (1977) did not control for ADD. They also reported longer latencies in children with RD suggesting a slower rate of processing.

This study did not, however, employ the same time constraints as the present investigation (discussed below). Even in the letter and word conditions, the child could learn the discrimination based on the physical properties of the stimulus alone as opposed to its meaning.

One additional point in the ERP literature studying RD involves differences in the negative portion of the ERP associated with the anticipation of a stimulus, called the contingent negative variation (CNV). Fenelon (1968) first described reduced CNV in dyslexic children in response to tones, light flashes, and semantic stimuli. Cohen (1980) also found reduced CNV's for children with RD using tones and light flashes. These findings provide preliminary evidence that children with RD are not in the same state of preparedness even when the task employs fairly simple stimuli.

Event-related potentials have been found to provide a sensitive measure of visual attentional processes (Eason, Harter, & White, 1969; Harter & Salmon, 1972; Van Voorhis & Hillyard, 1977). Harter and Aine (1984) provide a summary of research on how attention to different types of stimuli is reflected by ERP's. By manipulating which dimension of multidimensional stimuli is relevant, Harter and colleagues have proposed a time course of ERP changes involving the selection of location, contour, color, spatial frequency, orientation, conjunction of features, and/or relevant stimulus per se, in that order. (Harter, Aine, & Schroeder, 1982; Harter & Guido, 1980; Harter & Previc, 1978; Harter & Salmon, 1972) Relevant stimuli yield greater amplitude waveforms than the same stimulus when irrelevant. They found both enhanced negativities peaking between 100-250 msec as well as an enhanced positivity peaking after 300 msec, depending on the paradigm and stimuli employed. These studies have indicated that a selective attention paradigm, and particularly an examination of difference potentials (relevant minus irrelevant), yields an attentional effect which would likely be quite sensitive to any differences in attentional processes between children with and without RD.

This was supported in a series of studies conducted by Harter and colleagues (Harter, Wood, & Diering, in press; Harter, Wood, & Marvin-Schroeder, in press; Naylor & Harter, 1985). Using visual attention paradigms with strict time contraints and which varied stimulus complexity, Harter and colleagues showed significant differences in the ERP's of children with and without RD.

A pilot study by Naylor and Harter (1985) revealed an attenuation of the amplitude and increased latency of the late positivity (around 300 msec) for relevant stimuli in children with RD. Children with RD also showed reduced CNV to relevant stimuli. Interpretation of the results of this study are limited by several factors. First, recordings were made only over the left occipital region. Also, sample size was small (eight in each group), and neither ADD nor IQ were controlled. This preliminary study, however, suggested that children with RD showed less differential processing of relevant versus irrelevant stimuli, slower processing, and less anticipation of positive feedback than normal readers. Although differences were found in all task conditions, the effects were greater in the letter identification tasks as compared to shape discrimination.

Harter and colleagues (Harter et al., in press) examined a larger number of RD children, with and without ADD, using a single flash attention paradigm. The children participating in this study underwent a series of neuropsychological tests including estimates of intelligence (Peabody Picture Vocabulary Test - Revised Version and Porteus Mazes) (Felton et al., in press).

The ERP effects and the role of verbal IQ in the ERP effects was assessed (both studies by Harter et al., in press). These authors reported independent effects for RD and ADD. First of all, children with RD had reduced left central positivity at 240 msec to both relevant and irrelevant stimuli. The authors interpreted this assymetry as representing a left parietal deficit. Second, children with RD also showed a reduction in central positivity around 320-340 msec in response to relevant stimuli. The difference tended to be slightly greater for tasks demanding semantic processing and was symmetrical across the two hemispheres. The authors proposed that this may represent an early stage of processing involving complex pattern discrimination in infero-temporal regions. A third difference was evident over left central-occipital regions at 400-440 msec characterized by reduced positivity following relevant stimuli in children with RD, the reduction being greater over the left hemisphere. The authors concluded that this may represent a later stage of processing in left parietal regions and could involve receptive reading. A fourth finding revealed a symmetrical increase in the amplitude of a late positive component over frontal regions in children with RD. This effect was slightly greater for the more complex letter task which supposedly demanded more semantic processing. In that behavioral differences (NRD vs. RD) in the children's ability to perform the tasks were not evident, the authors proposed that this late enhanced positivity over frontal regions may represent a compensatory mechanism in children with RD.

The effects of ADD were found to be independent from those of RD, that is, significant effects were found over different cortical regions and at different latencies. While the effects of RD were most evident over central leads in the left hemisphere, the effects of ADD were bilateral in nature evidenced by increased frontal positivity between 320 to 440 msec to relevant stimuli. The authors proposed that this later finding may represent a compensatory mechanism in subjects with ADD.

Thus, these authors proposed that ERP's may reflect a number of compensatory mechanisms to explain how children with RD and/or ADD were able to perform the behavioral task as efficiently as normal controls. If alternate strategies can be adopted, this could play a role in the remediation of certain individuals with RD.

It is also possible that the differences in neural function may involve a functional reorganization of the brain which would be observable using the evoked potential technique. Neville and colleagues (see review: Neville, 1980) have demonstrated the use of ERP's to study language processing in normal, hearing impaired, and CNS lesioned individuals. They have found functional changes in the ERP's of acquired alexics as they recover reading skills; this suggests the development of reliance on a more anterior language pathway. They also found evidence of a functional reorganization of left hemisphere skills in deaf children whose primary language was American Sign Language. This mode of communication relies more heavily on visual cues, particularly peripheral movement. It would not be surprising, therefore, to find that strategies adopted by individuals with RD to compensate for their deficit(s) are represented by a functional reorganization of cortical regions involved in language processing. One main problem to be considered in this area is the specification of which ERP components reflect deficits versus compensatory processes and mechanisms.

Statement of Purpose

Based on the findings of Harter and colleagues, the present study was undertaken to (a) investigate the presence of reduced amplitude ERP's, particularly in the left central regions, in adult dyslexics, and (b) attempt to identify possible deficits and compensatory mechanism(s) in individuals who have improved their reading skills. A unique population of subjects, who were tested approximately 20 years ago by Mrs. June Lyday Orton and diagnosed as dyslexic, were available to serve as subjects.

June Lyday Orton was a reading specialist who lived in Winston-Salem following the death of her husband, Dr. Samuel Orton, a neurologist known for his expertise in the field of dyslexia. Mrs.

Orton established the Orton Reading Center where she and her colleagues evaluated children for reading problems and initiated treatment programs based on those findings. Her focus was founded on a phonics approach to remediation. She made provisions in her will for the preservation of her files as well as those of her husband. These files contain a wealth of information on clients including raw test forms as well as summary scores, personality assesssment data, tutoring plans and notes, and personal correspondences with parents, teachers, and significant others. In its entirety, the information in Mrs. Orton's file provides a detailed picture of the individual in childhood, most often in elementary school. The files also attest to Mrs. Orton's excellent clinical insight and her expertise in the field of reading disability. It is without doubt that these files offer a unique opportunity for a longitudinal study of the behavioral characteristics and outcomes of reading disability as well as for a cross-sectional electrophysiological comparison to a sample of children who were seen by Harter et al.

The following hypotheses were tested:

1. If the developmental lag hypothesis is viable and children with RD "catch up" as adults, those subjects who showed the greatest deficit in childhood should show the greatest improvement from childhood to adulthood. This hypothesis cannot be directly tested electrophysiologically since the ERP data on these subjects when they were children are not available. No difference in ERP's between normal adults and improved readers who were RD as children could be interpreted as indirect support for this hypothesis. However, many other

interpretations of this null effect unrelated to reading are possible. The hypothesis can be tested behaviorally by examining the amount of improvement made by subjects within the RD group. Since a ceiling effect would prevent normal readers from making advancements, only subjects with RD were compared. Degree of childhood deficit should be negatively correlated with improvement (the poorest readers had the most catching up to do).

2. The hypothesis that there will be differences in the ERP waveforms of adult dyslexics and adults with no history of reading difficulty was tested. This was a test of the deficit hypothesis. It was addressed by two methods: (a) the entire sample of subjects with RD as children was compared to those without; and (b) subjects with RD in childhood who were identified as severely disabled using adult reading scores were compared to normal readers (Figure 1). The following specific components based on the findings of Harter et al. (in press) were subjected to evaluation: (a) central positivity at 240 and 500 msec to all stimuli; (b) the relevance effects in the occipital and central regions at 330 and 420 msec; and (c) the relevance effects in the late negativity over central regions. Given that adults may vary from children 20 years their junior, a post hoc inspection of the ERP waveforms served to identify other indicants of dyslexia in adults. These a posteriori findings will be interpreted with caution.

3. Another possibility is that RD could be the result of both a sustained deficit in some subjects and developmental lag in other subjects. A correlation between reading and electrophysiological

measures would be expected in this case. That is, some subjects will continue to have reading problems and will show (a) reduced left central positivity at 240 and/or 500 msec; and/or (b) reduced occipital-central positivity to relevant stimuli at 330 and/or 420 msec. These subjects would not be able to compensate behaviorally for their neural deficit. Others may improve in reading and show a shift on all ERP measures identified as related to RD in the direction of normal controls with no history of RD.

4. Another possibility is that the adults still may have a neural deficit but may compensate and improve in reading. Improved readers may still show persistent deficits in neural processing on any of the measures outlined above supporting a deficit hypothesis (e.g., CP240; Figure 1). The following hypotheses regarding possible compensatory mechanism(s) in improved readers will be tested:

a. Improved readers should have the following ERP effects, interpreted by Harter et al. as possibly reflecting compensatory neural mechanisms: enhanced frontal positivity at 500 msec, enhanced central positivity at 500 msec, and/or enhancement of task relevant occipital or central positivity between 320-440 msec.

b. Alternatively, improved readers may show changes in other measures and brain regions not evident in the earlier study on children. Early lesion studies suggest that the right hemisphere is capable of language acquisition when the left hemisphere is damaged. Neville's findings further support the notion of developing alternate strategies for language processing in lesioned and hearing impaired individuals.

Therefore, one could propose a possible compensatory mechanism in remediated dyslexics involving a greater reliance on right hemisphere functioning. This would be supported by enhanced right hemisphere ERP's in remediated adults. Any hypotheses generated by such post hoc analysis will be interpreted cautiously.

CHAPTER II

METHOD

Subjects

The subjects were 38 adult males ranging from 24 to 49 years of age. The majority of subjects had been tested as children by Mrs. June Orton, 24 of whom had RD and 8 of whom had no RD based on childhood reading scores (NRD-ort). The reasons for referral are discussed in the results section under childhood behavioral data. The remaining 6 subjects were volunteers with no history of academic difficulty (NRD-cont). This second control group was included given that the eight "normal" readers seen by Mrs. Orton still represented a "referred", though not reading disabled, population and thus may not have been normal. All subjects were paid $75.00 for participating in the study.

Subjects classified as RD had to meet the following criteria as children based on tests administered by Mrs. Orton or her colleagues: (a) a verbal or performance IQ of at least 85 determined by Wechsler Intelligence Scale for Chidren (WISC) scores; and (b) a reading achievement score(s) which was at least two grade levels below expectation (based on the Gray Oral Reading Test (GORT) and/or the Wide Range Achievement (WRAT) Reading Subtest). A more complete description of the subjects' test scores in childhood is provided in the results section under childhood intelligence and achievement test scores as well as in Tables 1 & 2 (Tables 1 & 2 and all subsequent tables may be found in Appendix A). The Orton control subjects must have achieved a

WISC IQ of 85 or above on both verbal and performance scales as well as having achieved reading scores at or above grade level.

Subjects were formally interviewed and excluded if there was any current diagnosable major psychopathology, as operationally defined by the Schedule for Affective Disorders and Schizophrenia, Lifetime Version (SADS-L; Endicott & Spitzer, 1978). Only one subject had to be excluded due to the presence of major affective disorder. The childhood files were studied to screen out subjects with a history of significant attentional or emotional problems. Because the files varied in the content of information provided, subjects were asked a number of questions in reference to their attention and behavior in childhood. If the subject's answers suggested that they may have had ADD, this was noted for use in the outcome analysis.

All subjects were required to meet the same criteria on an IQ test administered by the author (Wechsler Adult Intelligence Scale - Revised Version; WAIS-R). No subject had to be excluded for reasons of low intelligence in adulthood.

Psychological Tests Administered

The Weschler Adult Intelligence Scale-Revised Version (WAIS-R) was administered to all subjects. The IQ scores served three purposes: (a) to determine if a subject met the criteria outlined above; (b) to determine reading quotients; and (c) to assess any general improvement or deterioration in overall intellectual functioning when compared to childhood scores.

The Gray Oral Reading Test (GORT) and the Wide Range Achievement Test - Revised Version (WRAT-R) were administered to all subjects in order to determine current achievement level. Adult reading quotients were used to infer the degree of improvement in subjects with RD after considering degree of deficit in childhood based on childhood quotients. Both of these tests are oral reading tests. They are commonly used with adults since they have adult norms. Past research has suggested that oral reading is one of the skills most resistent to remediation (Finucci et al., 1984). The GORT requires the subject to read paragraphs out loud which are graded in difficulty. The WRAT-R involves single word recognition and pronunciation which are also graded in difficulty.

A standard method of deriving a reading quotient from childhood based on grade level values could not be used in adulthood. Generally, the grade level a child achieves on a test is compared to his IQ and chronological age (see results section on childhood achievement test scores). This poses two problems when evaluating adults: (a) the adults who participated in this study were rarely in school and therefore assigning a "grade level" is dubious; and (b) adults often score outside of the grade level values available (i.e., above twelfth grade level) creating a ceiling effect. Therefore, it was necessary to devise a different procedure to assess the degree of reading deficit in adulthood.

Two methods for calculating the degree of reading disability were employed. First, a procedure used by Finucci et al. (1984) was followed. They devised a regression equation that described achievement relative to the level expected of an adult given IQ, sex, and education. A deviation score was calculated which represented the difference between a subject's expected score (predicted by the regression equation) and the subject's actual score on the Gray Oral Reading Test. Finucci's sample was quite similar to this group in terms of age, socioeconomic status, and education (Table 3). Although the subjects with RD who participated in the present study scored somewhat lower on IQ tests, IQ was weighted appropriately in the regression equation as a predictor of expected achievement. Thus, the use of Finucci et al.'s regression procedure was judged to be a valid method of determining the degree of deficit in reading for the adults in this study. A second method was employed to analyze the WRAT-R reading scores. A quotient was obtained by taking the age-corrected reading standard score and dividing it by the full scale WAIS-R score, then multiplying this figure by 100. This method did not account for differences in education but did control for IQ and age.

Therefore, it should be noted that, due to the problems discussed earlier, different methods were used to determine the degree of deficit in childhood and adulthood. Although the scores obtained were not directly comparable due to scaling discrepancies, appropriate statistical procedures (analysis of covariance) allowed the relationship and/or independence of childhood and adult deficits to be compared. These are discussed at length under data analysis and again in the results section.

As noted earlier, an extensive interview of all subjects was conducted in order to obtain the following information: history and amount of special tutoring or class placement, family history of reading disability, family structure in childhood and at present, grade completed in school, socioeconomic status, history of medical complications, marital status, occupation, handedness, as well as the questions mentioned previously to rule out a history of emotional and attentional problems.

Event-related Potential Test Procedure

The procedure used to collect event related potential (ERP) data were virtually identical to that employed by Harter et al. (in press). ERP data were recorded from all 38 subjects. Each recording session lasted approximately two hours. The initial 1/2 hour included an explanation of the games (see below) to be played, the signing of a consent form, and the application of the electrodes. The data collection itself took approximately 1 to 1 1/2 hours.

The subject was seated in an electrically shielded, partially sound- proofed room in an adjustable chair in front of a video monitor. The subject was instructed to lift his right index finger off a key when the target (relevant) stimulus was presented. He was allowed to practice on his own until meeting a criterion of at least 75 % Hits and no more than 25 % False Alarms. The experimenter monitored the subject's performance on another video screen outside the testing room and provided further instructions, feedback, and encouragement via an intercom system. The subject was able to start or stop the game at any time by releasing the reaction time key.

The stimuli were presented using an IBM-PC and displayed on a Princeton Color Graphics monitor. The interstimulus interval varied from 1.5-2.0 seconds depending on how quickly the subject pushed the key down after making a behavioral response. IBM-PC character code stimuli were flashed in the center of the screen for a 50 msec duration, subtending about .7 degrees visual angle. The subject was required to fixate a dot in the center of the screen surrounded by a 1.75 x 2.00 degree magenta rectangle. The target and nontarget stimuli were flashed randomly in blocks of 24 with a rest period between each block. The subject was instructed to respond only to the target stimuli by lifting his finger off of the key as quickly as possible.

All subjects worked against their own mean reaction time for bonus points. Responses within a critical reaction time interval of 500 msec were classified as Hits, Misses, Correct Rejections, or False Alarms. Visual and auditory feedback was provided as to the accuracy of their response. Dots which vertically converged on the fixation point visually signaled the accuracy of performance while "beeps" and "boops" provided auditory information regarding correct and incorrect responses, respectively. The subject won or lost points according to the accuracy of his response. He also won bonus points for three successive Hits. Only correct responses, that is, Hits and Correct Rejections, were included for the ERP data analysis. This ensured that any differences in the ERP data were attributable to differences in neural processing rather than behavioral performance.

Behavioral measures were recorded for each subject using the IBM-PC including the number of practice trials before reaching criterion, Hits, Misses, Correct Rejections, False Alarms, total points won, reaction time measures, and standard deviation of reaction times.

Experiments (games). A single stimulus presentation paradigm was employed. The subject simply made a behavioral response whenever the target stimulus was detected. Each subject performed five games, although only two are presented in this paper. The two presented here were the same games employed by Harter and colleagues (Harter et al., in press) in studying child dyslexics.

Twelve letters ("K", "T," "V," "W," "X," "Y," "a," "e," "n," "m," "h," and "f") and twelve geometric nonletter patterns (IBM-PC Character Codes 198, 199 , 202, 204, 188, 207, 235, 232, 224, 15, 247, and 236) were flashed in both black and white. In the first game, the subject was required to respond to any black stimulus, whether it was a letter or nonletter. This task required a simple physical discrimination based on color. In the second game, the subject was required to respond to any letter, black or white. As in the Harter studies, this game was intended to be a more complex task requiring the processing of letter meaning. As mentioned above, the subjects performed three other games which are not presented in this paper. One involved responding to black letters only, ignoring black nonletters and all white stimuli. This task involved attending a conjunction of feature. The other two games employed CVC trigrams presented in an identical fashion to the two games described above. In one game, subjects attended to black stimuli, and in the other game, words were relevant. Order of presentation of the games was counter-balanced across subjects.

Event-Related Potential Data Collection. ERP data were recorded using an electrode cap made by International Electro-cap Incorporated. Recordings were made from the left and right occipital (O1 and O2), central (C3 and C4), and frontal (F3 and F4) leads. The Fpz served as ground. An EOG electrode was placed 2 cm to the right and 2 cm below the right eye to monitor eye movements. All electrodes were referenced to yoked ears.

An electrode gel was used to reduce skin resistence to less than 10 kohms. ERPs were amplified by six 7P511 Grass amplifiers, while EOG activity was amplified by a wide band 7P5 AC amplifier. Half amplitude high and low frequency filters were set on 100 and .3 Hz, respectively.

The channels were digitized at a rate of 1 per 20 msec. for a period of 1000 msec following stimulus presentation. This was then fed into a Plessey Micro II computer system (based on a DEC LSI 11-23 central processor). Data collection continued until a minimum of 24 trials were collected for each condition, both target and nontarget. Both the mean ERP and the standard deviation of individual ERPs were computed for each channel under each condition.

A rejection system was used to exclude ERP data contaminated by eye or body movement. The occipital alpha rhythm with eyes closed was used as a ceiling voltage such that any EEG activity exceeding this amplitude was rejected. EOG activity exceeding the noise level when the subject was fixating resulted in rejection of ERP data. Finally, ERP data were excluded when a behavioral error (Miss or False Alarm) was made. A record was kept of the number of rejections due to artifacts in the electrical activity and/or behavioral errors.

Data Analysis

Behavioral Test Results. Group differences on the behavioral test results and historical information (e.g., age, education, SES, IQ) were tested using an analysis of variance procedure. If the ANOVA revealed a significant group effect, posthoc comparisons were performed to determine which group(s) differed. An analysis of covariance procedure was employed to test the ability of various behavioral or historical variables (childhood SES, family history of RD, or a history of attentional problems) to predict adult reading after covarying for the degree of childhood deficit (i.e., the degree of reading improvement).

ERP behavioral data. The ERP behavioral data were analyzed using a two way analysis of variance procedure with two levels of groups (RD versus NRD) and two levels of games (letter relevant versus color relevant). The two control (NRD) groups were not found to differ on ERP measures and therefore were combined for analysis as described in the results section.

ERP data analysis. The ERP data were subjected to analysis following the procedure outlined in detail in the results section. An analysis of variance was performed to test a priori and a posteriori hypotheses. The data were combined across the irrelevant dimension (i.e., black and white combined when letters were relevent, and letters and nonletters were combined when black was relevant). Analysis of predicted relevance independent effects was performed after combining across relevant and irrelevant conditions. An analysis of covariance procedure was employed to assess the role of IQ in the group effects found using the method outlined above. The next step tested the hypotheses of possible compensatory mechanisms in improved dyslexics using an analysis of covariance which covaried for childhood reading deficit. The dependent measures were based on specific ERP indices at given homologous leads derived by Harter and colleagues as sensitive to RD in children, i.e., (a) Greater central positivity at 240 and 500 msec over left hemisphere for NRD; (b)increase in central positivity bilaterally for NRD at 320-340 msec for relevant stimuli; (c) increase in occipital positivity for NRD at 400-440 msec. following relevant stimuli and greater over the left hemisphere; and (d) greater frontal positivity at 500 msec for RD. Given that the subjects in this study were adults, the latencies of these components varied somewhat. These effects as well as a posteriori testing of major components of the ERP waveform served as dependent measures that were subjected to analysis.

CHAPTER III

RESULTS

Childhood Behavioral Data

The 32 subjects for whom earlier test scores were available were evaluated by Mrs. Orton between 1957 and 1972 and ranged in age from 9 to 23 at the time of testing. The mean age was 13.8 for subjects with RD and 14.1 for the normal subjects. The average grade level was 7.8 for the subjects with RD and 9.0 for normal subjects.

All subjects with RD were referred for problems involving basic reading skills, with difficulties in spelling being a common associated complaint. Of the 22 subjects with RD for whom diagnoses were available in Mrs. Orton's records, seventeen were diagnosed as having a specific reading or language disability. Descriptions of difficulties included: poor visual memory for whole words, lack of accurate sound-letter associations, reversals, sequencing errors, poor auditory memory and perception, poor spelling and handwriting, visual perceptual problems, and/or poor vocabulary and comprehension. Four others were not formally diagnosed but were described as having similar problems. Only one subject classified as RD by the criteria of this study was not described by Mrs. Orton as having a reading problem, although he was noted to have difficulties with spelling, auditory discrimination, sequencing, and pronunciation.

Two of the subjects with RD were college students when they were tested by Mrs. Orton. They were included because they met the criteria and both had been identified as reading disabled early in their school careers, although no test scores were available from this time in their life. Also, one had improved considerably while the other had not. It was felt, therefore, that including these subjects in the study could aid in our knowledge of why some individuals improved in reading ability.

Six of the subjects without RD were described as having no specific learning disability. These subjects were generally average to good readers who were not working up to their potential or who were being tested for reasons of academic placement or admission to private school. One NRD was described as having a "specific disability or lag in graphic encoding skills," though this subject also was described as having good language and reading skills. Only one subject meeting the criteria of this study for inclusion as NRD was originally classified as having a specific language disability by Mrs. Orton. This subject had problems in spelling, handwriting, and oral reading (although his oral reading scores were within normal limits). This same subject was described as having well-developed silent reading and vocabulary skills.

Although no childhood test data were available on the other six normal subjects, an interview established that these subjects had no history of academic difficulty in reading or language related subjects and none had required any special academic help. One subject had repeated the seventh grade due to relocation of his family and some difficulty in math after changing schools.

Childhood Intelligence Scores. For the subjects with RD, overall intelligence test scores, using the Full Scale Intelligence Quotient (FSIQ) from the Wechsler Intelligence Scale for Children (WISC) or the Wechsler Adult Intelligence Scale (WAIS) depending on the age of the child, were in the average range (M = 107.29). There was no significant difference between verbal (M = 106.92) and performance (M = 107.46) IQ scores (Table 1).

The normal Orton subjects (NRD-ort) scored in the above average range as a group overall (M FSIQ = 118.75) with the verbal scores falling in the superior range overall (M = 121.13) while performance scores were more comparable to the group with RD (M = 111.87). A t-test testing for group differences was significant for Verbal IQ, $t(27) = -4.81$, $p < .01$, and FSIQ, $t(28) = -4.71$, $p < .01$, although there was no difference in Performance IQ between the groups.

Childhood Achievement Test Scores. Achievement test scores showed an average delay of three years for RD on the GORT and two years on the WRAT reading (Table 1). Achievement quotients were calculated to provide a more accurate representation of each subject's achievement relative to expected performance. This was accomplished using the following learning quotient formula (Boder & Jarrico, 1982):

$$\text{Reading Quotient} = \frac{2 \text{ X reading age}}{\text{mental age + chronological age}} \text{ X } 100$$

The majority of subjects with RD were classified as deficient (< 80) on both GORT and WRAT reading achievement quotients (Table 2). Over half of the subjects with RD had Gray Oral reading quotients of < 70. It should be noted that a subject was included in the study if he was at least two years behind grade level on either the GORT or WRAT reading tests. Therefore, while most of these subjects were deficient on both measures, at times one of the quotients fell in the borderline range (between 81 and 90). Two subjects fell in the borderline range on the GORT quotient, while four fell in the borderline range on the WRAT reading quotient and two actually scored within normal limits on this latter test. Most subjects had been given some test of spelling achievement (WRAT or Stanford Achievement). On the one hand, spelling quotients were in the deficient range for all but two of the subjects with RD. The remaining two subjects performed in the borderline range on spelling tests. On the other hand, less than half of the subjects fell in the deficient range in terms of arithmetic scores (WRAT or Stanford Achievement), with five scoring in the normal range. None of the NRD-ort was in the deficient range on any of the achievement quotients. Three NRD-ort fell in the borderline range in spelling and one in math, although all NRD-ort fell in the normal range on both reading measures.

RD and NRD-ort differed significantly on all measures of achievement in childhood. On the WRAT reading quotient, $\underline{t}(28) = -5.31$, $\underline{p} < .01$. Spelling quotients yielded a difference with $\underline{t}(30) = -6.18$, $\underline{p} < .01$. The math quotient also differed significantly, with $\underline{t}(24) = -3.24$, $\underline{p} < .01$. The $\underline{t}$ (29) value testing the difference on the GORT $= -7.56$, $\underline{p} < .01$.

Childhood Remediation

All but one Orton subject with RD and three without received some type of remedial help prior to high school graduation. Although difficult to determine, the duration of tutoring appeared to range from six weeks to seven years. Sixteen subjects with RD were tutored at the Orton Center which involved intensive phonics instruction, work on reading speed and comprehension, spelling and written expression. Five NRD-ort received special help primarily focusing on reading rate, vocabulary development, and comprehension. Some also received instruction in basic phonics, written expression, and study skills.

Of the remaining subjects with RD, three were tutored by individuals who had been trained by Mrs. Orton and worked under her direction at other settings. Four others received services from persons not associated with the Orton Center.

Adult Behavioral Data

The 32 Orton adults were tested in 1986, an average of 21 years after their initial evaluation by Mrs. Orton. The subjects with RD ranged in age from 24 to 48 with a mean age of 33.87 (Table 3). The NRD-ort ranged in age from 31 to 40 with a mean age of 36.01. Subjects in the other normal control group (NRD-cont) ranged in age from 27 to 41 with a mean age of 33.88. There was no significant difference between the groups in terms of age. Using a revision of Annett's hand preference questionnaire (Briggs and Nebes, 1975), all but 1 subject with RD and 1 NRD-ort were classified as right-handed. The remaining two subjects were classified as left-handed.

Adult Intelligence Scores. As mentioned, all subjects met the IQ criteria for inclusion in the study. The subjects with RD scored in the average range (M = 100.62), with no discrepancy between verbal (M = 101.04) and performance (M = 100.79) skills (Table 3). When compared to childhood scores, the subjects with RD dropped an average of 5.9 points in verbal and 6.7 in performance IQ, yielding an overall drop in full scale intelligence of 6.7 points. Using a paired t test, the drop in IQ was significant for VIQ, $t(23) = 3.39$, $p < .003$, PIQ, $t(23) = 3.96$, $p < .001$, and FSIQ, $t(23) = 4.61$, $p < .001$.

The NRD-ort obtained overall IQ scores in the above average range in adulthood (M FSIQ = 115.75), with only a three point drop from childhood. This was consistent with the reports of expected reduction in scores using the revised Wechsler series. NRD-ort obtained a mean verbal IQ score of 115.87 (drop of 5.25 points) and a mean performance IQ score of 112.25 (gain of .38 points). The drop in VIQ approached significance, $t(7) = 2.23$, $p = .06$, but the drop in FSIQ was not significant.

The groups did not differ significantly in IQ loss from childhood to adulthood. However, the drop in performance IQ was negatively correlated with the deviation scores derived from the Finucci formulae based on the GORT, $r(22) = -.35$, $p = .05$, and Wrat-R spelling, $r(21) = -.43$, $p < .02$. The lower the deviation score (the greater the degree of disability), the greater the loss in performance IQ from childhood to adulthood.

The NRD-cont, who were not tested in childhood, scored in the average range (M FSIQ = 104.33) as a group on IQ tests. There was little discrepancy between verbal (M = 103.00) and performance (M = 105.83) IQ measures.

An overall ANOVA revealed a significant group difference in VIQ, $F(2,35) = 7.61$, $p < .002$. Post hoc comparison between the means (Tukey) revealed that this was due to a difference between the NRD-ort and the other two groups, with no significant difference found between RD and NRD-cont. ANOVA on PIQ scores revealed a significant group difference, $F(2,35) = 4.16$, $p = .02$. Comparison between the means revealed that subjects with RD were significantly lower than the NRD-ort with no difference between the NRD-cont and either group. ANOVA on FSIQ scores showed a significant group effect, $F(2,35) = 8.36$, $p < .01$. Post hoc analysis revealed that the subjects with RD scored significantly lower than NRD-ort with no difference found between the NRD-cont and either group.

In summary, NRD-ort scored significantly higher on all IQ measures. NRD-ort scored higher than the NRD-cont only on VIQ. The NRD-cont and the subjects with RD did not differ on intelligence measures.

Adult Achievement Test Scores. Two methods were employed to describe adult reading achievement, given that the standard childhood formula based on grade level values would not be applicable. Using the Finucci et al. regression formula derived from their normative sample

(See Table 3 for comparison), reading and spelling deviation scores were calculated for each subject, using the GORT raw score and the WRAT-R spelling raw score (minus five points for pre-spelling trials) respectively. In the Finucci et al. (1984) study, the average of the reading deviation score and the spelling deviation score was used to obtain an average deviation score (Table 4). This average deviation score defined the presence or absence of reading disability in any given individual. Scores which fell in the range of less than or equal to -2.0 were judged to indicate a specific reading disability. Scores between -2.0 and -1.0 were described as falling in the borderline range, and scores greater than -1.0 as not indicative of any significant reading problem. These criteria, based on reading deviation scores, were adopted in this study to establish extreme groups within the RD sample to be used in ERP data analysis.

Calculating an average deviation score for all subjects resulted in all NRD and 10 (42 %) of the subjects with RD falling in the normal range (-1.0 or above) (Table 5). Seven subjects with RD fell in the borderline range and seven met the criteria for specific reading disability using this procedure. Most subjects were in the deficient range on both reading and spelling scores in childhood.

If we look at reading and spelling separately, seven subjects with RD as children fell in the deficient range on adult reading deviation scores alone. Ten subjects with RD scored within normal limits on the reading test alone, while only seven scored in the normal range in terms of spelling in adulthood. Eight subjects continued to score in the deficient range on spelling tests alone. All NRD achieved reading quotients in the normal range. One NRD-cont had a borderline spelling deficit.

A second method was used to describe a subject's degree of deficit in adulthood and to form extreme groups for use in the ERP analysis. This second method involved determining a WRAT-R reading quotient by dividing a subject's WRAT-R reading standard score by his Full Scale IQ score. This method yielded higher values in general than the childhood formula since it does not take into account educational level (Table 6). Adopting the same criteria for degree of impairment, only six subjects with RD fell in the deficient range (< 80) in adulthood, ten in the borderline range (80 to 90), and eight in the normal range (> 90) (Table 5). The WRAT-R adult reading quotient was in the normal range for all NRD-ort. One NRD-cont scored in the deficient range on the WRAT-R reading quotient measure, although this subject's deviation scores using the other method described above were both within normal limits. There were only three subjects with RD who scored in the deficient range on both the GORT and WRAT measures.

An ANOVA showed a significant difference between the groups on all measures of reading: GORT Deviation Score, $F(2,35) = 18.13$, $p < .001$; WRAT-R quotient, $F(2,35) = 6.56$, $p < .004$; and spelling: WRAT-R spelling deviation score, $F(2,35) = 19.79$, $p < .001$. Post hoc comparison between the means revealed that the group with RD scored significantly lower than both groups with NRD on the reading and spelling deviation scores. The two groups with NRD did not differ. On the WRAT-R quotient, the group with RD scored significantly lower than NRD-ort, but no difference was found between NRD-cont and either group. The absence of a difference between RD and NRD-cont on the WRAT-R quotient was due to the single NRD-cont who performed in the borderline range on the reading of single words in conjunction with IQ scores in the high average to superior range.

Although the overall ANOVA revealed a significant difference between the groups on the arithmetic subtest of the WRAT-R, $F(2,35) = 3.67$, $p = .04$, none of the pairwise comparisons in the post hoc analysis reached significance. Thus, there were no pairwise differences in arithmetic achievement between the groups.

In summary, while NRD-ort performed better than the subjects with RD on all measures of reading and spelling achievement, the difference between RD and NRD-cont was limited to a difference in oral reading of paragraphs and spelling. The disability in the group with RD was restricted to problems in reading and spelling, with no deficit evident on a math achievement test.

Direct Test of the Developmental Lag Hypothesis

If the developmental lag hypothesis is viable, subjects with the greatest reading deficit in childhood would have the most "catching up" to do and thus should show the greatest improvement from childhood to adulthood. The differences in the scaling of achievement measures in childhood and adulthood made a direct comparison of childhood and adult scores impossible. It was therefore necessary to convert each score to a z-score by finding the deviation from the group mean and dividing that difference by the group standard deviation. Improvement on a given reading test (GORT or WRAT) was the difference between the adult and childhood z-scores. This difference was then correlated with childhood deficit. Only the subjects with RD were included in the analysis since a ceiling effect for NRD-ort would have artificially biased the results in the predicted direction.

A significant correlation was found between childhood deficit and degree of improvement on both the GORT, $r(22) = -.45$, $p < .05$, and the WRAT, $r(21) = -.41$, $p < .05$ (Figure 2). The most impaired readers in childhood showed the greatest relative improvement in reading over the twenty year period between testing.

Educational Outcomes

The majority (N = 21) of the subjects with RD attended public schools for all or most of their educational career. About half (N = 13) repeated one or more grades. All subjects with RD completed high school and the majority went on to some form of additional instruction (Table 7). Six obtained technical or Associate Degrees, five finished college, and three had completed a Master's Degree. In general, these individuals chose fields of study that were not reading intensive, e.g., mechanics, engineering, graphics, or fine arts.

Most NRD-ort attended public schools and two had repeated one grade. All had obtained post high school degrees: six Bachelor's Degrees, one Master's Degree and one Doctoral Degree. Interestingly, the subject who achieved the highest educational training was the one NRD whom Mrs. Orton diagnosed as having a specific language disability. He had repeated a grade and received extensive remedial help at the Orton Center.

Of the remaining six NRD who were not seen in childhood, only one had not finished high school (10th grade education), although this subject had obtained a high school equivalency degree. All the others had taken some post high school courses, for the most part in management or business related fields, although only one had received his Bachelor's Degree. The subject with the most education is the one subject who had difficulty on a reading test (the WRAT-R). He attributed this to poor phonics training and some difficulty with pronunciation of words.

An ANOVA revealed a difference between the groups in educational attainment, $F(2,35) = 4.47$, $p < .02$. Post hoc comparisons between the means revealed that NRD-ort had significantly more education than the subjects with RD or NRD-cont, with no difference between these latter two groups.

Occupational Outcomes

All of the Orton subjects were gainfully employed at the time of this follow-up evaluation. The occupations of subjects with RD ranged from semiskilled to professional, although almost all subjects chose professions that were not highly verbal in nature (Table 8). Examples included engineer (metalergy), computer graphics or technology, store or business management, commercial art, computer technology, or mechanics. The business management positions tended to be family businesses such as garment, furniture, or cleaning businesses. Around half of the subjects with RD were either actively employed as mechanics (automobile, boat, or airplane) or had moved up into a higher level supervisory positions in the field of mechanics. The NRD-ort were largely in professional or executive positions such as psychologist, investment broker, or president/owner of a company.

Compared to their fathers' occupations, NRD-ort were distributed in virtually identical categories. The subjects with RD, however, had changed considerably. While the fathers of subjects with RD were distributed more heavily in professional and executive categories, their sons with RD tended to drift toward management, technical, or skilled manual jobs.

Of the six NRD who were not seen in childhood, there were three in supervisory positions, one computor operator, and two in maintenance. The father's occupations followed a similar pattern and included a Doctor of Divinity, two owners of medium sized construction businesses, and the others falling in clerical, skilled, and semiskilled professions.

Socioeconomic Status in Childhood and Adulthood

Using the Four Factor Index of Social Status (Hollingshead, 1975), current and childhood family socioeconomic status (SES) was estimated. Family SES was based on the subject's education and occupation when single or the sole income earner of the family. Both husband and wife's education and occupation were used to derive a score when the spouse also worked (Table 9). On the one hand, only two out of fourteen (14 %) of the mothers of NRD were working while the child was growing up. Thirteen out of twenty-four (54 %) of the mothers of subjects with RD were working while their child was in elementary or junior high school. On the other hand, of the subjects now married, ten out of fourteen (71 %) of the wives of subjects with RD and three out of six (50 %) of the wives of NRD were employed at the time of the study.

The parents of Orton subjects fell predominantly in the upper SES categories of major and minor business owners or professionals. While the NRD-ort fell in a similar pattern to their parents, the subjects with RD tended to be in slightly lower SES categories and to be skilled craftsman and clerical workers. The fathers of NRD-cont were fairly evenly distributed across SES categories. The distribution of the NRD-cont was bimodal in nature with four falling in the upper SES groups while the two janitors fell in the lowest group.

Statistical analysis of the results revealed no RD versus NRD group differences in either childhood or current SES status. Neither SES value was significantly correlated with either reading quotient. SES in childhood was significantly correlated with SES in adulthood, $r(22) = .36$, $p < .03$.

An analysis of covariance model was used to assess the role of SES in predicting adult reading after covarying out the role of childhood reading deficit. The results approached significance, $F(1,21) = 3.85$,

$p = .06$, on the GORT Deviation Score. SES in childhood was not a factor in outcome of WRAT-R reading scores.

The Role of Symptoms of Attention Deficit Disorder in Childhood

Nine out of 24 (37.5 %) subjects with RD reported symptoms of Attention Deficit Disorder (ADD) in childhood. All of these nine admitted to a short attention span but only two possibly had hyperactivity. Two of the remaining seven stated that they may have been more active than normal. Four complained of being poorly organized, and four remembered getting into trouble for their behavior. None of the normal subjects reported a history of attentional or behavioral problems in childhood.

Each subject's childhood file was carefully reviewed for additional information regarding the presence of symptomotology suggestive of ADD, although none of the subjects was labeled as having significant problems in Mrs. Orton's final report or diagnosis. In reviewing the files, six (25 %) of the subjects with RD were described as having a short attention span, one also being described as disorganized and two as having discipline problems in addition to mild inattention. None was labeled as hyperactive by Mrs. Orton or her colleagues. Only three of the subjects with hints of attentional problems in their childhood files acknowledged difficulties in attention by self report. One of these subjects had described himself as hyperactive, one as rather active and one as not hyperactive but a discipline problem. The extent of difficulty was often difficult to assess. This was due to the fact that it was often difficult for these subjects to remember their childhood accurately. Two independent reviewers looked at childhood and adult files, and a total of 12 of the 24 (50 %) subjects with RD fell into the possible ADD category by self report and/or file information. None of the NRD reported attentional problems in childhood.

Possible symptoms of ADD did not predict adult scores on the GORT Reading Deviation Score or the WRAT Reading Quotient. The presence of possible symptoms of ADD was not a predictor based on self-report alone or using an either/or criterion based on self report and/or mention in the childhood files of attentional difficulties. Possible ADD also failed to predict childhood reading quotients. Symptoms of ADD also failed to account for reading improvement within the dylexic sample using an analysis of covariance model, which covaried for the degree of childhood deficit.

Other Historical Predictor Variables

Although some information was available on the amount of tutoring each subject underwent, most subjects were rather poor historians regarding their early childhood. The information in the Orton files was often qualitative and imprecise. Many of the subjects reported receiving tutorial help from Mrs. Orton and/or her colleagues, particularly after visiting Mrs. Orton. It was judged, therefore, that the information regarding the amount of remediation was incomplete and should not be used in an analysis predicting adult reading scores.

Only three subjects in the group with RD were from homes with a single parent at the time of Mrs. Orton's evaluation. One subject's parents were in the process of a divorce, and in the other two cases, the father had passed away very early in the subject's childhood. All other subjects had intact nuclear families. One subject was adopted prior to school age. Thirteen out of twenty-three (57 %) of the subjects with RD and three out of fourteen (21 %) of the NRD had a family history of reading disability or learning problems.

Only two subjects with RD reported a history of medical problems. One had a history of seizures in childhood which had subsequently resolved. The other had had several mild head traumas from racing motocross with some mild post concussional symptoms but no longterm residual problems.

Subjects were excluded if the interview revealed the presence of major psychopathology. Only one subject had a past history suggestive of an episode of major psychopathology which was diagnosed as situational depression requiring brief treatment (psychotherapy and pharmacotherapy). This subject was judged to be euthymic at the time of the study.

Current marital status of the subjects with RD was 7 never married (29 %), 14 married (58 %), and 3 separated or divorced (13 %). Two were in subsequent marriages following a divorce, and one had remarried after losing his first wife in a motor vehicle accident. Three NRD-ort were single (27.5 %) and five (62.5 %) were married. One of these had been divorced and remarried. Four out of six (67 %) NRD-cont were single, one married (17 %), and one divorced (17%).

No subjects were included if the childhood file revealed significant emotional problems which Mrs. Orton judged to be a major factor in the child's difficulties. Careful inspection of the childhood files revealed only three (12.5 %) RD and no NRD who were having possible emotional difficulties in childhood. This was generally related to feelings of inferiority or a "defeatist" attitude. One subject who was described as rebellious and immature was having family difficulties as well.

The variance was generally not sufficient to analyze the contribution of the above variables to the subjects' reading performance. The single exception was the presence of a family history of reading disability. This factor was not found to predict adult scores on the GORT Deviation Score or the WRAT-R reading quotient.

Further analyses were performed to assess the possible relevance of a family history of RD in reading improvement within the dyslexic sample. Using an analysis of covariance model, this factor did not predict adult reading quotients after taking into account childhood reading quotients.

ERP Behavioral Data

The two normal reading groups were found to be comparable on ERP measures and thus were combined for all ERP analyses. This resulted in two groups, one with RD and one with NRD. A two by two analysis of variance with groups and games as factors was performed on the following behavioral measures: total score, trials to criterion, per cent Hits, per cent False Alarms, Reaction Time for Hits, Standard Deviation of Reaction Time, and accuracy (d') (Table 10). The only group effect to reach significance was due to subjects with RD making fewer Hits in the letter game (group X game interaction: $F(1,36) = 11.85$, $p < .01$). The groups did not differ on the number of False Alarms or in overall accuracy of performance (d'). There was no difference between the groups in the number of points scored or the number of trials required to obtain an acceptable sample of neural measurements. The latency of reaction times for subjects with RD was equivalent to normal readers, and they were no more variable in the latency of reaction time.

There were several main effects of game. All subjects were faster and more accurate when color was relevant as compared to when letter was relevant. Reaction times were significantly faster in the color game compared to the letter game, $F(1,36) = 212.6$, $p < .001$, for both RD (M = 336.5 msec vs. M = 387.7 msec, respectively) and NRD (M = 333.6 msec vs. M = 390.0 msec, respectively. All subjects made fewer False Alarms, $F(1,36) = 32.54$, $p < .001$, in the color compared to the letter game. Mean percent Hits and False Alarm values for RD were 96.9 and 1.3 in the color game and 91.3 and 5.5 in the letter game, respectively. For NRD, Hits and False Alarm rates were 96.6 and 1.5 in the color game and 95.5 and 4.3 in the letter game, respectively. There was a significant main effect of game in the accuracy of responding, all subjects being more accurate in the color game, $F(1,36) = 61.74$, $p < .001$. For RD, d' in the color and letter games was 4.69 and 3.23, respectively and for NRD, 4.49 and 3.61, respectively. There was no main effect of game on total score, number of trials, or variance of RT measures.

Extreme group comparisons, i.e., normal readers versus subjects diagnosed as RD in childhood who remain severely impaired readers as adults, revealed identical results to those found with all subjects. RD who performed poorly on the GORT obtained fewer Hits than NRD for the letter game, $F(1,19) = 6.8$, $p = .02$. This was also the case comparing poor readers on the WRAT-R to normal readers for the letter game, $F(1,18) = 5.16$, $p = .04$. There were no other main effects of group or significant interactions with group and game. The same main effects of game (reaction time, False Alarms, and accuracy) were evident in both extreme group comparisons. Therefore, the group performance of all subjects with a history of RD was quite representative of those who remained substantially impaired on current tests.

Event Related Potential Data

The analysis of the event related potential data proceeded as follows:

Phase I: The first phase involved testing a priori hypotheses of absolute differences between RD and NRD generated by the Harter et al. study (in press) of children at 240 msec, 330 msec, 420 msec, and 690 msec. The first step in this phase involved testing for any differences between the two normal groups before combining them to form one normal population for comparison. An analysis of variance procedure was used to test every 20 msec bin for significant effects of group, relevance, electrode, hemisphere, and their interactions. No significant group differences were found in either game with the exception of a difference in the late negativity after 600 msec. The NRD-cont showed reduced negativity over posterior regions compared to the NRD-ort. However, this did not appear to be related to IQ or reading disability, since visual inspection of the data for all subjects showed that Orton subjects, both RD and NRD, were more negative than NRD-cont. The data of the two normal groups were combined with the reservation that evaluation of any late components should consider this normal group variance.

The next step in Phase I of the analysis tested the specific hypotheses of the effects of RD versus NRD based on the findings of Harter et al. An analysis of variance was performed on central P240, occipital and central P330, occipital and central P420, and central N690 msec with one between subject variable (group) and three within subject variables (hemisphere, relevance, and game). The subjects with RD varied considerably in terms of current reading skills. Some RD's now performed within the normal range on reading tests based on the methods outlined earlier. Therefore, the effect of RD versus NRD was also tested using an extreme groups approach, that is, RD who scored in the severely deficient range on reading tests were compared to normal readers. Two separate analyses were performed, one based on the Gray deviation score and a second based on the WRAT-R quotient. This provided a more direct comparison to Harter et al.'s findings in terms of the severity of the current reading deficit.

Significant effects were then subjected to an analysis of covariance to assess the independence of these effects from intelligence. Verbal IQ from adult test results was chosen as a covariate since this procedure was used in the Harter study.

Phase II: The second phase involved a posteriori testing for effects of RD in prominent components of the ERP waveforms of adult subjects. The same procedure of data management was used in Phase II to test for effects of RD, first comparing all subjects followed by an extreme groups method. Since these comparisons were a posteriori in nature, electrode was treated as a within groups variable in addition to relevance, hemisphere and game. A more stringent criterion for further analysis and interpretation of significant effects was adopted due to the a posteriori nature of this aspect of the analysis. Only effects that were (a) consistent with other findings in the literature; (b) replicated across different group comparisons; and/or (c) highly significant in one comparison were subjected to further inspection.

Phase III: The third phase addressed a priori and a posteriori testing of hypotheses regarding correlates of reading improvement within RD. An analysis of covariance procedure was used to assess the relationship between ERP measures and improvement. Childhood deficit served as a covariate to assess the degree to which the relationship between adult reading and ERP measures was independent of childhood reading level. The analysis of covariance showed: (a) the extent to which childhood disability predicted the variance of an ERP component found to be related to RD in Phase I or II; and (b) the additional predictive power gained by considering the degree of adult disability, above and beyond that which was predicted by the childhood disability. If childhood deficit accounted for a large proportion of the variance of an ERP component, adult reading ability often added little predictive power. If variance in an ERP component is to be interpreted as reflecting a compensatory mechanism related to reading improvement, adult reading scores must contribute additional predictive power beyond that attributable to childhood deficit alone. The analysis of covariance was first performed using all subjects with RD, where adult reading quotients were entered as a continuous variable. The analysis was then repeated by establishing extreme groups based on adult quotients (severely impaired versus normal readers within the dyslexic group). This procedure was followed for all significant group differences found by testing both the a priori and a posteriori hypotheses.

Phase I: Analysis of the RD Effect - Replication of Harter, et al.

Relevance Independent Effects:

The most obvious difference between the groups was that the groups with NRD showed a slow prolonged increased positivity relative to the group with RD. This difference started as early as 150 msec and varied depending on the electrode and hemisphere (Figures 3 and 4). The graphs of raw waveforms and difference potentials (Figures 3, 4, and 9 - 14) include all subjects. Extreme group comparisons are presented using line or bar graphs (Figures 5 - 8 and 15 - 26).

Central P240 (all subjects)- Although the mean amplitude of the positive component at 240 msec over central regions was greater in the normal group over both hemispheres and in both games (Figures 3 and 4), there were no significant group effects comparing all subjects. Both groups showed greater amplitude P240 over the left hemisphere, $F(1,252) = 21.0$, $p < .001$, and greater amplitude P240 in the color game, $F(1,252) = 4.46$, $p = .04$.

Central P240 (extreme groups)- Based on the GORT deviation score (N = 7 for RD), there was a significant main effect of group where NRD had greater amplitude P240 over both hemispheres in both games, $F(1,19) = 5.66$, $p < .03$. This group difference was found only over the left central hemisphere in the Harter et al. studies. The impaired readers showed a 2 to 2.9 uV reduction in the amplitude of P240 (Figures 5 and 6). The group difference was reduced to borderline significance after covarying for verbal intelligence, $F(1,18) = 3.75$, $p < .07$. Although a trend toward reduced central P240 was evident for poor readers on the WRAT-R (Figures 5 and 6), the effect was not significant. The main effects of hemisphere and game were again evident on both extreme groups methods.

Central and Frontal P400 (all subjects)- The late positivity in the Harter et al. study at 500 msec was judged to occur slightly earlier in adults by examining group waveforms (Figures 3 and 4). The P400 component was measured using a window sufficient to assess this late positive component (360-380 msec in the color game and 420-440 msec in the letter game. The hypothesis of greater frontal positivity in subjects with RD was not supported by the results of this study. However, consistent with findings reported by Harter et al. of reduced central positivity, adult dyslexics showed reduced positivity over both central, $F(1,36) = 4.02$, $p = .05$, and frontal, $F(1,36) = 4.84$, $p = .03$, regions. Also consistent with the Harter et al. studies is that this group difference tended to be greater over the right hemisphere for both groups and both relevance conditions, although this interaction did not reach significance.

There was no main effect of hemisphere in the central regions, but all subjects showed greater amplitude P400 in the right hemisphere over frontal regions (main effect of hemisphere; $F(1,252) = 6.58$, $p = .01$). All subjects had larger ERP's at this latency in the color game over both frontal, $F(1,252) = 4.41$, $p < .04$, and central regions, $F(1,252) = 5.67$, $p < .02$. There were no relevance independent interactions with group. There was a group X relevance interaction over frontal regions which will be discussed under Phase II relevance effects since it was not a test of an a priori hypothesis. After covarying for verbal IQ, the group difference in the amplitude of P400 was no longer significant over central, $F(1,35) = 2.85$, $p = .10$, and frontal, $F(1,35) = 3.36$, $p < .08$, regions.

Central and Frontal P400 (extreme groups)- When severely impaired readers were compared to normals, no relevance independent effects were significant at this latency. Impaired readers often resembled NRD over central and frontal regions (Figures 7 and 8).

Relevance effects:

Occipital and Central DP330 (all subjects)- When all subjects were included in the analysis, the hemispheric differences between subjects with and without RD in the amplitude of the relevance effect over occipital and central regions found by Harter et al. was not found in these adults. In occipital regions, subjects showed a greater relevance effect (relevant - irrelevant or attended - ignored) in the color game (relevance X game interaction: $F(1,252) = 75.92$, $p < .001$; Figures 9 - 14). All subjects showed larger ERP's in the right hemisphere, $F(1,252) = 4.32$, $p < .04$.

In central regions, no group by relevance effects were significant comparing all subjects. NRD were, however, more positive than RD (main effect of group: $F(1,36) = 3.98$, $p = .05$), but this did not interact with relevance, game, or hemisphere. This group difference was no longer significant after covarying for verbal intelligence. The response to relevant stimuli was greater than to irrelevant stimuli in both groups, the effect being greater in the color game (relevance X game interaction: $F(1,252) = 18.57$, $p < .001$). This was due to the longer latency of neural processing in the letter game. Both groups showed a greater relevance effect over the right central hemipshere (hemisphere X relevance interaction: $F(1,252) = 9.70$, $p < .01$) The hemisphere and relevance effects did not interact with group in central regions when all subjects were compared.

Occipital and Central DP330 (extreme groups)- When normals were compared to severely impaired readers based on GORT deviation scores, there was a group X relevance X game interaction over occipital regions, $F(1,133) = 4.28$, $p = .04$ (Figures 15 and 16). NRD showed a greater relevance effect in the letter game, whereas the relevance effect in the color game was similar for RD and NRD. This same trend was found by Harter et al. (in press). The interaction was due to a larger group difference in the response to irrelevant stimuli. This interaction was no longer significant after covarying for verbal IQ, $F(1,18) = 1.63$, $p = .22$. No group X relevance interactions were evident over central regions in this extreme groups comparison.

Severely impaired readers based on the WRAT-R quotient showed reduced relevance effects compared to normals (group X relevance interaction) at 330 msec over both occipital, $F(1,126) = 4.82$, $p < .03$, and central, $F(1,126) = 4.09$, $p < .05$, regions. Again, this same trend was found by Harter et al. (in press). These effects became insignificant after covarying for verbal intelligence ($p > .30$).

Occipital and Central DP420 (all subjects)- All subjects showed a large relevance effect at approximately 420 msec over occipital regions of both hemispheres (5 to 6 uV difference: $F(1,252) = 550.42$, $p < .001$; Figures 13 and 14). The amplitude of the relevance effect was smaller over central regions, but remained highly significant, $F(1,252) = 92.29$, $p < .001$. In central regions, the relevance effect was greater over the right hemisphere for both groups (relevance X hemisphere interaction: $F(1,252) = 4.50$, $p < .04$). When all subjects were included, the relevance effects did not interact with group at occipital or central regions at 420 msec.

Occipital and Central DP420 (extreme groups)- There was a trend for severely disabled readers on the GORT deviation score to show a greater relevance effect over central regions than NRD, although this did not reach significance (group X relevance interaction: $F(1,133) = 3.10$, $p = .08$; Figures 17 and 18). This effect was reduced considerably after covarying for verbal intelligence. No group by relevance effects were found in occipital regions.

A significant group X relevance interaction was found comparing normal readers versus subjects severely impaired on the WRAT-R quotient over occipital regions, $F(1,126) = 5.18$, $p < .03$. In this case, subjects with RD showed a reduced relevance effect at 420 msec (Figures 17 and 18). This group difference was no longer significant after covarying for verbal intelligence. No group by relevance interactions were significant over central regions comparing normals and poor readers on the WRAT-R.

Central DN690 (all subjects)- A relevance effect over central regions (greater negativity to relevant stimuli) was greater in the color game (game X relevance interaction: $F(1,252) = 34.09$, $p < .001$; Figures 13 and 14). There was a group difference in the relevance effect at 690 msec over central regions (group X relevance interaction: $F(1,252) = 6.18$, $p < .02$). Counter to prediction based on children, subjects with RD showed a greater relevance effect. This effect was not evident on extreme group comparisons. Due to the inconsistency of this effect and the fact that it was confounded by the reduced negativity evident in the NRD-cont, no further analyses were explored.

Phase II: A posteriori analysis of RD effects at other major ERP components

Relevance Independent Effects:

P150 (all subjects)- Two comparisons reached significance in the overall ANOVA comparing NRD versus RD at 150 msec. The amplitude of P150 was smaller in subjects with RD, an effect evident but not discussed in the Harter et al. study (in press). Here it was more so for the color game (group X game interaction: $F(1,828) = 4.05$, $p < .05$; Figures 3 and 4). This interaction became insignificant after covarying for verbal intelligence. A significant group X electrode interaction, $F(2,828) = 4.42$, $p = .01$, revealed that the difference between the groups was greatest over central regions, regardless of the game. The difference between the groups at central P150 was no longer significant after covarying for verbal intelligence, $F(1,35) = 2.51$, $p = .12$.

P150 (extreme groups)- Based on the GORT deviation score, severely impaired readers showed reduced amplitude P150 over both central and occipital regions but not over frontal regions (group X electrode interaction: $F(2,437) = 7.49$, $p < .001$; Figures 19 and 20). This group effect was no longer significant over occipital regions after covarying for verbal intelligence. In central regions, the group effect also became insignificant after covarying for IQ, $F(1,18) = 2.96$, $p = .10$.

Based on WRAT-R scores, the severely impaired RD had reduced P150 over all electrode locations in both games, $F(1,18) = 5.16$, $p < .04$ (Figures 19 and 20). This effect did not interact with electrode, game, or hemisphere. The group difference was independent of verbal intelligence, $F(1,17) = 5.30$, $p = .03$, after covarying for verbal IQ).

N290 (all subjects)- The ERP's of subjects with RD were significantly more negative at 290 msec, particularly over occipital and central regions (group X electrode interaction: $F(2,828) = 3.39$, $p < .04$; Figures 3 and 4). The group difference over occipital and central regions became insignificant ($p = .23$) after covarying for verbal intelligence.

N290 (extreme groups)- The enhancement of N290 over posterior regions was also evident in both extreme group comparisons (Figures 21 and 22). Poor readers on the Gray Oral showed greater negativity at N290, particularly over occipital and central regions (group X electrode interaction: $F(1,437) = 4.96$, $p < .01$). The effect was reduced to borderline significance in the central region after covarying for verbal intelligence, $F(1,18) = 3.51$, $p < .08$, and became insignificant in the occipital region, $F(1,18) = 2.16$, $p = .16$. The greater negativity at 290 msec in comparisons between WRAT-R impaired versus NRD did not reach significance.

Relevance effects:

DN290 (all subjects)- NRD showed a greater relevance effect at 290 msec (group X relevance interaction: $F(1,828) = 12.16$, $p < .001$; Figures 13 and 14). This group difference was due to greater negativity to irrelevant stimuli for subjects with RD (Figures 11 and 12). This effect was reduced to marginal significance after covarying for verbal intelligence, $F(1,35) = 3.43$, $p = .07$.

There was a significant relevance X game X electrode interaction which did not interact with group, $F(2,828) = 7.17$, $p < .001$. The relevance effect was negative over occipital and central regions, but shifted in polarity over frontal regions. The relevance effect was greater in the letter game (more negative over posterior regions and more positive over central regions). This effect did not interact with group (Figures 13 and 14), with NRD always being more negative than subjects with RD.

DN290 (extreme groups)- Poor readers on the WRAT-R also showed a reduced relevance effect (reduction in the negativity of the difference potential) compared to NRD (group X relevance interaction: $F(1,414) = 4.22$, $p = .04$; Figures 23 and 24). As found in the analysis comparing all subjects, the group difference in DN290 was due to a greater negativity to irrelevant stimuli for RD with no difference between the groups in the neural response to relevant stimuli. The difference in the relevance effect between NRD and RD (poor WRAT-R performers) was no longer significant, $F(1,17) = 3.19$, $p = .09$, after covarying for verbal intelligence. The relevance X group effect did not reach significance comparing NRD and poor readers on the GORT.

Frontal DN400 (all subjects)- There was a significant group X relevance interaction over frontal regions at the peak positivity in the raw waveform (360-380 in the color game and 420-440 in the letter game). NRD showed greater negativity in the difference potentials (Figures 13 and 14). This was due to a greater positivity to irrelevant stimuli for NRD when compared to RD, $F(1,252) = 4.46$, $p < .04$ (Figures 11 and 12). The group difference became insignificant after covarying for verbal intelligence ($p = .26$).

Frontal DN400 (extreme groups)- The difference between NRD and poor readers on the GORT was highly significant (group X relevance interaction: $F(1,133) = 12.36$, $p < .001$; Figures 25 and 26). As in the overall analysis, NRD showed greater positivity to irrelevant stimuli, resulting in greater DN400. The group difference in this extreme group comparison became insignificant after covarying for VIQ, $F(1,18) = 2.20$, $p < .16$. The group difference in frontal DN400 did not reach significance comparing NRD and poor readers on the WRAT-R.

Phase III: Effects related to improvement in reading within RD

Relevance independent factors:

When all subjects with RD were included in the analysis of the relevance independent effects for possible predictors of improvement, none reached significance. This was due to the strong relationship between the amplitude of these effects and childhood reading scores. The variance in the amplitude of central P240 could be explained by the covariate of childhood GORT deficit alone, $F(1,21) = 4.66$, $p < .05$. Childhood WRAT quotients predicted the amplitude of central P150, $F(1,20) = 4.98$, $p < .04$. The ability of childhood scores to predict ERP measures was often borderline in significance, particularly the measures over central regions. Therefore, after covarying for the degree of childhood deficit, adult reading disability did not contribute additional predictive power in terms of the amplitude of the relevance independent effects. No relevance independent effects were related to improvement using an extreme groups method.

Relevance factors:

When looking at the relationship between the relevance effects and adult reading quotients after covarying for childhood deficit, only one factor was significantly related to reading improvement independent of childhood deficit. After covarying for the role of childhood deficit, adult GORT deviation scores predicted the amplitude of the difference potential at DN290, $F(1,21) = 4.42$, $p < .05$ (Figure 23). This effect was present combining across electrodes and hemispheres.

There was a non-significant tendency for improved readers on the GORT to show greater amplitude DP330 in the letter game over occipital regions, $F(1,21) = 2.34$, $p < .14$, even though childhood deficit on the GORT was predictive of the amplitude of DP330 by itself, $F(1,21) = 5.62$, $p < .03$ (Figure 16). Improvement on the WRAT-R was related to enhancement of later relevance effects. There was a suggestion of greater DP420 in improved readers over central regions, $F(1,20) = 3.68$, $p < .07$ (Figures 17 and 18). Although the results of extreme group comparisons followed similar patterns, none reached significance.

Summary of Significant ERP Group Effects

Phase I:

1) Subjects with a history of RD showed a general and sustained reduction in positivity compared to NRD, including the predicted reduction in the late positivity over central regions.

2) Subjects with RD who, as adults, continue to read poorly showed reduced Central P240. This effect was reduced to borderline significance after covarying for Verbal IQ.

3) Extreme group comparisons showed reduced relevance effects at DP330 and DP420 over posterior regions for subjects with RD who read poorly as adults compared to NRD.
This effect became insignificant after covarying for Verbal IQ.

Phase II:

1) RD showed reduced P150, particularly over central regions.

2) RD showed enhanced N290, particularly over occipital and central regions. This effect became insignificant after covarying for Verbal IQ.

3) RD showed a reduced relevance effect at DN290 which was due to greater negativity to irrelevant stimuli compared to NRD. This effect was reduced to borderline significance after covarying for Verbal IQ.

4) RD showed a reduced relevance effect at frontal DN400 which was due to a reduction in the positivity to irrelevant stimuli compared to NRD. This effect became insignificant after covarying for Verbal IQ.

Phase III:

1) The reduction in DN290, that is, the enhancement of the neural response to irrelevant stimuli, was related to improvement in reading on the GORT independent of childhood deficit.

2) Childhood deficit alone often predicted the amplitude of other ERP components which were found to be related to RD in Phase I or II. Specifically, the amplitudes of central P240, central P150, and occipital DP330 could be predicted by childhood deficit alone. Thus, adult reading level often failed to add predictive power, and the hypotheses of neural compensation for childhood deficit at these components could not be confirmed.

CHAPTER IV

DISCUSSION

Behavioral Assessment Results

The most encouraging finding of this study was the favorable outcomes for many of the adult reading disabled subjects in terms of reading improvement, educational attainment, and occupational success. Although field of study and type of employment tended to shift somewhat (away from professional and reading intensive areas toward technical and skilled craftsman), all had finished high school and most had attained some post secondary training. All subjects were gainfully employed. Many subjects showed a marked improvement in reading skills, some now reading within the normal range and others falling only slightly below expectation given their educational background and intelligence. Most read at a functionally adequate level, although the group with RD as a whole remained impaired relative to normal readers from the Orton sample as well as relative to a normal reading control group matched for education and intelligence.

The specificity of the disability in this sample could be questioned. The subjects classified as reading disabled also had difficulty in other areas of achievement, such as math, in childhood. The math problems were not, however, as pervasive or severe. Over half of the subjects with RD scored within normal limits on math tests. One could still argue that at least some of these subjects had a more generalized learning disability. Unfortunately, problems in reading alone can impair one's ability to perform math operations and thus impede progress in this area. As mentioned in the introduction, severe reading disability often results in more generalized academic failure since reading is fundamental to the acquisition of other skills. Mrs. Orton recognized this relation and often labeled the math problems of a child as secondary. Most of the subjects in this study were diagnosed by her as having a specific reading disability or at least language disability. She often predicted that math ability would improve when the child underwent tutoring in reading alone with no emphasis on math skills. This was indeed often the case. Such improvement is further supported by the lack of any pairwise differences in adult arithmetic achievement between the groups. Although a larger sample may shed light on any fine differences between those that have secondary math problems and those that do not, this sample was felt to be representative of individuals with primary reading problems.

The marked improvement in reading skills is inconsistent with most outcome studies in the literature as reviewed by Schonhaut and Satz (1983). The few studies to report favorable outcomes have evaluated subjects from upper socioeconomic strata. Individuals in this sample would fit into this category. However, even though childhood SES was marginally related to adult reading quotients in this study, it failed to predict reading improvement after taking into account the severity of the reading disability in childhood. This emphasizes the need for comparing childhood and adult scores in any outcome study.

The favorable outcome is consistent with two other follow-up studies in the literature, both of which involved subjects taught by the Orton-Gillingham method. This technique uses a phonics approach to remediation. Kline and Kline (1975) reported a 95 percent reading improvement rate while Rawson (1968) also described a favorable prognosis in terms of occupational and educational attainment using these techniques. Since the majority of the subjects in this study were tutored by Mrs. Orton or her associates who also used a phonics approach to remediation, this study supports a favorable outcome for subjects taught by a phonics method.

However, it remains a consideration that this sample is not typical of the normal population. As noted earlier, families were primarily in the upper SES categories, very motivated, and financially able to seek help. All subjects were referred to this special clinic, and most were seen after a number of years of schooling. As noted in the results section, it was often difficult to assess the exact nature and extent of the educational services a subject received or other possible contributing factors, such as attentional or emotional problems. In as much as these variables were identifiable, however, they did not appear to play a role in reading outcome or degree of reading improvement.

One heretofore unreported and troublesome finding of this study is the drop in IQ scores from childhood to adulthood in reading disabled subjects. Although the number of subjects in the Orton group without RD was not sufficient to verify a significant difference between the groups, the trend for subjects with RD to show a greater drop in intelligence was evident. The significant correlation between loss of performance IQ and adult reading deficit suggests that the most severely impaired readers showed a disproportionate loss in nonverbal skills from childhood to adulthood. These findings are inconsistent with previous studies which have reported stable IQ scores from childhood to adulthood (e.g., Frauenheim & Heckerl, 1983).

The drop in intelligence would be easily interpreted if it were limited to verbal IQ given that these subjects drifted from verbal intensive fields of study and employment. However, the drop was primarily in performance IQ which should tap areas of strength rather than weakness. As mentioned, the drop in performance IQ was correlated with adult reading deficit on the Gray Oral Reading Test (GORT). One possible explanation is that the GORT is a timed test, and subjects who score poorly may have adopted a more careful, less assured, and therefore slower approach to problem solving. This is consistent with the reports in the literature (Finucci et al., 1984) and the findings of this study which document a residual deficit in adult dyslexics on timed oral reading tests.

Test of Hypothesis 1

The first hypothesis testing the viability of the developmental lag hypothesis was supported by the behavioral results of this study. Within RD, the most severely impaired readers in childhood made the greatest advancement in reading. Thus, the poorest readers did "catch up" the most in terms of behavioral performance. Although the negative correlation between childhood deficit and reading improvement supported the developmental lag hypothesis, an alternative explanation should be considered. The significant correlation may represent regression toward the mean within the group with RD. Such an explanation would not, however, support a deficit hypothesis. If regression toward the mean played a role, one must assume that the extreme scores obtained by the poorest readers did not represent a true deficit but were subject to fluctuation at retest.

Behavioral and Historical Predictors of Improvement

None of the behavioral or historical variables such as family history of reading disability, attentional problems in childhood, or SES predicted reading improvement. The role of emotional problems, broken homes, or a history of medical problems could not be assessed due to the low incidence of occurrence. This was in part due to careful initial screening to eliminate severe emotional, attentional, or medical problems. Even though individuals with major problems in these areas were excluded, many subjects reported general feelings of inferiority, insecurity, and frustration. After interviewing adults who have suffered from reading problems, one gains an appreciation for the emotional as well as academic ramifications such a disorder has on an individual. It is without doubt that further studies investigating this issue rather than controlling for it would aid in our understanding of dyslexia. Finally, since most of the subjects were tutored using the same phonics approach and since the amount of tutoring was difficult to quantify, the role of type and amount of remediation in improvement remains unanswered.

Thus, no clearcut behavioral or historical predictors of improvement were found outside of the severity of the reading deficit in childhood. In view of this, identifying electrophysiological correlates of reading improvement would be informative. The discovery of markers of RD and compensatory mechanism(s) would be of diagnostic benefit even if no physiological correlates of improvement were found. Since the task is simple and easily administered to even young preschool children, such identification via physiological correlates would be possible even at pre-reading ages. An understanding of the compensatory strategies in adults could have implications for remediation.

ERP Behavioral Results

Subjects with RD made fewer Hits than those without RD in the letter game only. This suggests that the subjects with RD had more difficulty discriminating simple letter stimuli. However, there was no difference between the groups in the number of Hits in the color game, even though group differences in the ERP waveforms were evident in this game as well. The percentage of False Alarms and overall accuracy did not differ between the groups on either game. There was also no difference between the groups in terms of speed of response or in number of trials to criterion. Therefore, any differences in their ERP waveforms cannot be attributed to differences in behavioral performance on the tasks.

Test of Hypothesis 2

Hypothesis 2 predicted that the ERP waveforms of subjects with RD would be different from those with no history of RD. Both a priori and a posteriori findings supported this hypothesis. Even individuals with RD who have improved their reading skills by adulthood showed differences in neural processing compared to those with no history of RD. All subjects with RD showed a general reduction in positivity starting at 150 msec, well before the initiation of the behavioral response. This was true across both hemispheres which is inconsistent with researchers who have proposed lateralized deficit based on adult models of alexia (Benton & Pearl, 1978). Even supporters of the developmental lag hypothesis have proposed a lateralization to the lag in brain maturation (Satz & Fletcher, 1980; Satz et al., 1974; Satz & Van Nostrand, 1973). Harter et al. (in press) found lateralized deficits in children. However, the generalized reduction in brain physiology in adults is consistent with bilateral physiological deficit in reading disability.

This study served to replicate several of the specific effects found in the Harter et al. (in press) studies. The a priori hypothesis of attenuated amplitude of P240 was supported. The amplitude of this component was significantly correlated with adult reading. Adults who still suffer from reading problems showed significantly reduced P240 compared to normal readers. The difference between normals and the combined dylexic group did not reach significance, suggesting that the amplitude of central P240 was greater in improved readers. The finding that childhood deficit predicted the amplitude of central P240 suggests that the amplitude of this component may be a marker of reading improvement. That is, the larger central P240, the better the prognosis for improvement in reading skills. The replication of attenuated central P240 as a marker of RD using adults twenty or more years older than the sample of Harter et al. is truly remarkable. The stability of this component and its relation to reading disability is strongly supported by this replication. Although verbal IQ was implicated in the analyses of covariance, its ability to totally explain the difference between the groups is unclear.

One important difference in the characterization of attenuated P240 found in this study should be noted. Unlike the Harter et al. study, the effect was bilateral in nature for adults rather than lateralized to the left hemisphere as found for children. One possible explanation for this difference is that those with bilateral temporal lobe deficits in childhood do not improve as much as those whose deficit is restricted to the left hemisphere. In childhood, a unilateral left hemisphere deficit alone may be sufficient to result in impaired reading on behavioral tests. Thus, children with unilateral left hemisphere impairment, as well as those with bilateral involvement, will present with reading difficulty. The children with bilateral involvement will remain more impaired in adulthood. This could be addressed by examining the childhood data. If some have unilateral and others bilateral deficits, one should find greater variance in the amplitude of central P240 over the right hemisphere compared to central P240 over the left hemisphere within the group of children with RD. Those with unilateral deficit should show a right central P240 similar to NRD while those with bilateral involvement should show an attenuation of right central P240. This would result in greater variance of right central P240. If this were the case, the amplitude of right central P240 in childhood may be a predictor of adult reading level.

The bilateral nature of the deficit in adults is consistent with the findings of Geschwind and Galaburda (1985) who reported bilateral temporal lobe anomalies in severely impaired adult dyslexics at autopsy. If the relationship between right hemisphere involvement and severity of adult deficit is viable, less severely impaired adults should have more lateralized structural anomalies at autopsy.

These data also support the a priori hypothesis of reduced late positivity over central regions found by Harter et al. as well as other authors. However, in adults, the reduction in positivity extended more anteriorly, involving frontal areas as well. Thus, unlike children who showed an increase in positivity over frontal regions, these subjects showed a general reduction in the amplitude of the late positive component which extended over a wider cortical area. The right hemisphere involvement again suggests a bilateral deficit. In the case of this reduced late positivity at 400 msec, verbal IQ played a role, but clearly could not fully explain the effect of RD.

This study also replicated the relevance effects found by Harter et al. (in press) in the positivity ranging between 300 and 450 msec. Severely impaired adult dyslexics showed a reduced relevance effect at

P330 over occipital and central regions. No group differences in hemispheric asymmetry were evident, all subjects showing a greater relevance effect over the right hemisphere similar to what Harter et al. found in children without RD. The adult group difference in the relevance effect was clearly related to intelligence. Consistent with the relevance independent effects, the group difference in the relevance effect between adults with and without RD was more diffuse than that found in children.

Hypotheses regarding differences in the late negativity (DN690) were confounded by a difference in the NRD-cont. They showed an attenuation of the late negative component compared to both Orton groups. This was not related to the presence or absence of reading disability nor to intelligence. The most likely explanation was a difference in motivational level. On the one hand, these subjects were volunteers who were not being provided with feedback regarding childhood and adult test results. They participated primarily for the monetary compensation. Orton subjects, on the other hand, were typically less interested in the financial compensation but more concerned with receiving feedback regarding personal results and information about the project in general. In that no differences were evident between the two normal groups at earlier latencies, this was unlikely to have played a role in the interpretation of those components.

In addition to replicating some of Harter's findings, this study generated some new hypotheses regarding cortical deficit in dyslexia. Although the interpretation of these results must remain guarded until further replication, a few points are worth noting. Harter et al. did not report an effect at occipital and central P150. Inspection of the graphs presented in the paper is suggestive of such an effect. Previous studies (Conners, 1971; Preston et al., 1977) also found differences at or close to this latency.

The Preston et al. study is the only study known to this author that studied adult dyslexics. These authors studied nine subjects from the Finucci (1974) sample, the work that generated the deviation formulae used in this study. Preston et al. found differences in the P200 and late positive components over left parietal regions. RD subjects showed smaller ERP's to words versus flashes while normals showed larger response to words in the left parietal region.

As mentioned earlier, the difference in the late positivity was replicated in this study (reduced central relevance independent P400). However, in the present study the effect was more diffuse in cortical distribution, extending bilaterally and more anteriorly as well. The effect at P200 found by Preston et al. could represent the same component as the one in this study at P150 since the interstimulus interval (ISI) was longer in the Preston et al. study (2 sec). A longer ISI reduces the time constraints which in turn can shift the latency of an ERP component. Preston et al. interpreted the differences between RD and NRD in the amplitude of P200 as reflecting differences in the way the two groups processed written materials. They did not look at relevance effects per se.

In the present study, the P150 effect was bilateral in nature and extended over occipital as well as central regions. Also, it was found in the color game. This does not support the hypothesis that differences at these latencies were related purely to the processing of written information. An alternative interpretation would be a deficit in early visuospatial processing in posterior regions. This is supported by the finding that this effect is relatively independent of verbal IQ.

The reduced positivity (or increased negativity) at 290 msec could be the same as that reflected by attenuated P240, yet the N290 effect was significant comparing all subjects with RD to normals whereas the P240 effect was not. One possibility is that this represents enhanced negativity rather than reduced positivity. Enhanced negativity could reflect a means of compensation in adults with RD for the earlier deficits in processing at 150 and 240 msec. This will be discussed later in the section discussing compensation (test of Hypothesis 4).

NRD showed greater frontal positivity to irrelevant stimuli compared to RD. This was not an a priori hypothesis, yet is theoretically appealing given our knowledge of localization of brain function. There is ample evidence in the literature that the frontal lobes play a regulatory or modulatory role in cortical activation. The frontal activation to irrelevant stimuli for normals may relate to the inhibition of a behavioral response. If true, the findings of this study would suggest that the frontal lobes of adult subjects with RD are less active in the inhibition of the behavioral response to the irrelevant stimulus. The enhancement of N290 for RD was primarily to irrelevant stimuli. Since RD did not make more False Alarms, perhaps the enhanced N290 to irrelevant stimuli served as a compensation for the frontal deficit in addition to, or rather than, reflecting a compensation for earlier deficits in processing.

Test of Hypothesis 3

Hypothesis 3 stated that RD could be the result of both a sustained deficit in some subjects and developmental lag in other subjects. As mentioned earlier, the developmental lag hypothesis was supported behaviorally and the deficit hypothesis was supported electrophysiologically. The absence of electrophysiological data on these subjects in childhood prevented a direct test of the developmental lag hypothesis from an electrophysiological standpoint. However, based on Harter et al.'s findings in children, one can speculate as to possible physiological changes from childhood to adulthood for the present sample. Given that the subjects in this study were all reading disabled in childhood, one could assume that they would have shown similar electrophysiological results to those of the children in the Harter et al. study if such data had been collected. If that were the case, improved readers have changed on many of the electrophysiological measures found to be related to RD in children. This change was often in the direction of normality. As noted earlier, the amplitude of central P240 is correlated with reading deficit. Improved readers show greater central P240, similar to NRD. The trend of a shift toward ERP's that look like NRD is also evident for occipital DP330 in the letter game as well as the greater P150, a trend evident but not reported by Harter et al. for children.

In general, subjects with RD do not "catch up" behaviorally as has been proposed by some defenders of the maturational lag hypothesis, although some certainly do make advances. Often, reading improvement is correlated with physiological measures found to be related to RD in children, such that improved readers look more like NRD. Still, physiological differences between RD and NRD remain evident. A theory which proposes an interaction of developmental lag and deficit factors offers the most comprehensive explanation. There appears to be an underlying deficit in dyslexia, the severity of which determines the degree to which individuals can "catch up." Given this framework, behavioral acquisition of skills and physiological changes often follow a normal though delayed pattern of development. Other physiological changes may serve to compensate, perhaps to supplement normal maturation when it ceilings. This would be consistent with proposals that RD subjects reach a "premature plateau" in language development (Mann, 1986). The plateau would be determined by the severity of the underlying brain pathology.

One or more mechanism(s) may be operating from a developmental neurobiological perspective. Perhaps normal reading "experience" is required to "induce" (see Gottlieb, 1983 for review of theory) normal development of reading, but it would probably be an overstatement to regard reading as truly species-wide as well as species-specific. The advantage to an induction model, however, is that it would emphasize not only that reading experience is a necessary condition for the full development of the neurological substrate of reading, but also that this neurological development--induced by experience--is essential to certain other high level cognitive skills as well. A possible mechanism for induction is that experience may serve to provide the cellular competition required for normal cell death which results in the adaptive "pruning" required for normal brain function. If individuals with RD suffer from a neural deficit which disrupts the experiential inductive process, the behavioral endpoint of development would be lower than that of normal readers.

Another possibility is that normal reading experience is required only for maintenance of cortical integrity, not for actual induction of the relevant skills. Those unable to benefit from such experience may show a "failure to thrive" syndrome with some loss of ability over time. Such a notion would be supported by the apparent loss in intelligence which is related to the degree of deficit. However, if the neural deficit determines a premature plateau, and if that plateau had not been reached in childhood, the apparent loss could be explained by a ceiling effect in adulthood which was not yet evident in childhood. These alternative hypotheses could be tested by examining these subjects ten years from now. If no changes were observed, the premature plateau hypothesis would be supported. If a further decline was found, a failure to maintain coupled with a degenerative process would be indicated.

Test of Hypothesis 4

The fourth hypothesis addressed the possibility that subjects may compensate for a neural deficit and thus improve in their reading skills. Testing the hypotheses of changes in ERP's related to improvement in reading proved difficult. This was primarily due to the high correlation between the physiological markers of RD in adults and childhood reading deficit. The degree of disability in childhood accounted for a large proportion of the variance in the amplitude of components at 150, 240, and 330 msec. Adult deficit often failed to add significant predictive power after covarying for childhood deficit.

The sole electrophysiological component related to improvement in reading independent of childhood deficit was the relevance effect at 290 msec. Improved readers on the GORT had reduced relevance effects at N290. In other words, they showed greater negativity to irrelevant stimuli (which results in a more positive difference potential). The enhanced negativity to irrelevant stimuli could represent a compensation for the earlier deficits in processing at 150 and 240 msec. Perhaps this enhanced negativity to irrelevant stimuli reflects more extensive evaluation of stimuli before initiating a behavioral response. In the literature, this decision process has been linked to the positive component between 300 and 500 msec (generally referred to as P300). In this study, the late positivity occurred around 400 msec.

Another possibility is that enhanced N290 to irrelevant stimuli across all electrodes serves to compensate for reduced frontal activation to irrelevant stimuli at 400 msec compared to NRD. In either case, it suggests that a compensatory mechanism which is widely distributed (found at all electrode locations) is serving to compensate for a more localized deficit related to RD (earlier deficits in posterior areas and/or later deficits in frontal areas).

Since enhanced negativity to irrelevant stimuli was not an a priori hypothesis, it demands further replication before any firm conclusions can be drawn. If replicated, this could reflect an alternate strategy adopted by some subjects with RD which is not typical of NRD, as represented by the present sample. However, the finding that verbal intelligence accounted for a large portion of the variance would suggest that the potential for this strategy to compensate for a reading deficit may be limited by the person's intelligence.

Summary of the Conclusions

In summary, the deficits in brain function found in the present study of adults with a history of RD are bilateral in nature and therefore inconsistent with much of the literature suggesting focal left hemisphere dysfunction. There is evidence to suggest that the degree of improvement is related to the severity and perhaps the bilaterality of the brain dysfunction in childhood. This is supported not only by the ERP waveforms but in the drop in performance IQ from childhood to adulthood which was correlated with reading deficit in adulthood. Nonverbal skills have been linked with right hemisphere functioning. Thus, adults who remain poor readers appear to have suffered disproportionate loss of right hemisphere skills. This is consistent with the bilaterality of the ERP deficits in adults with RD, particularly the P240 and P400 components compared to the lateralized left hemisphere deficit found in children by Harter et al. Improvement may be linked more to the integrity of right hemisphere functioning than to the degree of deficit in the left hemisphere.

Many of the event related potential findings in this study were reduced in significance or became insignificant after covarying for verbal intelligence. This is not surprising given the evidence that intelligence and reading ability are not independent, that is, poor reading ability is related to IQ loss. It would be more surprising if intelligence did not account for some of the variance in the ERP waveforms given the generalized reduction in cortical activation found in subjects with a history of reading disability. It is without doubt that the impact of RD extends well beyond reading ability alone. Further delineation of the more global behavioral deficits associated with RD is a matter for future research.

Further replication is suggested on additional subjects from this Orton population to establish the validity of these findings. The role of attentional and emotional problems should be addressed rather than controlled for as more subjects are studied. Replication of these findings using other physiological methodologies (such as regional cerebral blood flow) on the same subjects would help to further delineate the nature and extent of the cortical dysfunction in dyslexic individuals as well as adding to our knowledge of compensatory strategies in improved readers.

BIBLIOGRAPHY

Ackerman PT, Dykman RA & Peters JE. Teenage status of hyperactive and nonhyperactive learning-disabled boys. American Journal of Orthopsychiatry, 1977, 47, 577-596.

Aman MG. Psychotropic drugs in the treatment of reading disorders. In RN Malatesha and PG Aaron (Eds.), Reading disorders: varieties and treatments. New York: Academic Press, 1982, 453-471.

Bakker DJ, Licht R, Kok A & Bouma A. Cortical responses to word reading by right- and left-eared normal and reading-disturbed children. Journal of Clinical Neuropsychology, 1980, 2, 1-12.

Balow B & Blomquist M. Young adults ten to fifteen years after severe reading disability. Elementary School Journal, 1965, 66, 44-48.

Benson DF, Brown J & Tomlinson EG. Varieties of alexia. Neurology, 1971, 21, 951-957.

Benson DF, & Geschwind NJ. The aphasias and related disturbances. In AB Baker & LH Baker (Eds.), Clinical Neurology (Vol. I). New York: Harper & Row, 1975.

Benton AL, & Pearl D. Dyslexia: an appraisal of current knowledge. New York: Oxford University Press, 1978.

Boder E & Jarrico S. The Boder test of reading-spelling patterns. New York: Grune and Stratton, 1982.

Briggs GG & Nebes RD. Patterns of hand preference in a student population. Cortex, 1975, 11, 230-238.

Cohen J. Cerebral evoked responses in dyslexia children. In: HH Kornhuber and L Deecke (Eds.). Motivation, motor and sensory processes of the brain. New York: Elsevier, 1980, 502-506.

Conners CK. Cortical visual evoked response in children with learning disorders. Psychophysiology, 1970, 7, 418-428.

Cromwell RL, Blashfield RK & Strauss JS. Criteria for classification systems. In: N Hobbs (Ed.). Issues in the classification of children: a source book on categories, labels and their consequences. San Francisco: Jossey-Bass, 1975, 4-25.

Danier KB, Klorman R, Salzman LF, Hess DW, Davidson PW & Michael RL. Learning-disordered children's evoked potentials during sustained attention. Journal of Abnormal Child Psychology, 1981, 9, 79-94.

Diagnostic and Statistical Manual of Mental Disorders (Third Edition). Washington, D.C.: The American Psychiatric Association, 1980.

Duffy FH, Denckla MB, Bartels PH, & Sandini B. Dyslexia: regional differences in brain electrical activity by topographical mapping. Annals of Neurology, 1980, 7, 412-420.

Duffy FH, Denckla MB, Bartels PH, Sardini G & Kiessling LS. Dyslexia: automated diagnosis by computerized classification of brain electrical activity. Annals of Neurology, 1980, 7, 421-428.

Eason RE, Harter MR & White CT. Effects of attention and arousal on visual evoked cortical potentials and reaction time in man. Physiological Behavior, 1969, 4, 283-289.

Endicott, J & Spitzer RL. A diagnostic interview: the schedule for affective disorders and schizophrenia. Arch. Gen. Psychiatry, 1978, 35, 837-844.

Felton RH, Wood FB, Harter MR, Brown IS, & Campbell SK. Seperate verbal memory and naming deficits in attention deficit disorder and reading disability. Under editorial review, Brain & Cognition.

Fenelon B. Expectancy waves and other complex cerebral events in dyslexic and normal subjects. Psychonomic Science, 1968, 13, 253-254.

Finucci JM. Follow-up studies of developmental dyslexia and other learning disabilities. In S Smith (Ed.), Genetics and learning disabilities. San Diego: College-Hill Press, Inc., 1986,

Finucci JM, Gottfredson LS & Childs B. A follow-up study of dyslexic boys. Annals of Dyslexia, 1985, 35, 117-136.

Finucci JM, Whitehouse CC, Isaacs SD & Childs B. Derivation and validation of a quantitative definition of specific reading disability for adults. Developmental Medicine & Child Neurology, 1984, 26, 143-153.

Frauenheim JE & Heckerl JR. A longitudinal study of psychological and achievement test performance in severe dyslexic adults. Journal of Learning Disabilities, 1983, 16, 339-347.

Fried I, Tanguay PE, Boder E, Doubleday C & Greensite M. Developmental dyslexia: electrophysiological evidence of clinical subgroups. Brain and Language, 1981, 12, 14-22.

Galaburda AM. Developmental dyslexia: a review of biological interactions. Annals of Dyslexia, 1986, 35, 21-33.

Galaburda AM, Sherman GF, Rosen GD, Aboitiz F & Geshwind N. Developmental dyslexia: four consecutive patients with cortical anomalies. Annals of Neurol., 1985, 18, 222-233.

Golden GS. Neurobiological correlates of learning disabilities. Annals of Neurology, 1982; 12, 409-418.

Gottlieb G. The psychobiological approach to developmental issues. In P Mussen (Ed.), Handbook of child psychology: Vol. 2. Infancy and developmental psychobiology. New York: John Wiley & Sons, 1983, 1-26.

Gray WS. Standardized oral reading paragraphs. Indianapolis: Bobbs-Merrill Co., Inc., 1955.

Harter MR & Aine CJ. Brain mechanisms of visual selective attention. In R Parasuraman & DR Davies (Eds.), Varieties of attention. New York: Academic Press, 1984, 293-321.

Harter MR, Aine C & Schroeder C. Hemispheric differences in the neural processing of stimulus location and type: effects of selective attention on visual evoked potentials. Neuropsychologia, 1982, 20, 421-437.

Harter MR & Guido W. Attention to pattern orientation: negative cortical potentials, reaction time, and the selection process. Electroencephalography and Clinical Neurophysiology, 1980, 49, 461-475.

Harter MR & Previc FH. Size-specific information channels and selective attention: visual evoked potential and behavioral measures. Electroencephalography and Clinical Neurophysiology, 1978, 45, 628-640.

Harter MR & Salmon LE. Intra-modality selective attention and evoked cortical potentials to randomly presented patterns. Electroencephalography and Clinical Neurophysiology, 1972, 32, 605-613.

Harter MR, Wood FB & Diering S. Reading disability with and without attention deficit disorder: brain potential indicants. Under editorial review, Brain and Cognition.

Harter MR, Wood FB & Marvin-Schroeder E. Reading disability with and without attention deficit disorder: selective neural processing of color and letters. Under editorial review, Brain and Cognition.

Hobbs N. The futures of children. San Francisco: Jossey-Bass, 1974, 19-41.

Hollingshead AB. Four factor index of social status. Unpublished manuscript, 1975. (Available from PO Box 1965 Yale Station New Haven, Connecticut 06520).

Horn WF, O'Donnell JP, & Vitulano LA. Long-term follow-up studies of learning disabled persons. Journal of Learning Disabilities, 1983, 16, 542-555.

Jastak J & Bijou S. Wide range achievement test. Wilmington: Jastak Associates Inc., 1946.

Jastak J & Wilkinson GS. Wide range achievement test - revised edition. Wilmington: Jastak Associates Inc., 1984.

John ER. Neurometric evaluation of brain dysfunction related to learning disorders. Acta. Neurological Scand., 1981, 89, 21-29.

John ER, Prichep L, Ahn H, Easton P, Fridman J & Kaye H. Neurometric evaluation of cognitive dysfunctions and neurological disorders in children. Prog. Neurobiol., 1983, 21, 239-290.

Johnstone J, Galin D, Fein G, Yingling C, Herron J & Marcus M. Regional brain activity in dyslexic and control children during reading tasks: visual probe event-related potentials. Brain and Language, 1984, 21, 233-254.

Kelley TL, Madden R, Gardner EF, Terman LM & Ruch GM. Stanford achievement test. 1958.

Kinsbourne M. The role of selective attention in reading disability. In: RN Malatesha and PG Aaron (Eds.), Reading disorders: varieties and treatments. New York: Academic Press, 1982, 199-214.

Kline C & Kline C. Follow-up study of 211 dyslexic children. Bulletin of the Orton Society, 1975, 25, 127-144.

Kooi, KA. Letter to the editor. Psychophysiology, 1972, 9, 154.

Ludlam WM. Visual electrophysiology and reading/learning difficulties. Journal of Learning Disabilities, 1981, 14, 587-590.

Money J. On learning and not learning to read. In J. Money (Ed.), The disabled reader: education of the dyslexic child. Baltimore: Johns Hopkins Press, 1966, 21-40.

Musso MF and Harter MR. Visually evoked potentials and selective masking with patterned flashes of different spatial frequencies. Vision Res., 1975, 15, 231-238.

Naylor CE & Harter MR. Event-related potential (ERP) and behavioral measures of shape and letter-meaning matching in reading disabled and normal children. Paper presented at the meeting of the International Neuropsychological Society, San Diego, February 1985.

Neville H. Event-related potentials in neuropsychological studies of language. Brain and Language, 1980, 11, 300-318.

Ornstein R, Herron J, Johnstone J & Swencionis C. Differential right hemisphere involvement in two reading tasks. Psychophysiology, 1979, 16, 398-401.

Preston MS. The use of evoked response procedures in studies of reading disability. In: H. Begleiter (Ed.), Evoked brain potentials and behavior. New York: Plenum Press, 1979, 247-268.

Preston MS, Guthrie JT & Childs B. Visual evoked responses (VERs) in normal and disabled readers. Psychophysiology, 1974, 11, 452-457.

Preston MS, Guthrie JT, Kirsch I, Gertman D & Childs B. VERs in normal and disabled adult readers. Psychophysiology, 1977, 14, 8-14.

Rawson M. Developmental language disability: adult accomplishments of dyslexic boys. Baltimore: The Johns Hopkins Press, 1968.

Satz P & Fletcher JM. Minimal brain dysfunctions: an appraisal of research concepts and methods. In: H Rie & E. Rie (Eds.), Handbook of minimal brain dysfunction: a critical view. New York: Wiley Interscience Press, 1980, 669-714.

Satz P, Friel J & Rudegeair F. Differential changes in the acquisition of developmental skills in children who later become dyslexic. In: DG Stein, JJ Rosen & N Butters (Eds.), Plasticity and recovery of function in the central nervous system. New York: Academic Press, 1974, 175-202.

Satz P, Taylor HG, Friel J, & Fletcher JM. Some developmental and predictive precursors of reading disabilities: a six year follow-up. In: AL Benton and D Pearl (Eds.), Dyslexia: an appraisal of current knowledge. New York: Oxford University Press, 1978, 313-347.

Satz P & Van Nostrand GK. Developmental dyslexia: an evaluation of a theory. In: P Satz & JJ Ross (Eds.), The disabled learner: early detection and intervention. Rotterdam, The Netherlands: Rotterdam University Press, 1973, 212-248.

Schonhaut S & Satz P. Prognosis for children with learning disabilities: a review of follow-up studies. In M Rutter (Ed.), Developmental Neuropsychiatry. New York: Guilford Press, 1983.

Sobotka KR & May JG. Visual evoked potentials and reaction time in normal and dyslexic children. Psychophysiology, 1977, 14, 18-24.

Sobotowicz WS & Evans JR. Cortical dysfunctioning in children with specific reading disability. Springfield, Ill: Charles C. Thomas, 1982.

Spreen O. Adult outcomes of reading disorders. In: RN Malatesha & PG Aaron (Eds.), Reading disorders: varieties and treatments. New York: Academic Press, 1982, 473-498.

Symann-Louett N, Gascon GG, Matsumiya Y & Lombroso CT. Wave form differences in visual evoked responses between normal and reading disabled children. Neurology, 1977, 27, 156-159.

Thompson J, Ross R & Horowitz S. The role of computed axial tomography in the study of the child with minimal brain dysfunction. Journal of Learning Disabilities, 1980, 13, 48-51.

Van Voorhis S & Hillyard SA. Visual evoked potentials and selective attention to points in space. Percept. Psychophys., 1977, 22, 54-62.

Weber BA & Omenn GS. Auditory and visual evoked responses in children with familial reading disabilities. Journal of Learning Disabilities, 1977, 10, 153-158.

Wechsler D. Manual for the Wechsler intelligence scale for children. New York: Psychological Corporation, 1949.

Wechsler D. Manual for the Wechsler adult intelligence scale - revised. New York: The Psychological Corporation, 1981.

APPENDIX A

Tables 1 - 10

TABLE 1

Intelligence and Achievement Variables for RD and NRD Samples at Orton Childhood Evaluation.

	RD			NRD		
	x age = 13.8 x grade level = 7.8			x age = 14.1 x grade level = 9.0		
Intelligence[a]	x	sd	range	x	sd	range
VIQ	106.92	(11.47)	91-134	121.13	(5.08)	115-131
PIQ	107.46	(11.47)	84-127	111.87	(6.58)	103-120
FSIQ	107.29	(9.56)	93-125	118.75	(4.10)	115-128

Achievement[b]	RD x	RD range	NRD x	NRD range
Gray Oral	4.8	1.0- 9.3	9.8	5.1-12.0
WRAT Reading	5.8	2.4-10.3	10.3	4.7-13.0
WRAT Spelling	4.7	1.9- 7.4	9.3	3.8-12.8
WRAT Arithmetic	6.0	3.6- 9.3	10.9	4.5-17.4

[a] Scores reported are from the WISC or WAIS.

[b] Scores reported are grade equivalents expressed in years and months.

TABLE 2

Achievement Quotients at Childhood Evaluation for RD and NRD-ort Samples

	Value of Quotient				
	≤.60	.61-.70	.71-.80	.81-.90	≥.90
			RD		
Gray Oral	2	11	9	2	0
WRAT Reading	1	4	12	4	2
WRAT Spelling	4	7	11	2	0
WRAT Math	1	5	3	8	5
			NRD-ort		
Gray Oral	0	0	0	0	7
WRAT Reading	0	0	0	3	5
WRAT Spelling	0	0	0	0	7
WRAT Math	0	0	0	1	3

Note: Missing data accounts for differences in column totals.

TABLE 3

Means and Standard Deviations of Predictor and Achievement Variables for Orton RD and NRD, NRD Control and Finucci's Regression Sample

	Orton RD (n = 24)		Orton NRD (n = 8)		Control NRD (n = 6)		Regression[a] (n = 46)	
	x	(sd)	x	(sd)	x	(sd)	x	(sd)
Predictor Variables								
Age	33.87	(5.71)	36.01	(3.70)	33.88	(4.43)	37.88	(11.34)
Education[b]	15.54	(1.96)	17.75	(1.49)	15.00	(2.24)	16.07	(2.48)
Verbal IQ[c]	101.04	(10.34)	115.87	(8.49)	103.00	(4.65)	122.67	(10.55)
Performance IQ	100.79	(9.32)	112.25	(11.57)	105.83	(9.79)	116.98	(11.82)
Full Scale IQ	100.63	(9.58)	115.75	(8.35)	104.33	(7.42)	not given	
Achievement Variables								
Gray Oral Score	60.25	(15.58)	94.00	(3.55)	86.00	(6.26)	85.09	(11.94)
WRAT Spelling Words Correct	17.17	(7.36)	37.13	(2.36)	31.00	(8.47)	33.28	(7.18)

[a] Source: Finucci, et al., 1984. Data reported are for males only.

[b] Reported as grade equivalents.

[c] Based on WAIS for Regression sample and on WAIS-R for Orton Samples.

TABLE 4

Achievement Deviation Scores Derived Using Finucci's Regression Formulae

	RD			NRD-ORT			NRD-CONT		
	x	(sd)	range	x	(sd)	range	x	(sd)	range
Reading	-1.12	(1.54)	-4.3 to 2.3	1.55	(0.79)	.7 to 2.8	1.66	(0.87)	.1 to 2.7
Spelling	-1.46	(1.15)	-3.0 to 2.8	1.29	(1.36)	-.6 to 3.8	1.38	(1.85)	-1.1 to 2.8
Average Dev. Score	-1.29	(1.23)	-3.5 to 2.0	1.42	(1.04)	.2 to 3.3	1.52	(1.28)	-.4 to 2.8

Note: Deviation Scores represent the difference between expected and obtained scores divided by the standard error of prediction (SEP) using the following Finucci et al., 1984 regression formulae to derive expected scores:
Predicted Gray Oral Score = .696VIQ + 9.296SEX - 9.565; SEP = 8.783 and SEX = 1
Predicted WRAT Spelling = .469VIQ + 6.224SEX - .093PIQ + .4EDUC - 26.059; SEP = 4.626 and SEX = 1

TABLE 5

Percentage Distributions for Six Measures of Reading and Spelling Proficiency Obtained at Initial and Follow-up Testings

	Childhood Testing			Adult Testing		
	Reading Quotient (Gray Oral)	Spelling Quotient (WRAT)	Reading Quotient (WRAT)	Reading Dev. Score (Gray Oral)	Spelling Dev. Score (WRAT-R)	Reading Quotient (WRAT-R)
Severity Level	RD					
Deficient	91.7 (22)	91.7 (22)	74.0 (17)	29.2 (7)	33.3 (8)	25.0 (6)
Borderline	8.3 (2)	8.3 (2)	17.3 (4)	29.2 (7)	37.5 (9)	41.7 (10)
Normal	00.0	00.0	8.7 (2)	41.6 (10)	29.2 (7)	33.3 (8)
	NRD-ort			NRD-combined		
Deficient	00.0	00.0	00.0	00.0	00.0	7.7 (1)
Borderline	00.0	37.5 (3)	00.0	00.0	7.7 (1)	00.0
Normal	100.0 (7)	62.5 (5)	100.0 (8)	100.0 (14)	92.3 (13)	92.3 (13)

Note: Categorization systems for initial and follow-up data are different and may not be directly comparable. Figures in parentheses are base <u>N</u>s for the adjacent percentages. Gray Oral Scores for one NRD-ort and WRAT scores for one RD subject were not available at initial testing. NRD-combined (N = 14) includes NRD-ort and NRD-cont subjects.

TABLE 6

WRAT-R Standard Scores for RD and NRD Samples at Adult Follow-up Evaluation

	RD			NRD-ORT			NRD-CONT		
	x	(sd)	range	x	(sd)	range	x	(sd)	range
Reading	85.00	(11.65)	62-102	112.88	(3.76)	105-118	96.83	(10.94)	80-112
Spelling	78.29	(12.60)	57-105	111.63	(4.03)	108-120	101.50	(15.74)	76-115
Arithmetic	92.96	(11.05)	73-118	104.25	(5.68)	97-114	102.67	(18.78)	74-127
Reading Quotient	84.54	(9.46)	69-110	98.19	(8.05)	87-111	93.37	(13.14)	68-108

Note: Reading Quotient = $\frac{\text{WRAT-R Reading Standard Score}}{\text{WAIS-R Full Scale IQ Score}}$

TABLE 7

Educational Outcomes for RD and NRD Subjects

Educational Attainment	RD N	RD (%)	NRD-ort N	NRD-ort (%)	NRD-Cont N	NRD-Cont (%)
High School Dropout	0		0		1	(16.7)
High School Graduate	3	(12.5)	0		1	(16.7)
High School and Some College Or Technical Training	7	(29.2)	0		2	(33.3)
Technical or Associates Degree	6	(25.0)	0		1	(16.7)
Bachelor's Degree	5	(20.8)	6	(75.0)	1	(16.7)
Master's Degree	3	(12.5)	1	(12.5)	0	
Doctoral Degree	0		1	(12.5)	0	

Fields of Study[a]	RD N	RD (%)	NRD-ort N	NRD-ort (%)	NRD-Cont N	NRD-Cont (%)
Liberal Arts Social Studies	4	(19.0)	3	(37.5)	1	(25.0)
Math Engineering, Sciences	5	(23.8)	0		0	
Business	3	(14.3)	4	(50.0)	3	(75.0)
Fine Arts	2	(9.5)	1	(12.5)	0	
Vocational	7	(33.3)	0		0	

[a] Percentages calculated on the 21 RD and 4 NRD-cont subjects who received some type of training beyond high school.

TABLE 8

Occupational Outcomes for RD and NRD Subjects and Their Fathers

	RD				NRD-Ort				NRD-Cont			
	Self		Father		Self		Father		Self		Father	
	N	(%)	N	(%)	N	(%)	N	(%)	N	(%)	N	(%)
Professional	2	(8.3)	6	(25.0)	4	(50.0)	4	(50.0)	1	(16.7)	1	(16.7)
Owner/Executive of Business	3	(12.5)	7	(29.2)	3	(37.5)	3	(37.5)	0		2	(33.3)
Managerial	6	(25.0)	4	(16.7)	0		0		2	(33.3)	1	(16.7)
Technical (art, graphics)	4	(16.7)	4	(16.7)	1	(12.5)	1	(12.5)	1	(16.7)	0	
Sales	2	(8.3)	1	(4.2)	0		0		0		0	
Skilled Manual (mechanics)	6	(25.0)	0		0		0		0		1	(16.7)
Semiskilled	1	(4.2)	2	(8.3)	0		0		2	(33.3)	1	(16.7)

TABLE 9

Current and Childhood Socioeconomic Status for RD and NRD Subjects

	RD (N = 24)		NRD-Ort (N = 8)		NRD-Cont (N = 6)	
Social Strata	current N (%)	as child N (%)	current N (%)	as child N (%)	current N (%)	as child N (%)
Major Business and Professional	4 (16.7)	11 (45.8)	3 (37.5)	7 (87.5)	1 (16.7)	1 (16.7)
Medium Business, minor professional technical	11 (45.8)	10 (41.7)	5 (62.5)	1 (12.5)	3 (50.0)	2 (33.3)
Skilled Craftsman, clerical, sales, workers	7 (29.2)	2 (8.3)	0	0	0	1 (16.7)
Machine operators, semiskilled worker	2 (8.3)	1 (4.2)	0	0	0	2 (33.3)
Unskilled laborers, menial service workers	0	0	0	0	2 (33.3)	0

TABLE 10

Behavioral Measures during Event Related Potential Recording

	Reading Disabled		Normal Readers Combined	
	Letter Game	Color Game	Letter Game	Color Game
	X (sd)	X (sd)	X (sd)	X (sd)
Total Score	112.8 (30.0)	127.1 (38.4)	118.3 (52.6)	106.6 (26.7)
Standard Dev. of RT	50.6 (6.5)	51.6 (7.1)	50.2 (6.4)	47.7 (7.9)
% Hits	91.3 (5.5)	96.9 (2.7)	95.5 (4.1)	96.6 (2.7)**
RT Hits	387.7 (23.5)	336.5 (35.0)	390.0 (19.4)	333.6 (26.8)*
% False Alarms	5.5 (5.1)	1.3 (1.9)	4.3 (3.3)	1.5 (1.7)*
Total Trials	168.8 (46.6)	156.0 (43.8)	161.9 (76.4)	136.6 (39.4)
Accuracy (d')	3.23 (0.89)	4.69 (0.88)	3.61 (0.52)	4.49 (0.88)*

** Group X Game Interaction ($p < .01$)

* Main Effect of Game ($p < .01$)

APPENDIX B

Figures 1 - 26

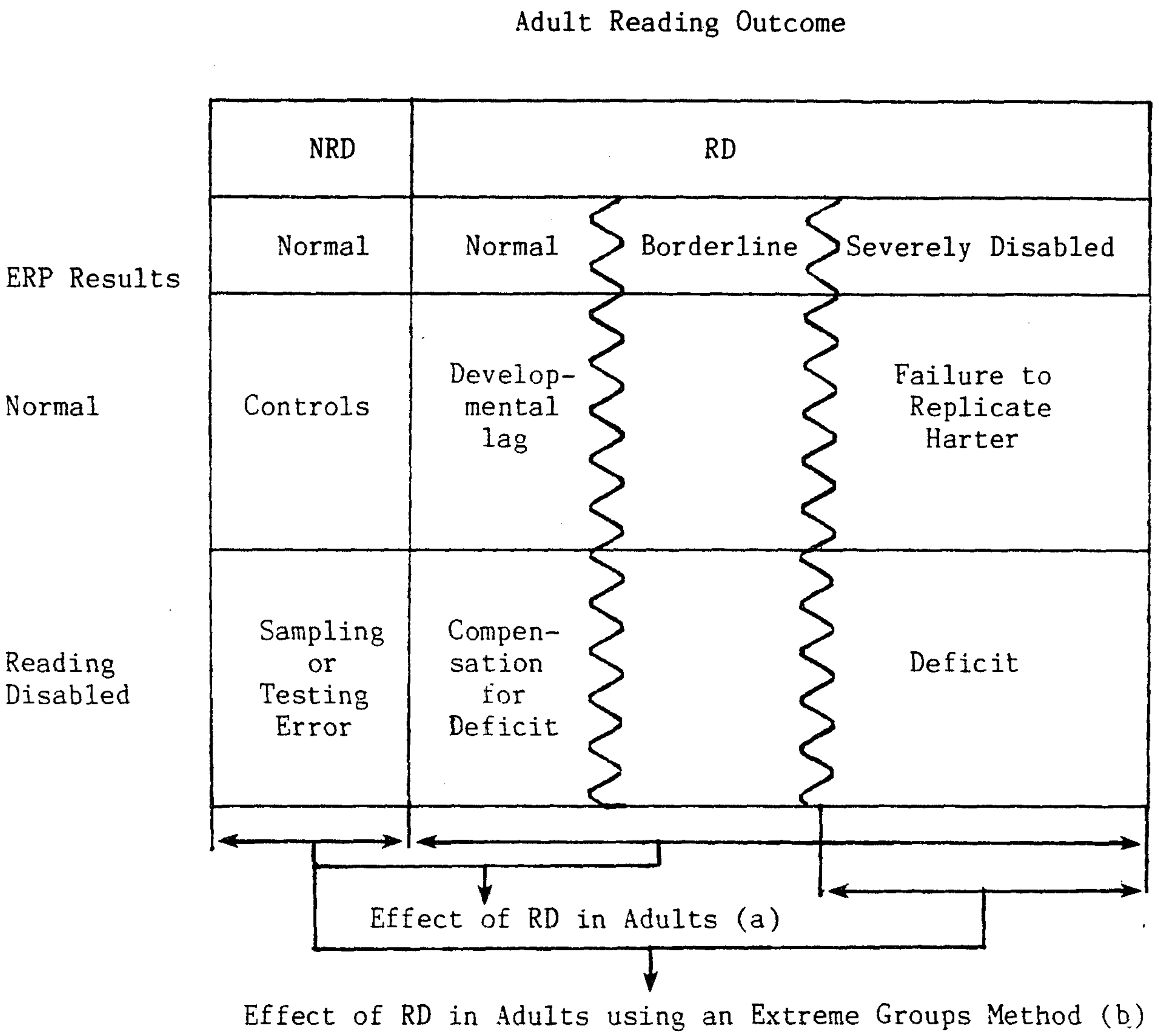

Figure 1. Experimental Design with an Outline of Possible Behavioral and Event-related Potential Outcomes and their Theoretical Implications.

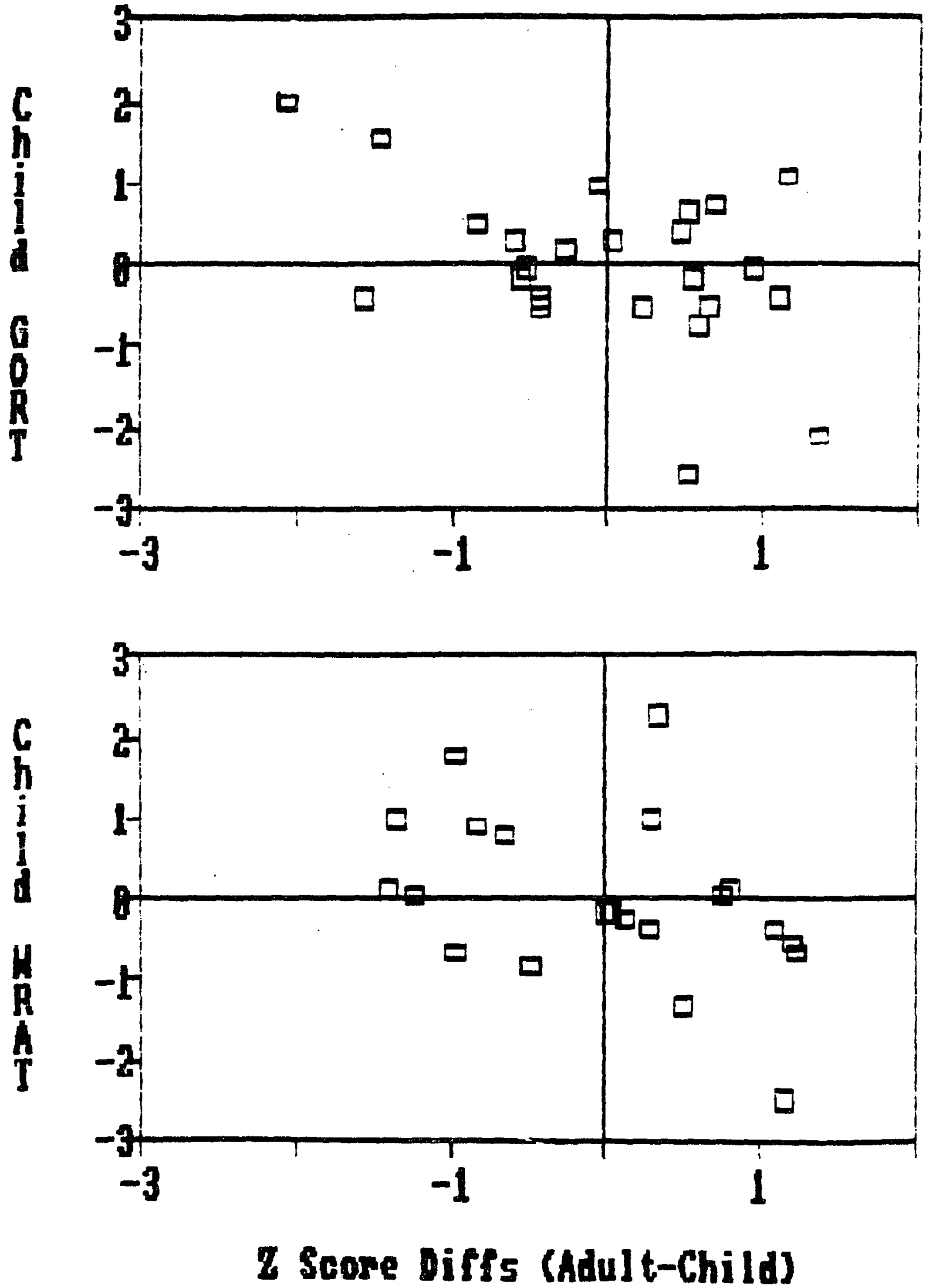

Figure 2. Relative improvement in terms of the severity of childhood deficit on the Gray Oral Reading Test (GORT) and the Wide Range Achievement Test (WRAT-R) for Individuals with RD.

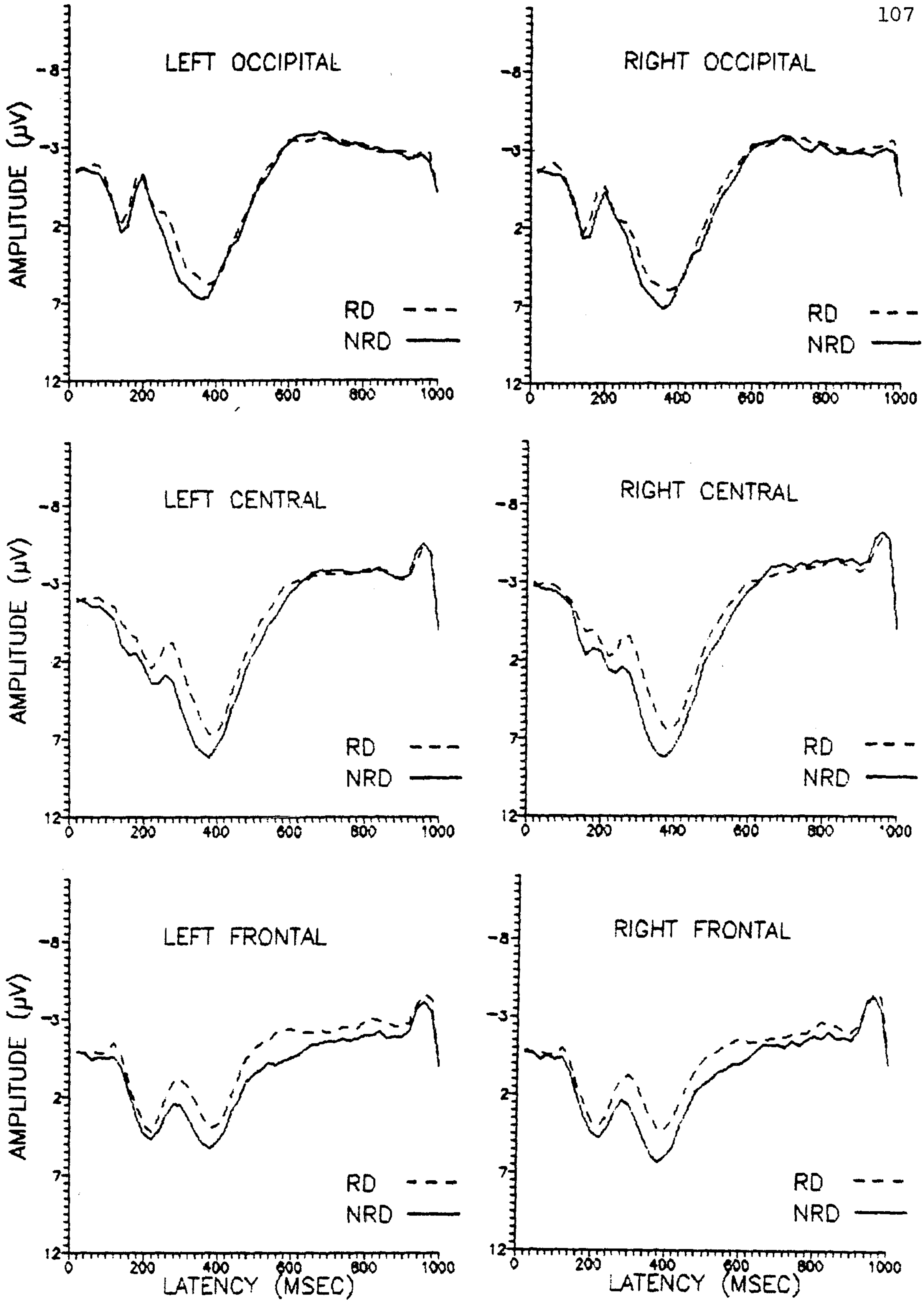

Figure 3. ERP raw waveforms for Reading Disabled (RD) and Normal Readers (NRD) - Relevance Independent Effects in the Color Game.

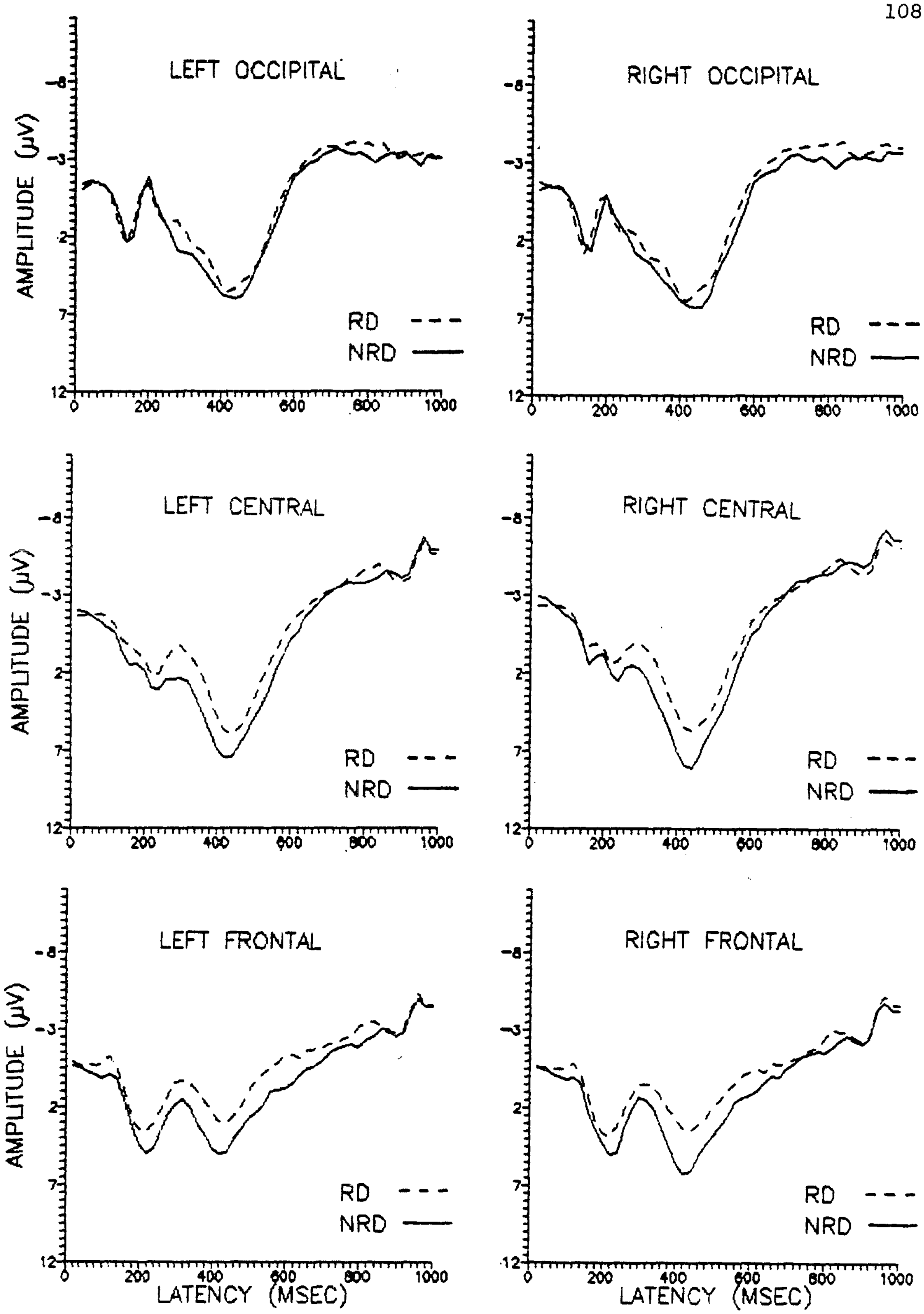

Figure 4. ERP raw waveforms for Reading Disabled (RD) and Normal Readers (NRD) - Relevance Independent Effects in the Letter Game.

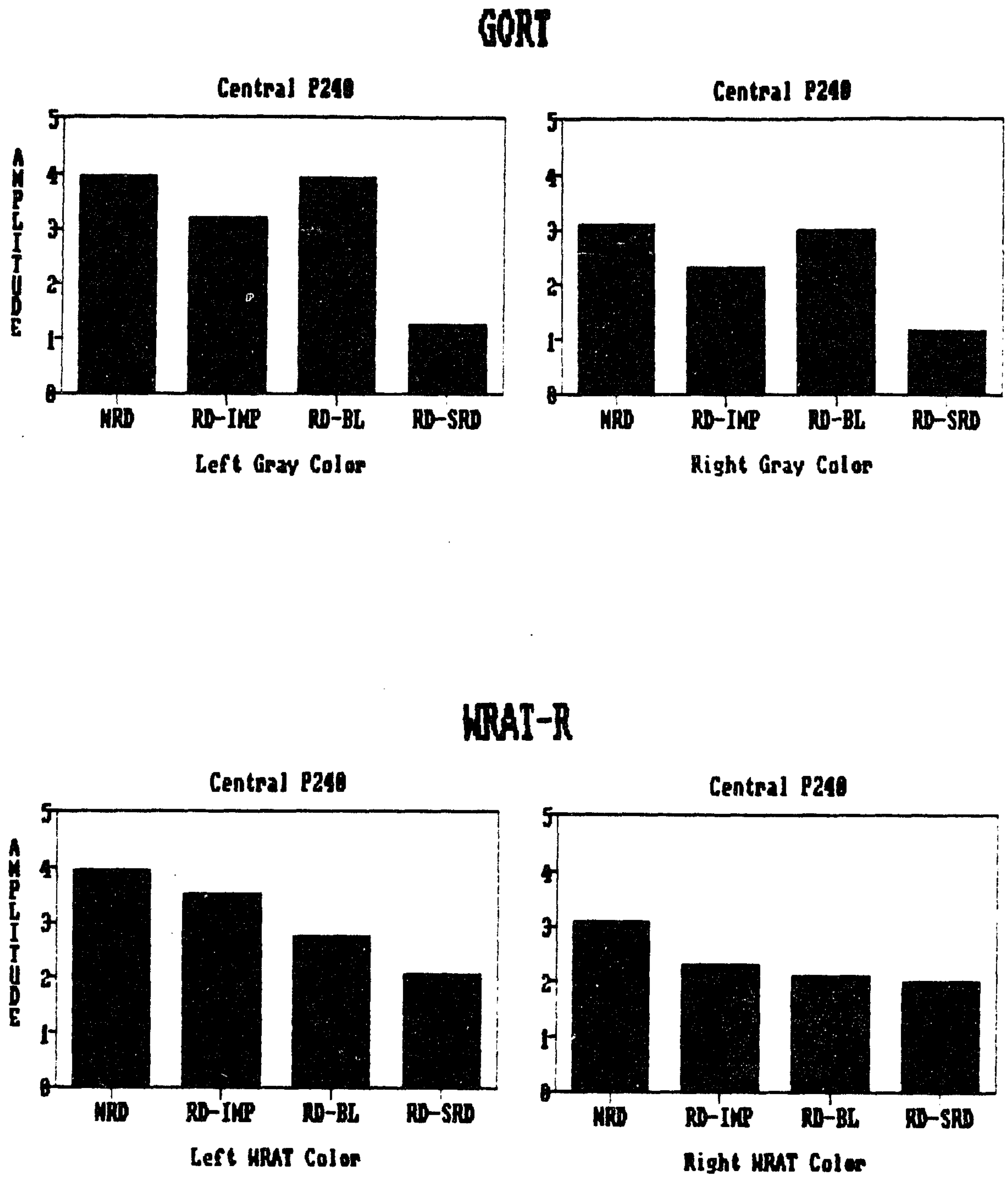

Figure 5. Amplitude of Central P240 in the Color Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL) or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement Reading Subtest (WRAT-R).

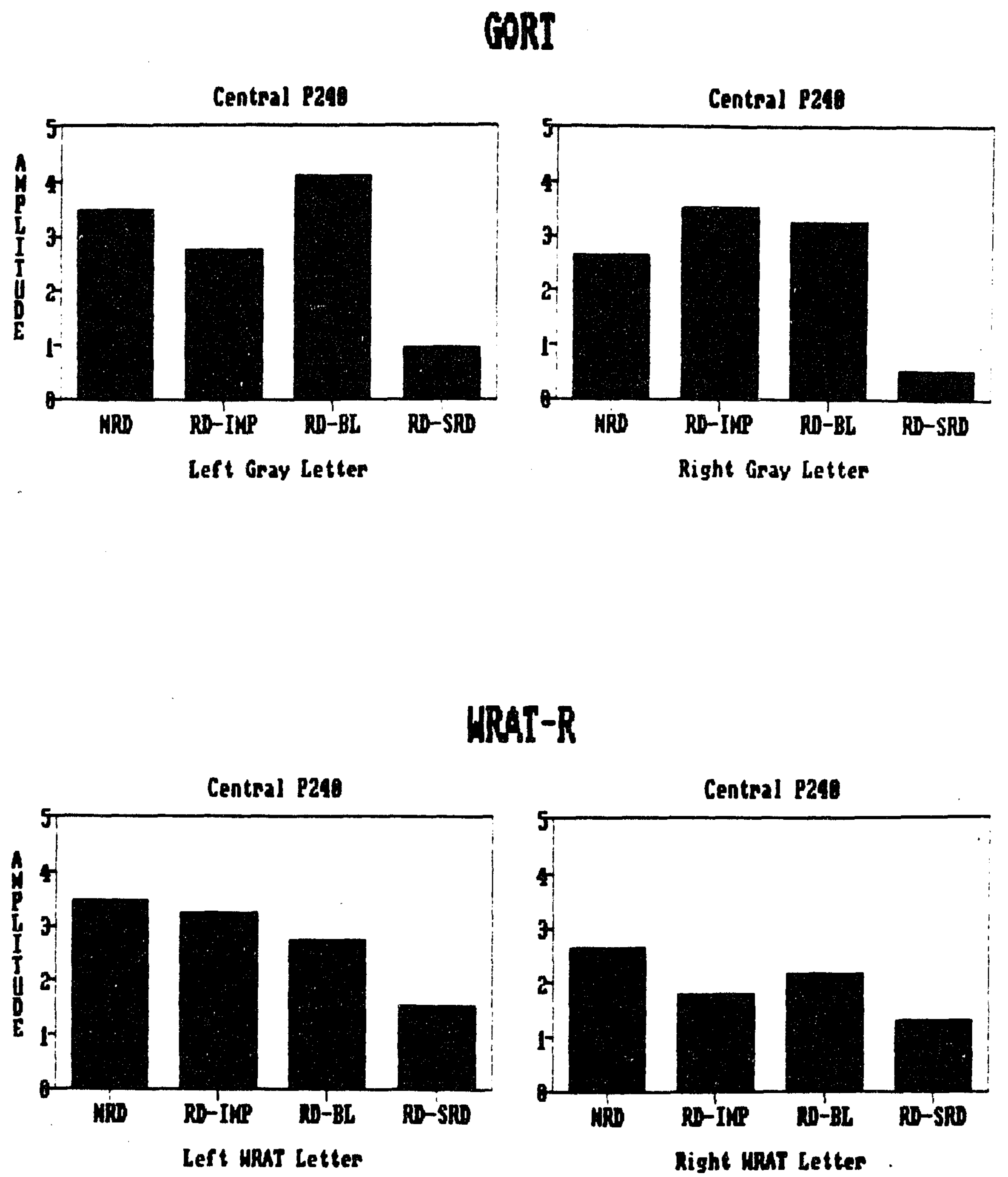

Figure 6. Amplitude of Central P240 in the Letter Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL) or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement Reading Subtest (WRAT-R).

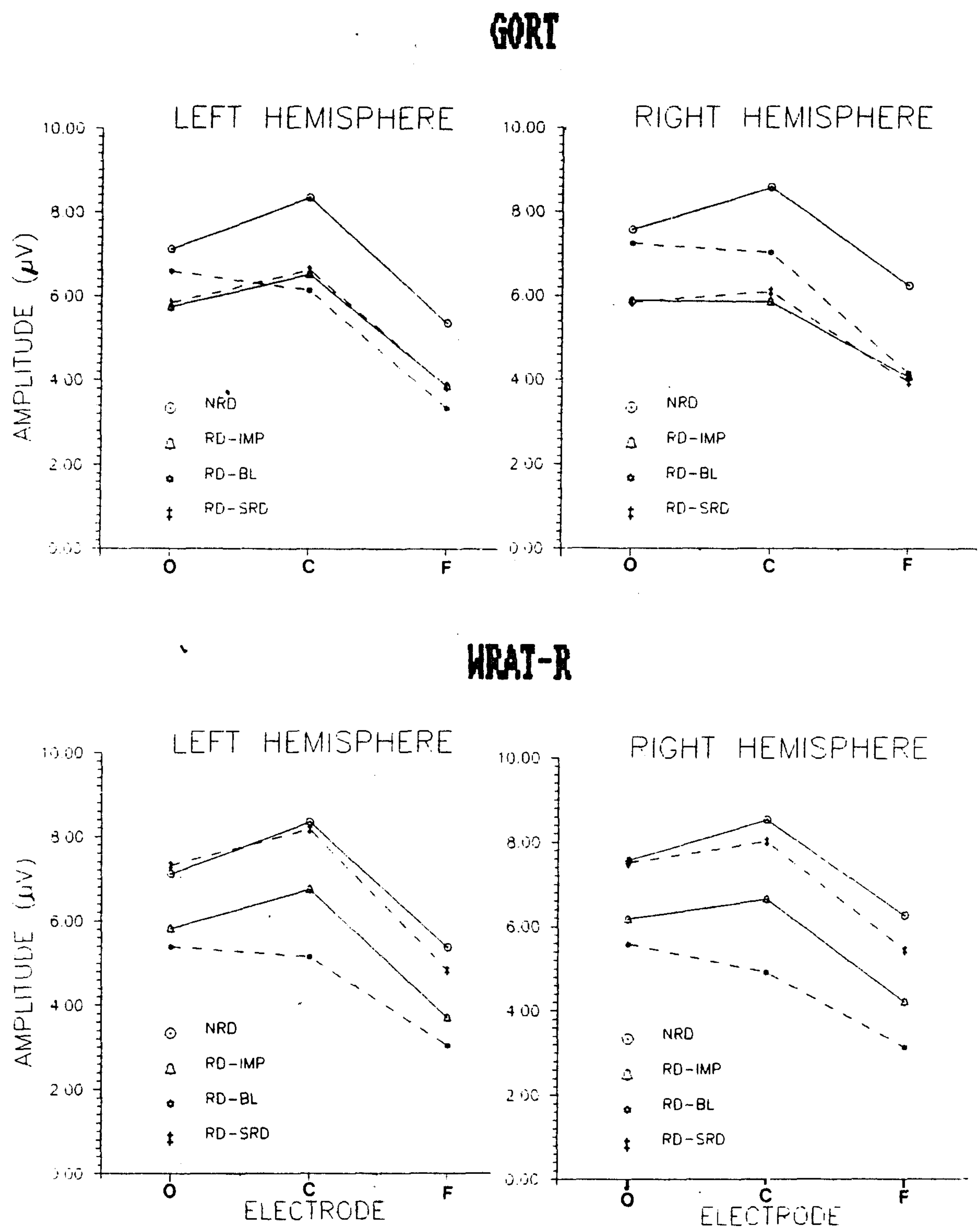

Figure 7. Amplitude of Central and Frontal P400 in the Color Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL) or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement Reading Subtest (WRAT-R).

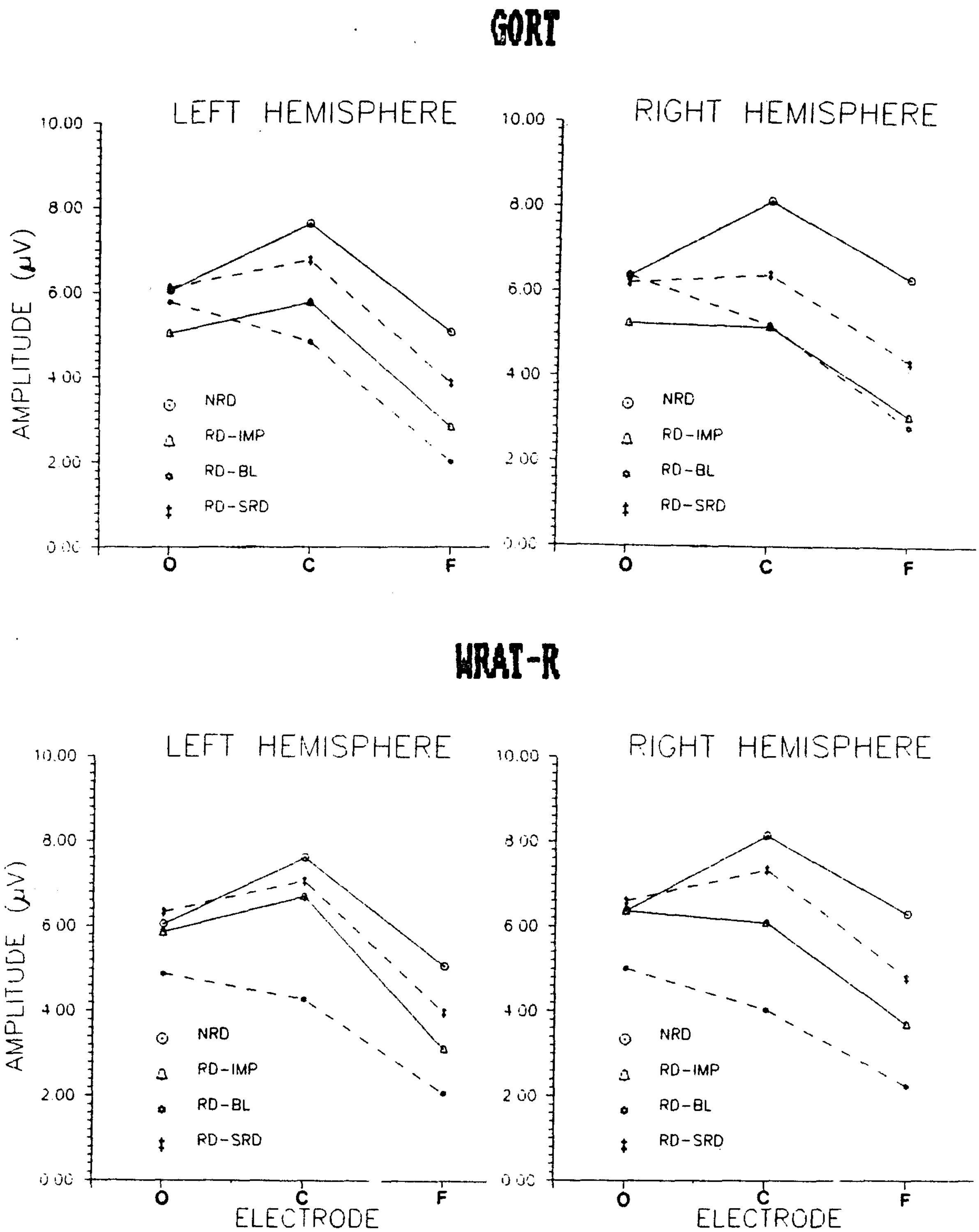

Figure 8. Amplitude of Central and Frontal P400 in the Letter Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL) or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement Reading Subtest (WRAT-R).

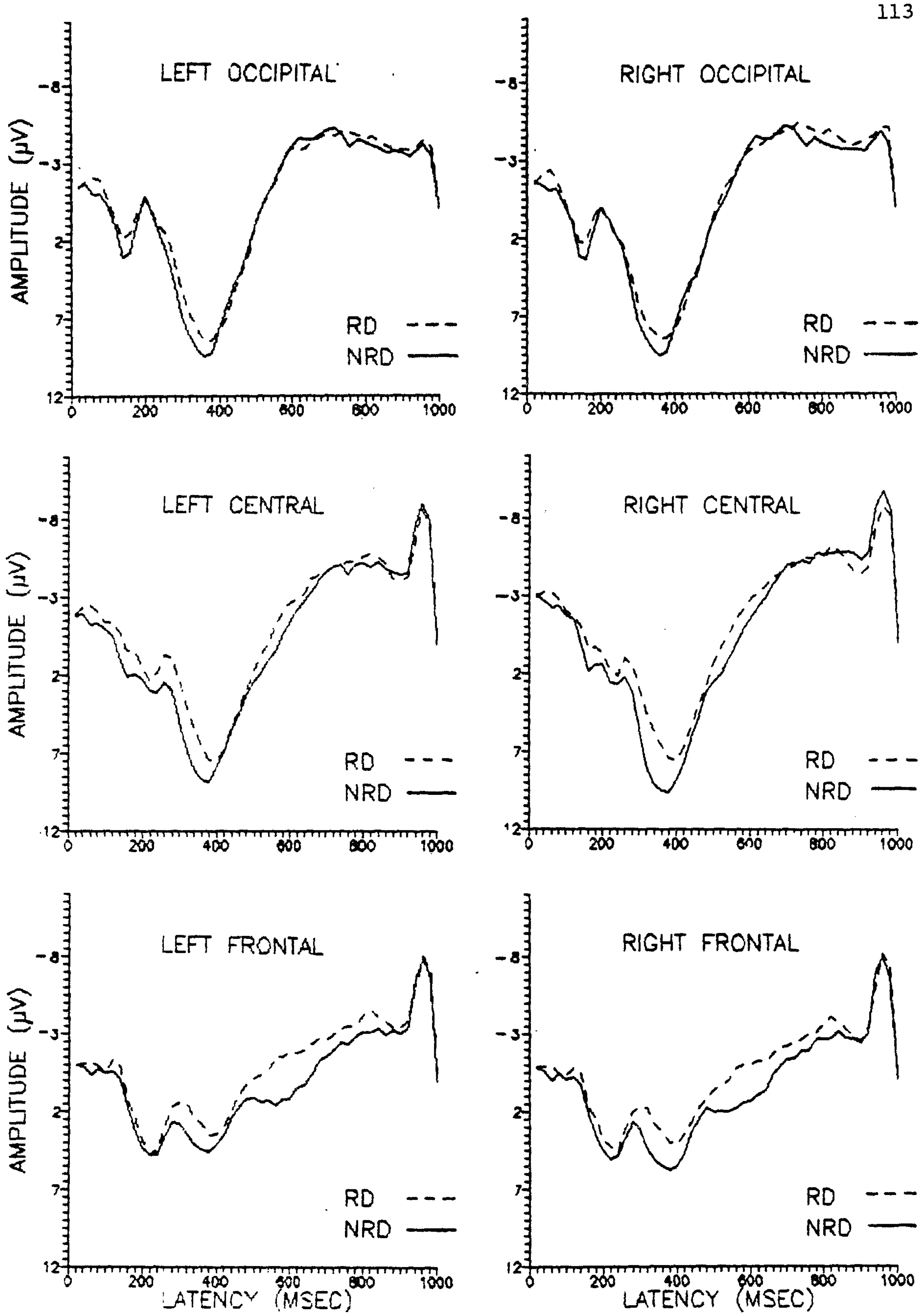

Figure 9. ERP raw waveforms for Reading Disabled (RD) and Normal Readers (NRD) - Relevant Condition in the Color Game.

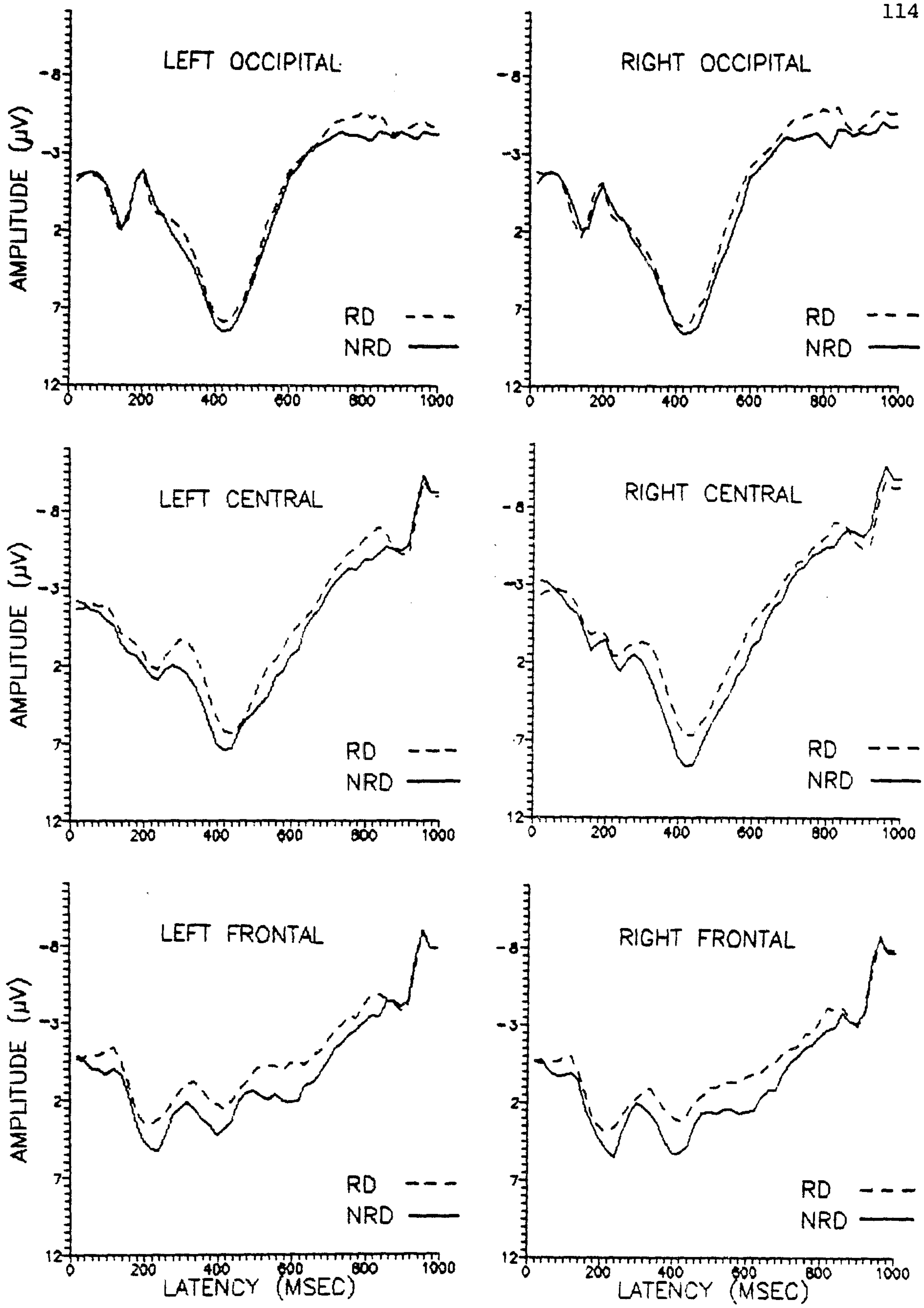

Figure 10. ERP raw waveforms for Reading Disabled (RD) and Normal Readers (NRD) - Relevant Condition in the Letter Game.

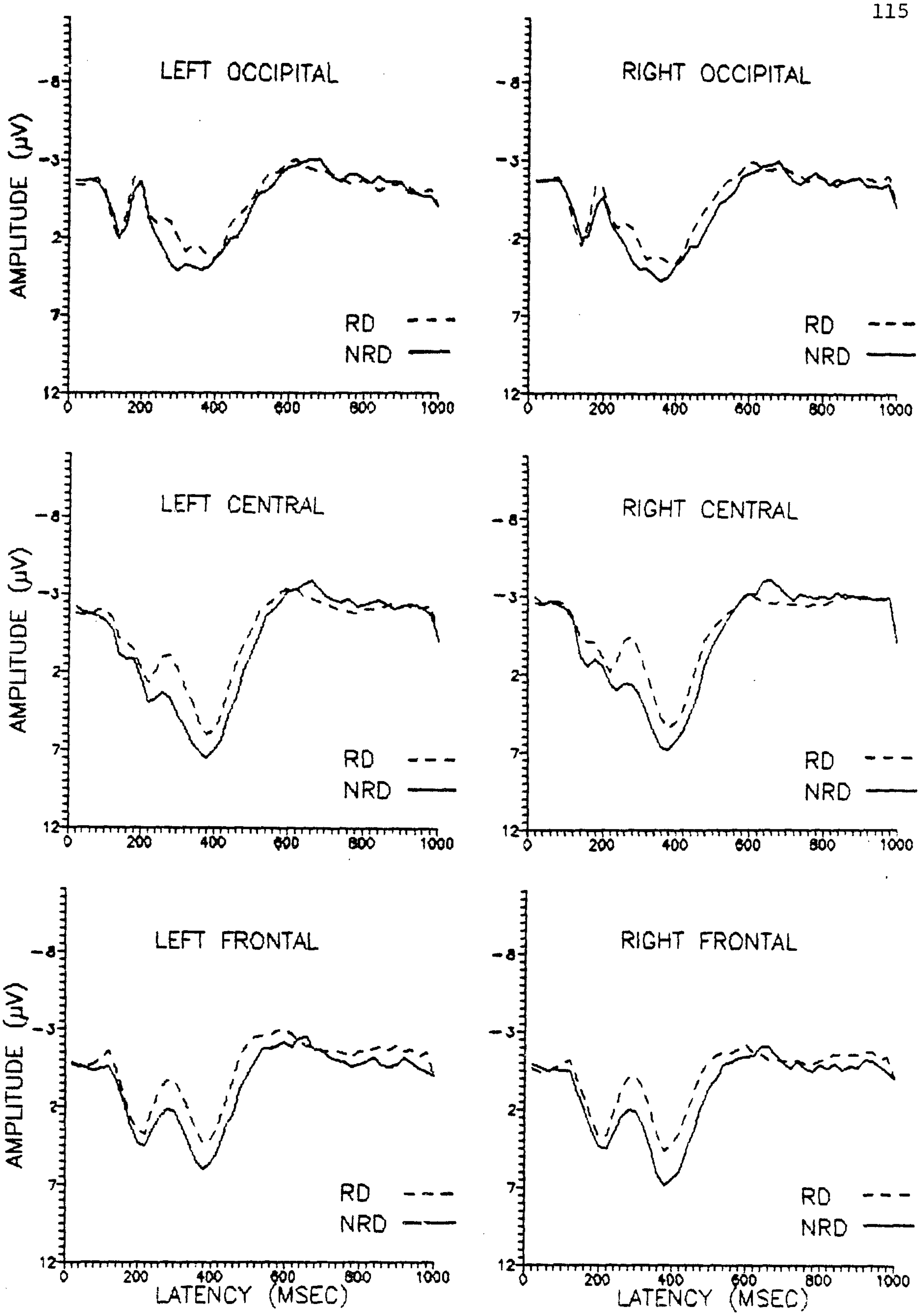

Figure 11. ERP raw waveforms for Reading Disabled (RD) and Normal Readers (NRD) - Irrelevant Condition in the Color Game.

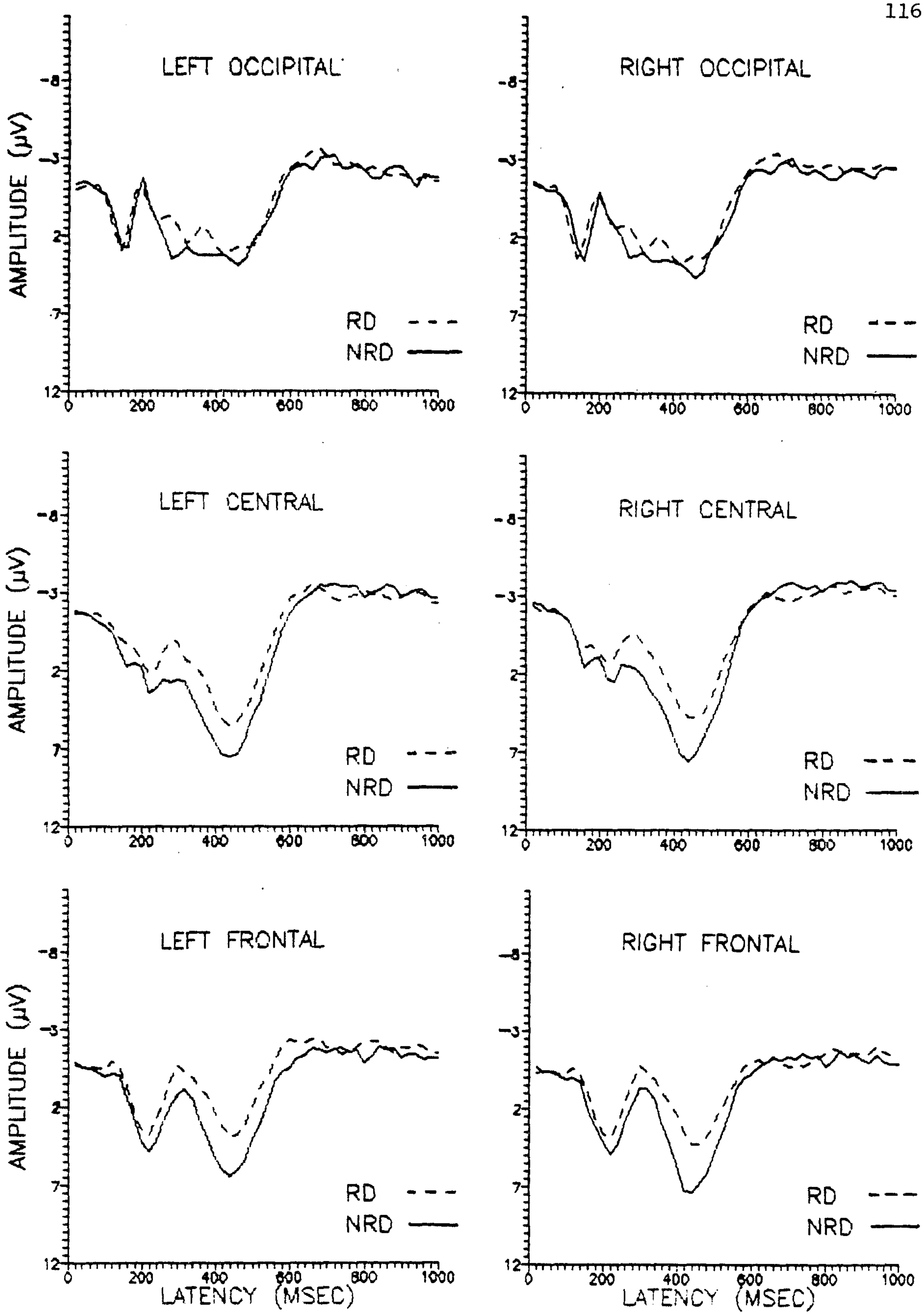

Figure 12. ERP raw waveforms for Reading Disabled (RD) and Normal Readers (NRD) - Irrelevant Condition in the Letter Game.

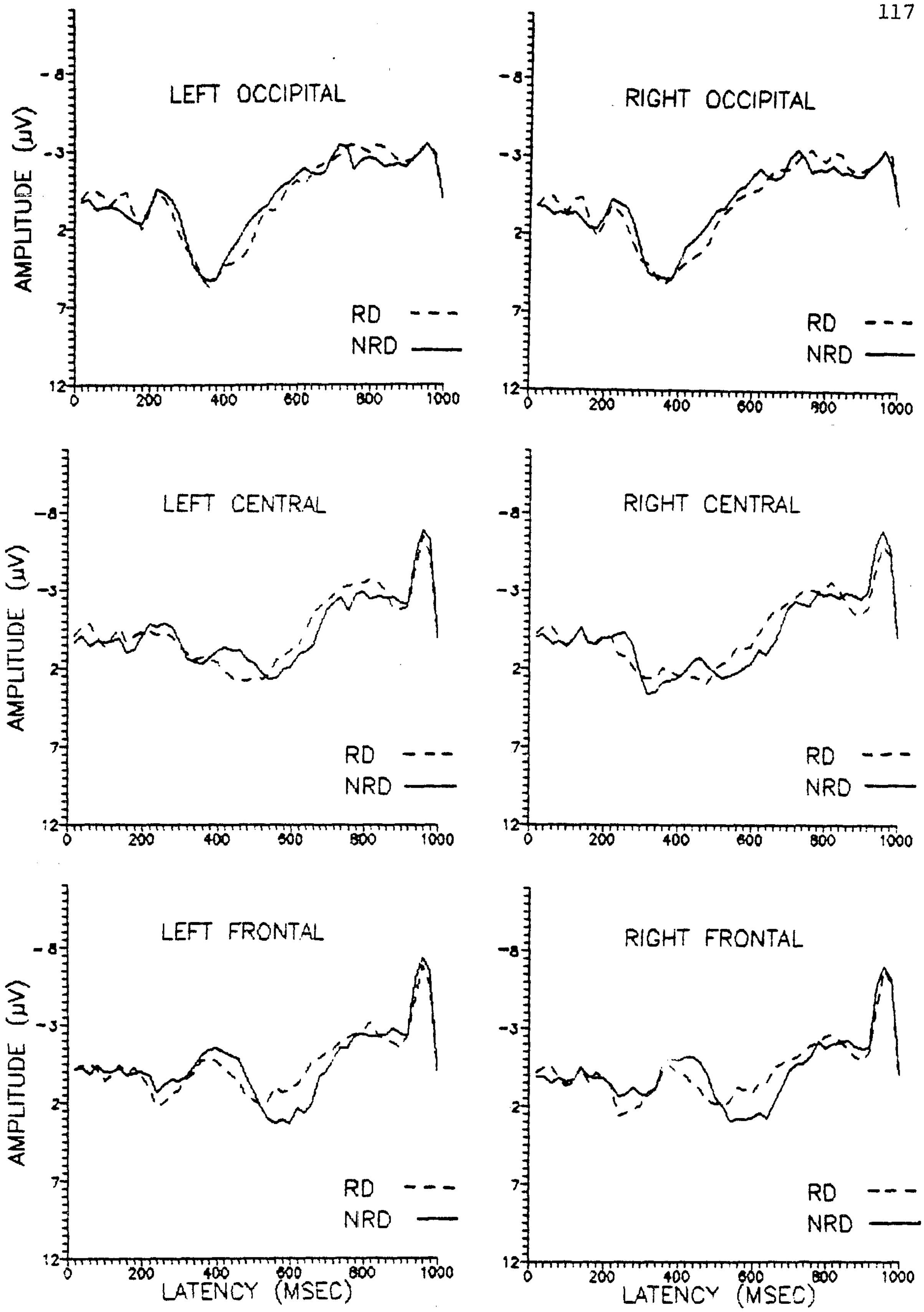

Figure 13. Difference Potentials (Relevant - Irrelevant) for Reading Disabled (RD) and Normal Readers (NRD) in the Color Game.

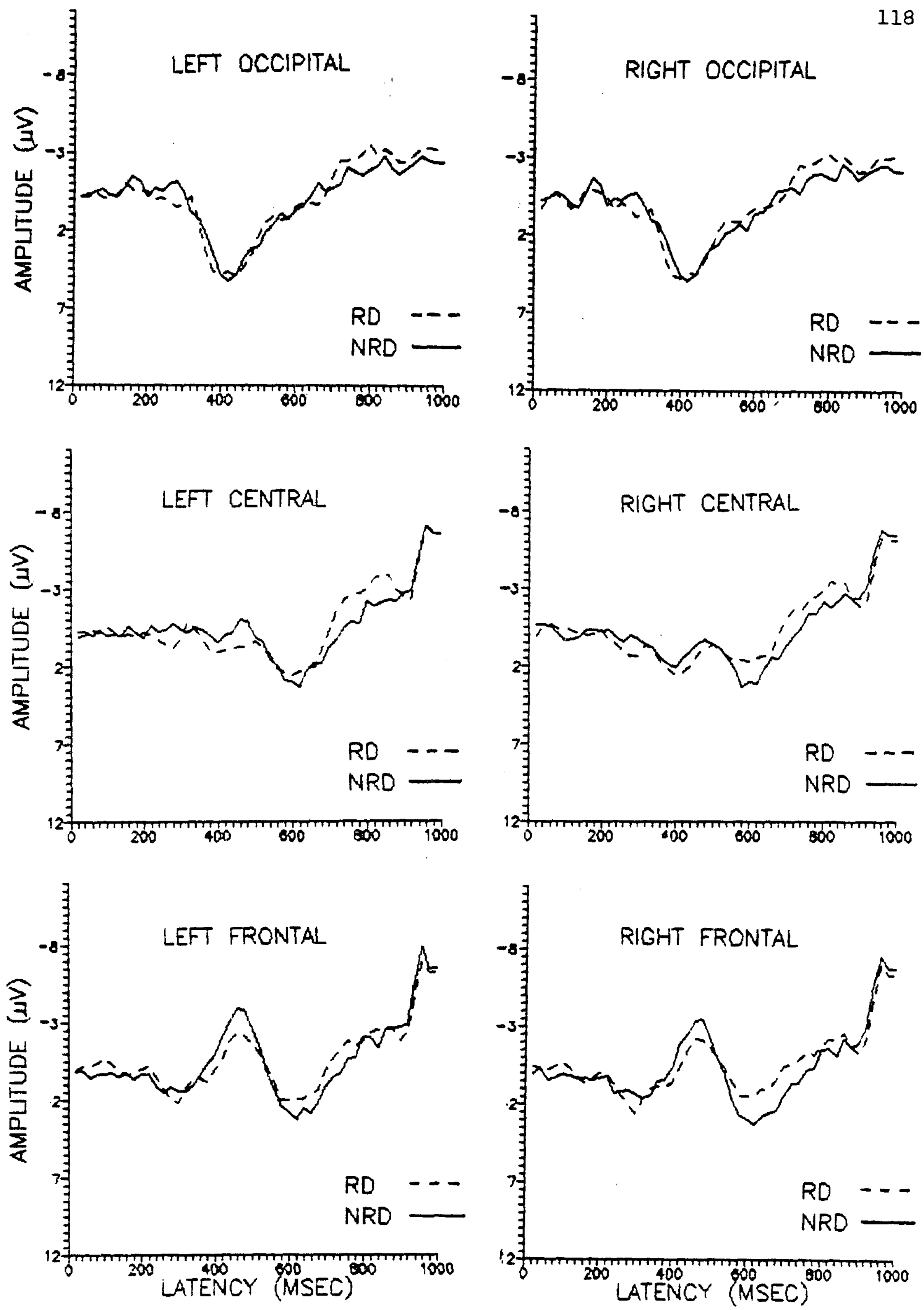

Figure 14. Difference Potentials (Relevant - Irrelevant) for Reading Disabled (RD) and Normal Readers (NRD) in the Letter Game.

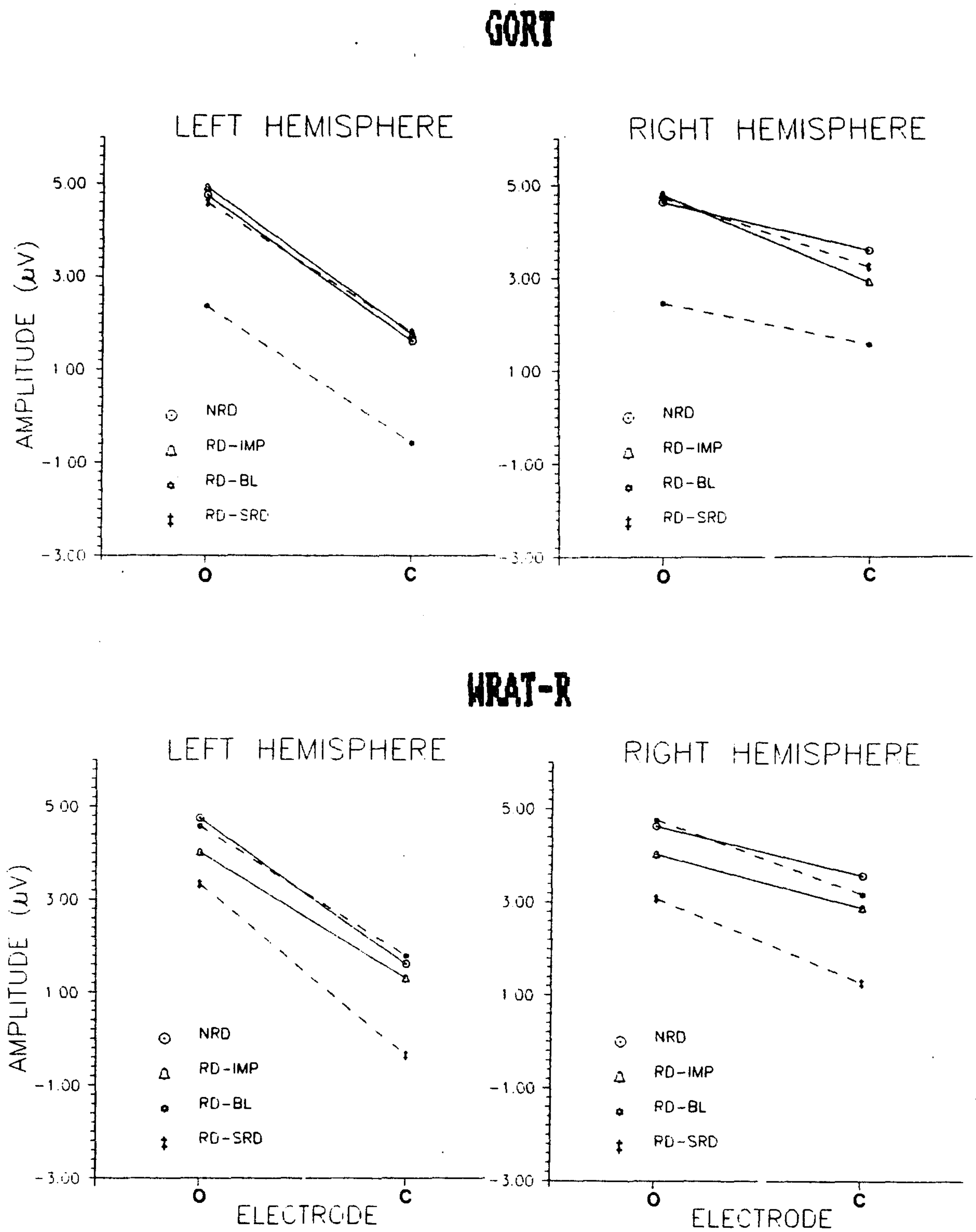

Figure 15. Amplitude of the Difference Potential at Occipital and Central P330 in the Color Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

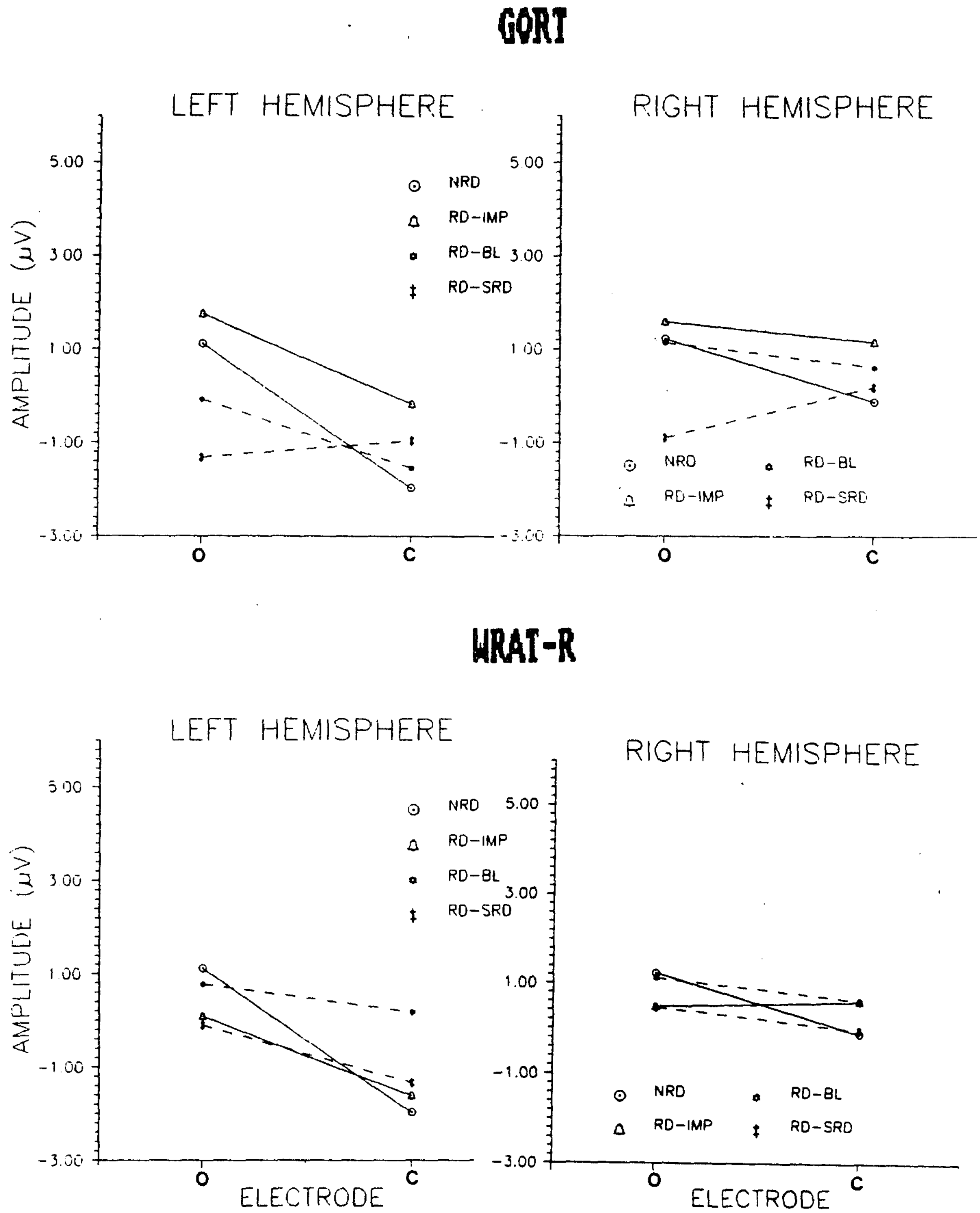

Figure 16. Amplitude of the Difference Potential at Occipital and Central P330 in the Letter Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

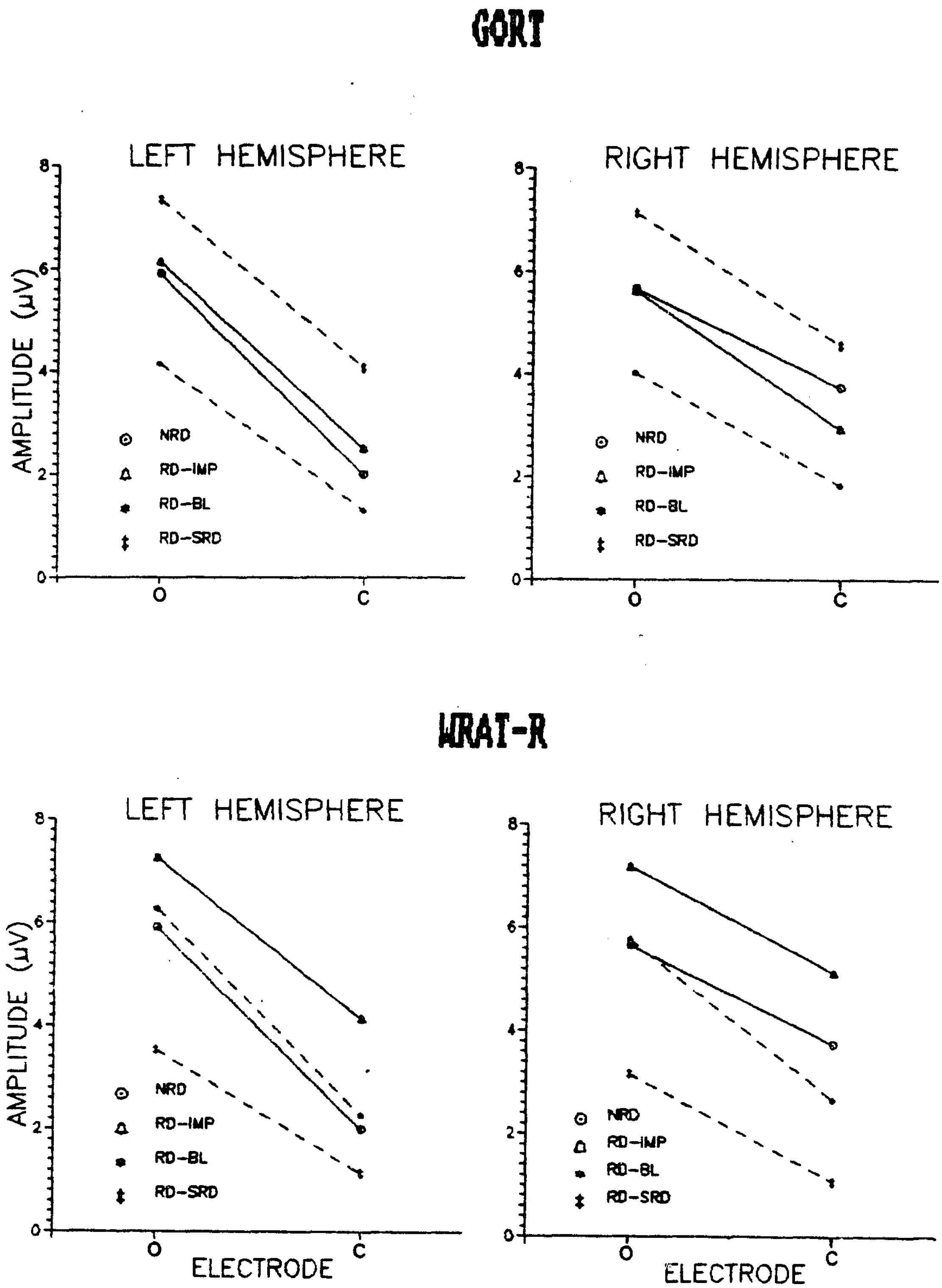

Figure 17. Amplitude of the Difference Potential at Occipital and Central P420 in the Color Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

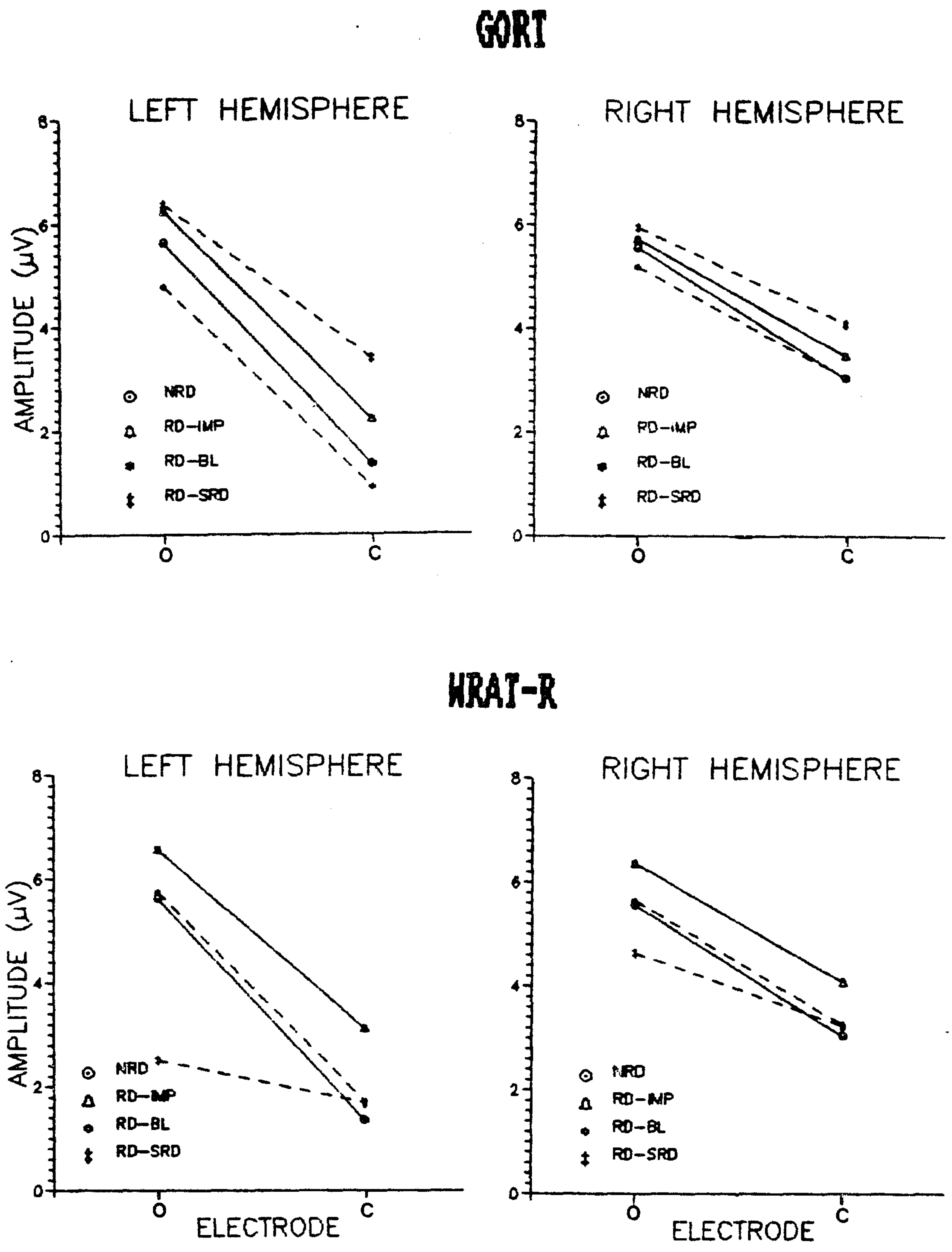

Figure 18. Amplitude of the Difference Potential at Occipital and Central P420 in the Letter Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

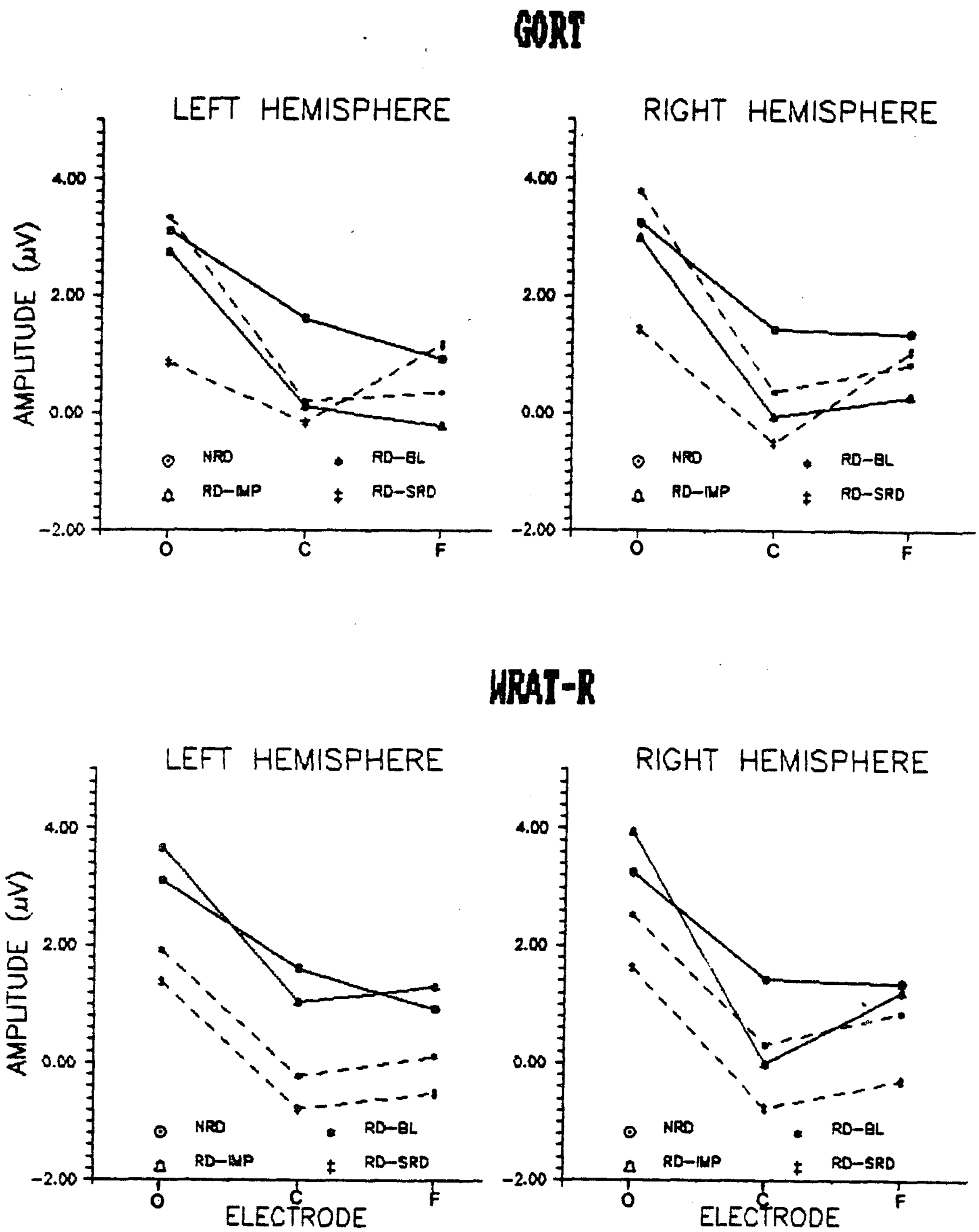

Figure 19. Amplitude of Occipital, Central and Frontal P150 in the Color Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

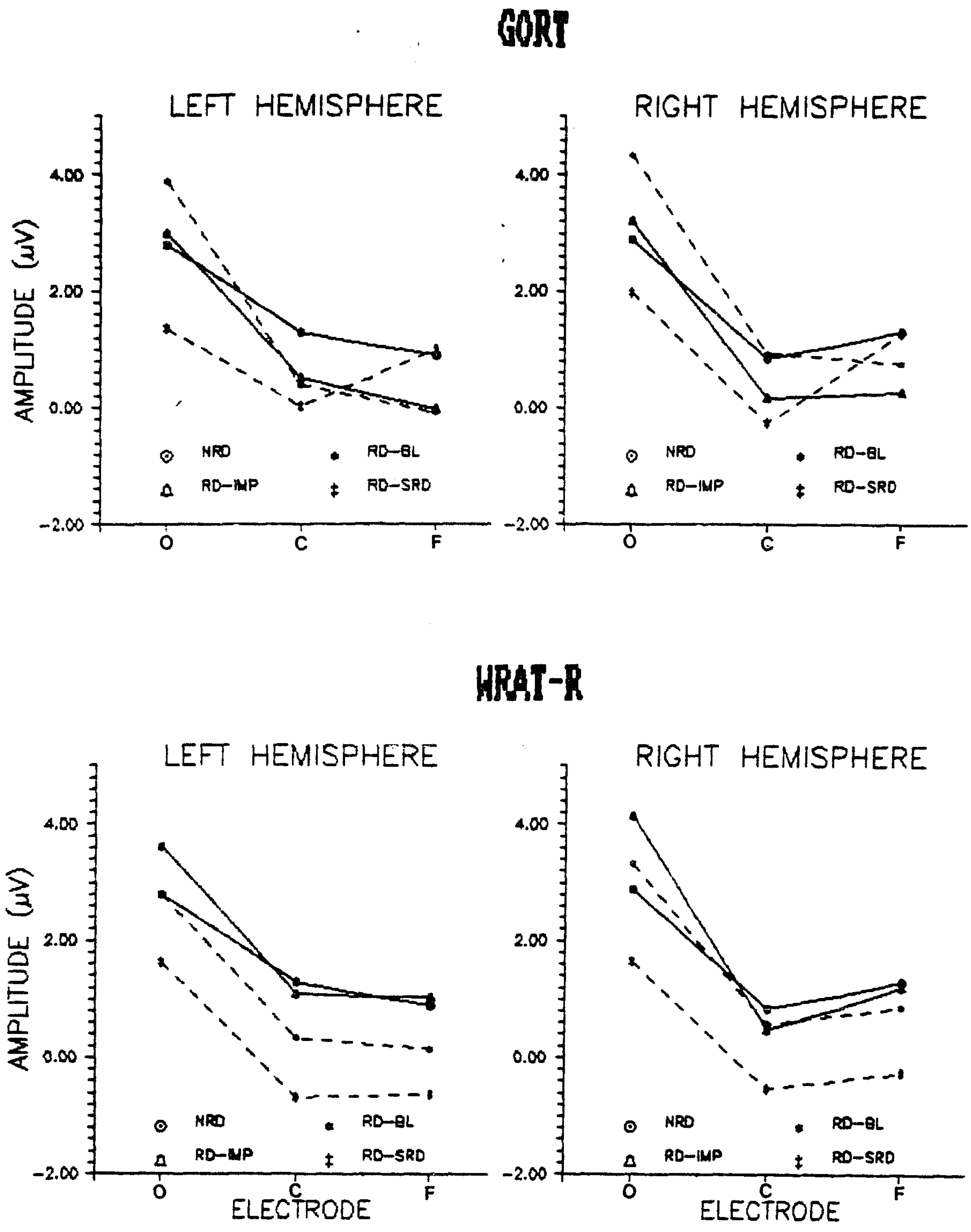

Figure 20. Amplitude of Occipital, Central and Frontal P150 in the Letter Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

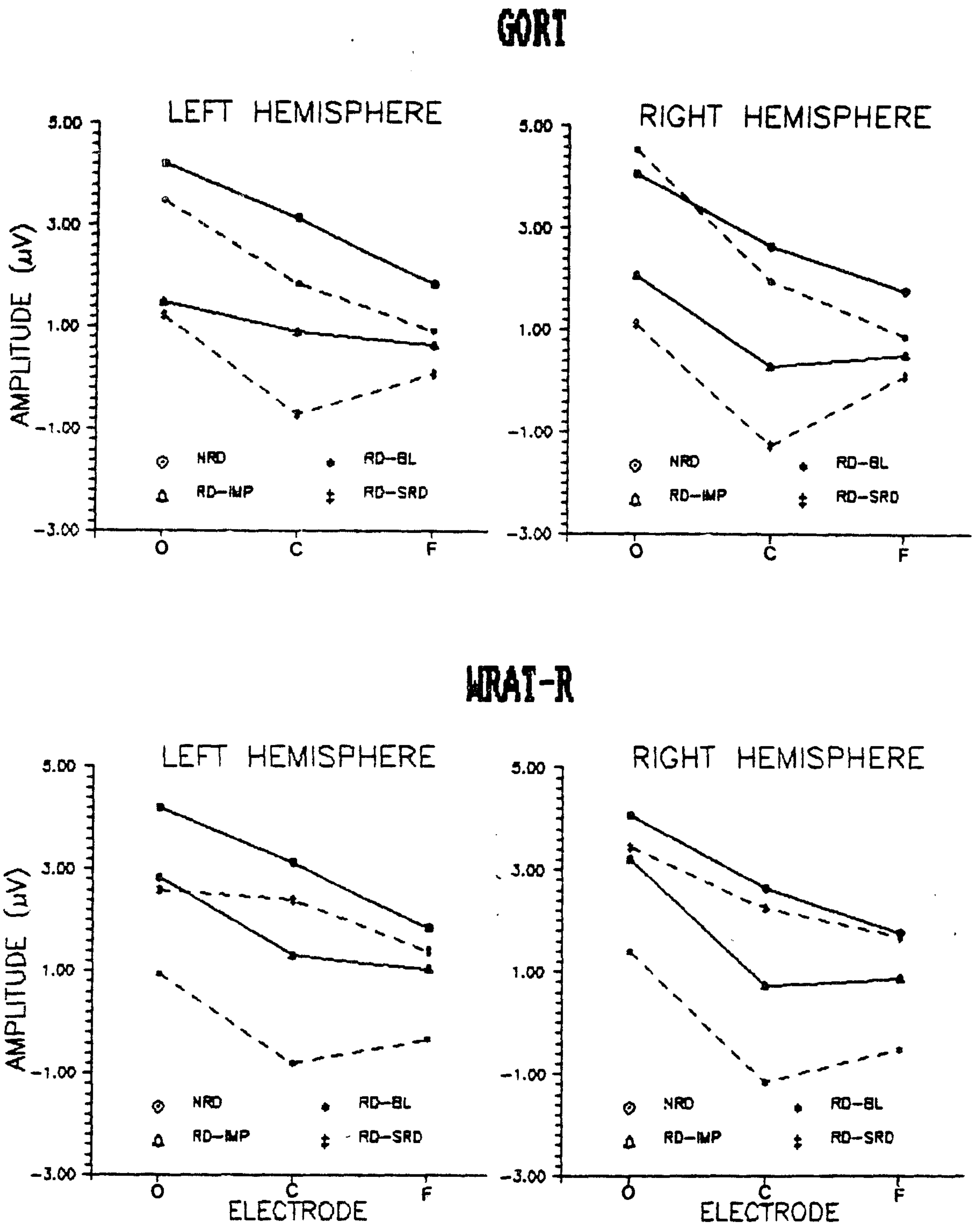

Figure 21. Amplitude of Occipital, Central and Frontal N290 in the Color Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

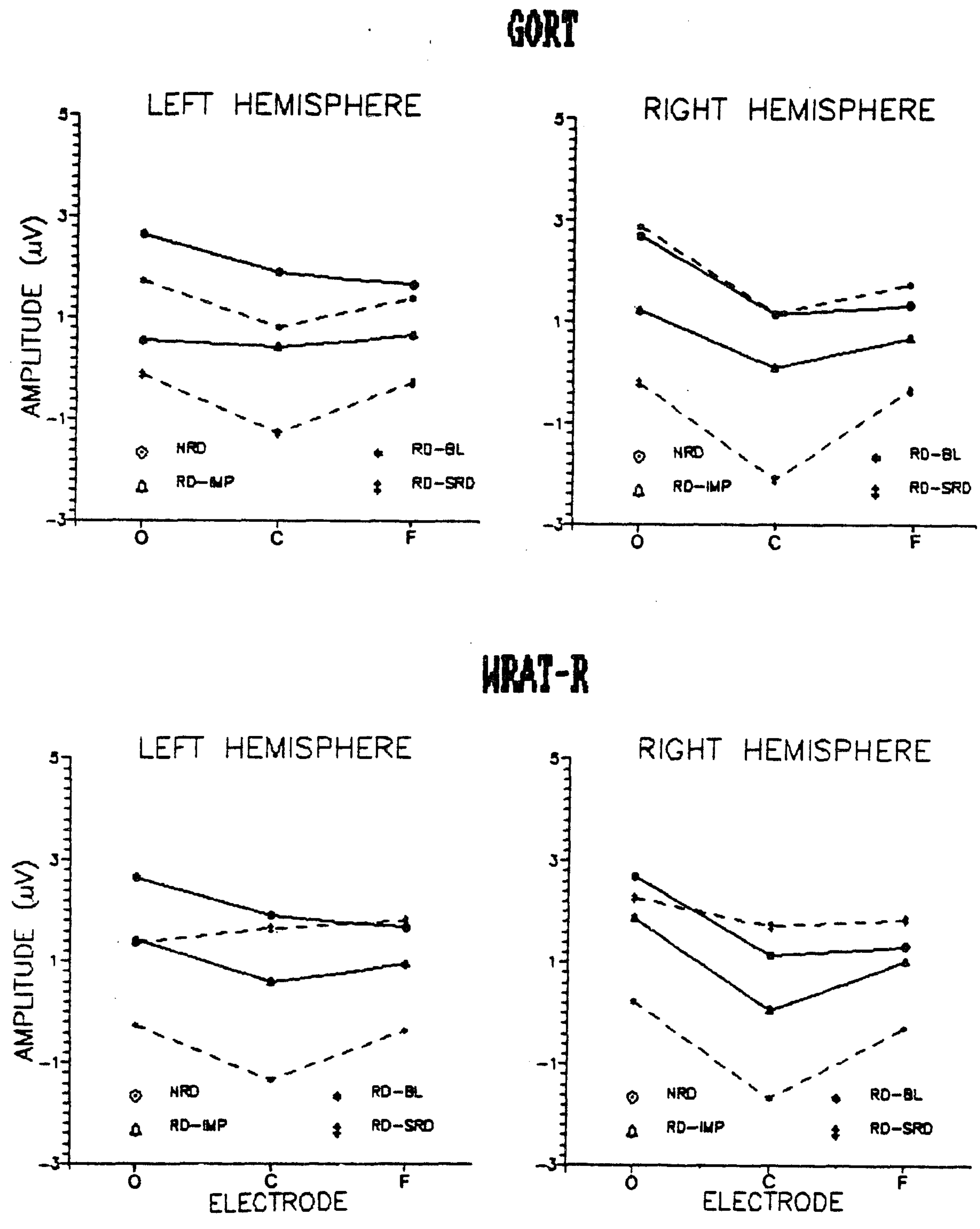

Figure 22. Amplitude of Occipital, Central and Frontal N290 in the Letter Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

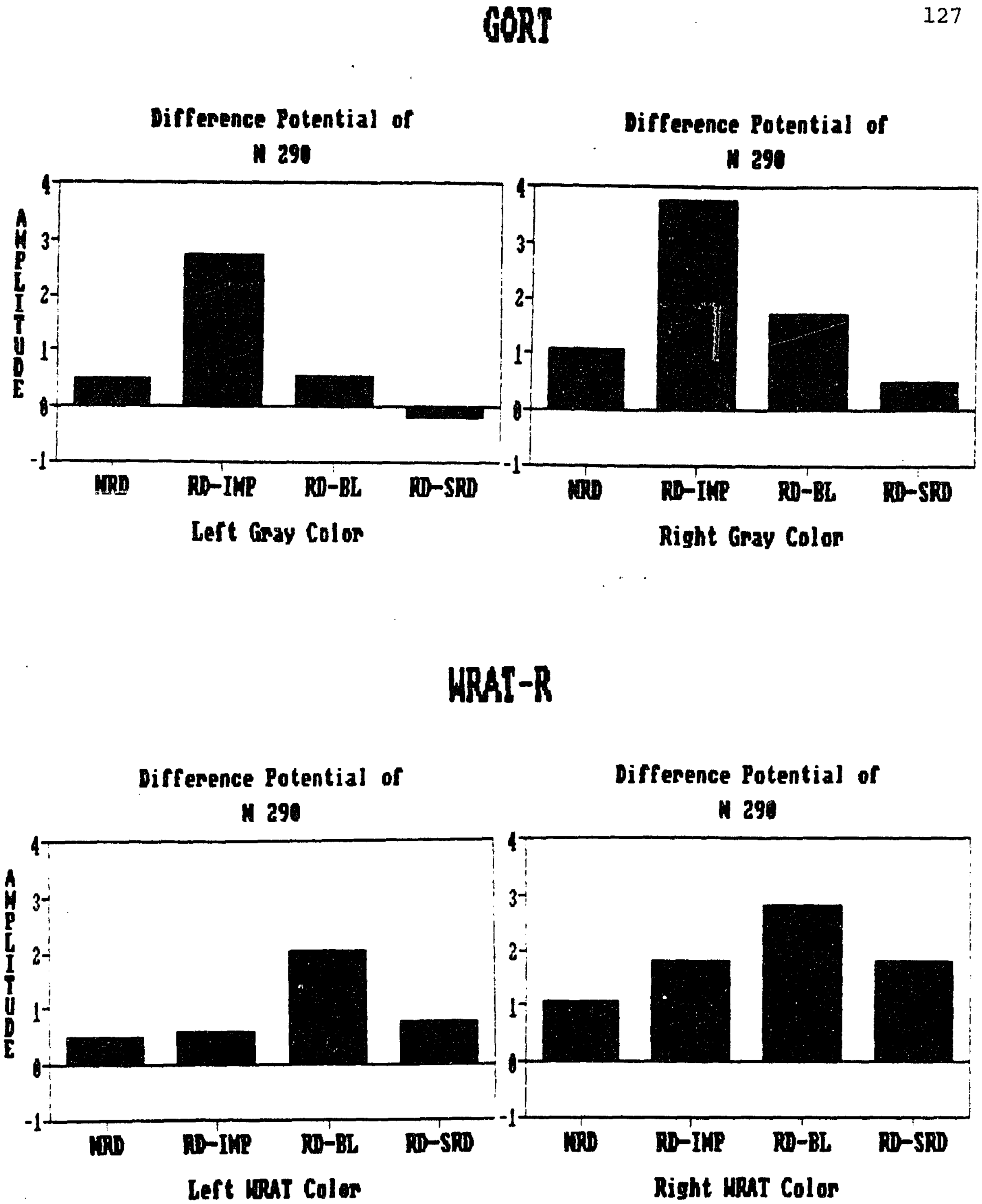

Figure 23. Amplitude of the Difference Potential at N290 in the Color Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

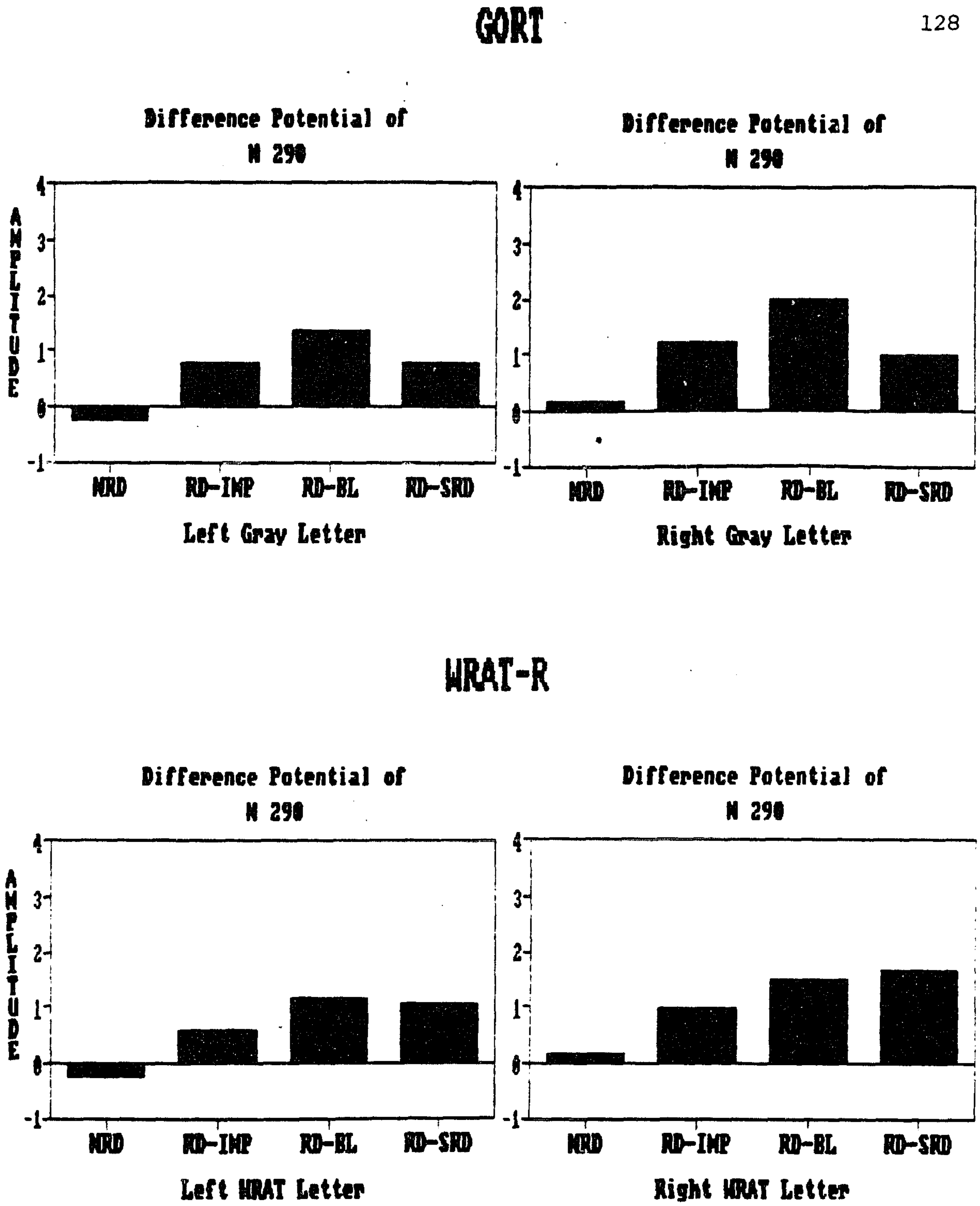

Figure 24. Amplitude of the Difference Potential at N290 in the Letter Game for Normal Readers (NRD) and Reading Disabled who, as Adult, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

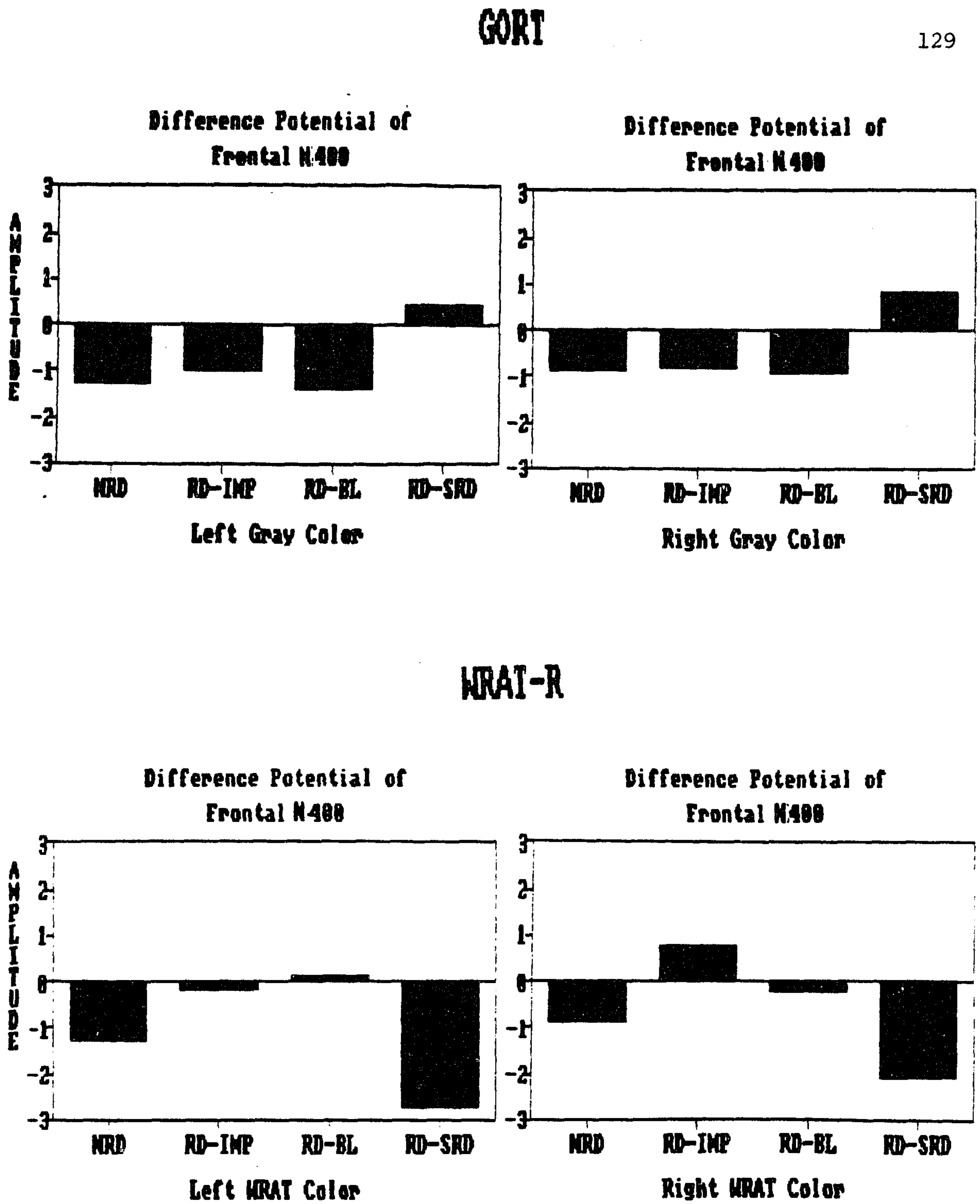

Figure 25. Amplitude of the Difference Potential at Frontal N400 in the Color Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.

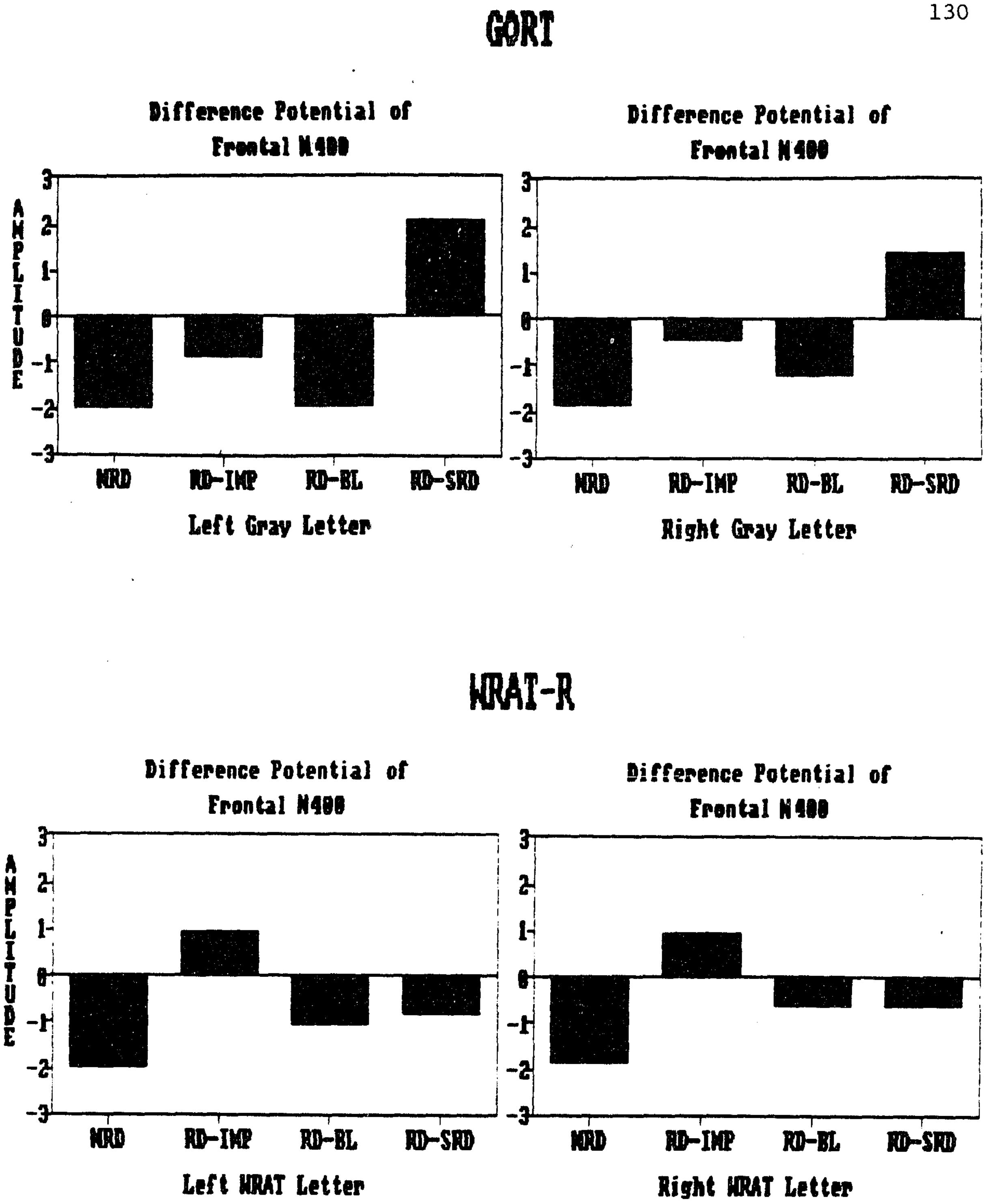

Figure 26. Amplitude of the Difference Potential at Frontal N400 in the Letter Game for Normal Readers (NRD) and Reading Disabled who, as Adults, scored in the Normal (RD-IMP), Borderline (RD-BL), or Impaired (RD-SRD) Range on the Gray Oral Reading Test (GORT) and the Wide Range Achievement (WRAT-R) Reading Subtest.