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Learning Disability Subtypes and the Effects of Auditory and Visual Priming on Event-Related Potentials

by

Jennifer Elizabeth Miles

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ABSTRACT

A control group of normal readers and three subtypes of learning disability (LD) were compared in their visual event-related potentials (ERPs) to primed and unprimed words. The LD subtypes are characterized by deficient performance on tests of arithmetic skill (Group A), reading and spelling skills (Group RS), or both (Group RSA). The primed words were preceded by pictures or spoken words having a related meaning, while unprimed words were preceded by pictures or spoken words having a non-associated meaning. For normal readers, N400 amplitude was greater to unprimed words than to words primed by pictures and spoken words. For Group A, parietal N400 was reduced by spoken word primes, but not by picture primes. For Group RS and Group RSA, neither picture nor spoken word primes reduced N400 amplitude. These groups were differentiated by the amplitude of parietal N400. The normal readers displayed a greater left than right hemisphere frontal N400 amplitude to unprimed words. This asymmetry was absent in the ERPs of all the LD subtypes. The pattern of ERP results supports an LD typology that characterizes subtypes on the basis of difficulty with arithmetic or reading and spelling, or with a combination of both. The hemispheric asymmetry results suggest that left hemisphere dominance is associated with skilled reading.

CURRICULUM STUDORIUM

Jennifer E. Miles was born in Ottawa, Ontario on November 19, 1957. Her High School education was obtained in Rockliffe, Ontario. She graduated from Elmwood School in 1976. In 1986 she completed an honours B.A. at the University of Ottawa.

PUBLICATIONS

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INTRODUCTION

In a society where reading is a factor in almost every aspect of daily life, up to 15% of school-aged children have been found to have reading difficulties (Mycklebust & Boshes, 1969). For some children, learning disability (LD) can contribute to social and emotional, as well as academic problems (Bender, 1958; Eisenberg, 1975). Furthermore, the National Advisory Committee on Dyslexia and Related Reading Disorders of the United States reports that 75% of juvenile delinquents displayed significant reading retardation (1969). If 15% of a population experiences such problems, the implications may be profound. Important objectives for researchers in this area are to define homogeneous subtypes and effective remediation strategies, and to identify the biological substrates of LD. If these investigations are successful, early identification and intervention may alleviate some of the consequences of LD.

The aim of the current research was to differentiate LD subtypes using event-related potentials (ERPs). The typology consists of three subtypes of LD, characterized by deficient performance on tests of arithmetic skill (Group A), reading and spelling skill (Group RS), or both (Group RSA) (Rourke & Finlayson, 1978). Each subtype has exhibited distinctive patterns of performance on neuropsychological test batteries that indicate auditory-verbal or visual-spatial impairment (Petrauskas & Rourke, 1979). The proposed biological determinants of each subtypes' deficits are understood in the context of hemispheric specialization during language acquisition (Rourke, 1982). However, the validity of the theoretical bases of this typology, using measures that are independent of the subject selection criteria, has not been extensively explored.

Cognitive psychologists aim to understand psychological processes by measuring changes in overt responses when stimulus parameters are manipulated. The development of ERP techniques has enabled the analysis of the electrical activity of the brain during cognitive tasks. This method allows researchers to base conclusions on the effects of manipulations during stimulus processing, rather than solely on the subsequent performance of responses.

One wave of the ERP, termed N400, is especially sensitive to linguistic processing. Cognitive psychologists have shown that responses to target words, such as the speed and accuracy of lexical decisions, are enhanced if the target is preceded or 'primed' by a semantically related word. ERP studies of the priming effect showed that the amplitude of N400 is smaller to primed words than to unrelated words (cf. Kutas & Van Petten, 1988).

LD subjects have been differentiated from normal readers by N400 amplitude elicited by a recognition memory task, wherein each word was preceded by a picture (Stelmack & Miles, 1990). Half the pictures had the same denotative meaning as the words and half were unrelated. For normal readers, words that were primed by related pictures evoked smaller N400 amplitude than did unprimed words. The LD subjects did not display this effect at parietal electrode sites. Thus, ERP indices are sensitive to differences in reading ability. The current research was conducted in order to determine if the N400 wave elicited by auditory and visual primes could distinguish normal and subtypes of LD subjects. As the subtypes differ on visual-spatial and auditory-verbal abilities tests, differential effects of auditory and visual priming on N400 amplitude would provide support for the modality - specific processing deficits associated with the typology.

Thirty-six boys, aged ten to thirteen, participated in this study. Each subject was identified as belonging to one of four groups: a control group of normal readers, Group A, Group RS, or Group RSA. Two sessions were conducted in a counterbalanced order. In each session, the subjects were instructed to read words presented on a television monitor. In the visual session, each word was preceded by a picture. In the auditory session, each word was preceded by a spoken word. In both sessions, half of the target words were preceded by a semantically related picture or spoken word, and half were preceded by an unrelated picture or spoken word. A recognition memory test was conducted after each session.

The normal readers displayed smaller N400 amplitudes to primed than unprimed words in both the auditory and visual sessions. For Group A subjects, N400 amplitude was reduced to auditory primed words but not to visually primed words. Group RSA and Group RS waveforms did not indicate significant priming effects in either session. In general, the N400 amplitude to primed words of Group RS were markedly larger than for all other groups. Thus priming effects on N400 amplitude differentiated subtype differences in reading ability. The normal readers also differed from the LD groups in the hemispheric asymmetry of frontal N400 amplitude. Normal readers exhibited a larger left than right amplitude N400 to unprimed words in both sessions. None of the LD subtypes displayed this effect.

The results are discussed in terms of their implications for the typology and for the model of language acquisition on which it is based.

CHAPTER I

Several LD typologies have been constructed on the basis that abnormalities in hemispheric specialization may affect certain types of linguistic information processing. Different types of information appear to be processed more efficiently by systems in particular hemispheres. Visual hemi-field and dichotic listening tasks indicate that for normal readers the left hemisphere appears to be specialized for verbal material, and the right hemisphere for spatial material (Kimura, 1966; Kimura & Durnford, 1974; Marcel, Katz, & Smith, 1974; Pirozzolo, 1979; Pirozzolo & Rayner, 1979; Pirozzolo, Rayner, Hansch, & Hynd, 1983). This effect is not consistently observed in LD groups (Bakker, Licht, Kok, & Bouma, 1980; Hynd, Obrzut, Weed, & Hynd, 1979; Kershner, 1977; Marcel & Rajan, 1975; Satz, 1976; Witelson & Rabinovitch, 1972). In addition, neuropsychological test batteries indicate that LD subtypes display performance patterns that are consistent with deficits of either auditory-verbal or visual-spatial processing (eg. Bateman, 1968; Johnson & Myklebust, 1967; Rourke, 1982). Thus, impaired processing of specific types of information has been implicated as a determinant of subtype deficits. However, the physiological concomitants of auditory-verbal and visual-spatial information processing have yet to be confirmed. The purpose of the present research is to determine if electrophysiological measures differentiate normal readers and LD subtypes.

In order to establish the current body of knowledge concerning LD, and the approach of this thesis, this chapter will be presented in several sections. Currently, LD research aims either to establish homogeneous subtypes and appropriate remediation strategies, or to identify the biological substrates of subtype deficits. Several issues and problems, as well as goals, that are common to both areas of research will be discussed. Classification system research, or the development of typologies, provides criteria that are used by biological researchers to select LD subjects. Thus, the methods used in typology research will be briefly reviewed. The rationale for selecting a particular typology, that of Rourke and Finlayson (1978), will be presented. Secondly, the biological correlates of LD will be summarized and abnormalities in brain structure and function will be reviewed. The utility of ERPs for psycholinguistic research will be considered in terms of a research design to identify the electrophysiological correlates of LD subtypes.

The Issues and Goals of LD Research

Definition

It is generally accepted that learning disability (LD) refers to the failure to acquire reading skills in the absence of obvious etiology (Boder, 1971; Doehring & Hoshko, 1977; Fisk & Rourke, 1979; Fletcher & Satz, 1985; Lyon, Stewart, & Freedman, 1982; Malatesha & Dougan, 1982; Mattis, French, & Rapin, 1975; Petrauskas & Rourke, 1979; Satz & Morris, 1981). Specifically, despite apparently adequate intellectual, neurological, and sensory functions, academic training does not result in normal reading ability. Such a definition is based entirely on exclusionary variables describing what LD is not, rather than what it is (Benton, 1978).

The absence of a consensus on an operational definition of LD has resulted in confusion regarding both the behavioral characteristics and neurological substrates of LD. This is reflected in the nomenclature found throughout LD research: "congenital word blindness" (Hinshelwood, 1904); "strephosymbolia" (Orton, 1928); "primary reading retardation" (Rabinovitch, Drew, De Jong, Ingram, & Withey, 1954); "reading backwardness" (Kinsbourne & Warrington, 1966); "unexpected reading failure" (Symmes & Rapoport, 1972); "specific reading retardation" (Yule & Rutter, 1976).

Single Syndrome - Single Source Bias

Early researchers considered that LD was a unitary syndrome with a single source (Bender, 1958; Delacato, 1959; Drew, 1956; Frostig & Maslow, 1973; Hermann, 1959; Jorm, 1979; Kephart, 1960; Orton, 1937; Smith & Carrigan, 1959). Over the past few years, there has been an accumulation of clinical evidence indicating that reading deficits are heterogeneous. Researchers have developed typologies that identify two subtypes (Bakker, 1979; Bannatyne, 1971; Johnson & Myklebust, 1967; Kinsbourne & Warrington, 1963; Zangwill, 1962). Others have proposed three subtypes (Albert, 1979; Bateman, 1968; Benson, 1977; deQuiros & Shrager, 1978; Doerhing & Hoshko, 1977; Hier, Lemay, Rosenberger, & Perlo, 1978; Mattis, French, & Rapin, 1975; Smith, 1970). Typologies based on four and five subtypes (DeFries & Decker, 1980; Mattis, 1978) have also been constructed.

These attempts to establish LD classification systems that organize subtypes of homogeneous deficit patterns reflect a consensus that a unitary concept of LD is untenable. However, there is no agreement regarding the subtypes that have been proposed. Many typologies have been influenced by Orton's view (1937) that abnormal hemispheric lateralization is a determinant of LD. Several explanations of abnormal lateralization have been proposed, including developmental lag, biological predisposition, linguistic deprivation, and interhemispheric communication deficiencies (cf. Bryden, 1988). These models have guided research in such areas as the neurophysiological bases of LD, studies of cognitive abilities, and clinical assessment, as well as the development of experimental paradigms.

Goals of LD Research

An important goal of current LD research is to establish homogeneous subtypes of LD that are based on discrete characteristics. A related goal is to identify the basic units of reading skill acquisition. Finally, researchers aim to identify the biological determinants of specific deficit patterns. If such research is successful, it will facilitate early identification prior to academic failure and enable disability-specific remediation.

Classification System Research

Principles of Classification System Research

Currently, criticisms of LD typologies are guided by three principles of classification system construction (Fletcher, 1985; Fletcher & Satz, 1985; Skinner, 1981).

Firstly, a theoretical framework should be used to select the variables that will be used to establish subtypes. The framework can also be used to delineate a model of LD development and to identify pertinent external criteria with which to test the model. Secondly, the reliability or replicability of the system should be determined. Thirdly, external validation indices should be obtained, based on variables not used to develop the original typology. The typology literature will be briefly reviewed with reference to these principles (see Fiedorowitz & Trites, 1987).

Subjective Techniques

Several methods have been used to construct typologies. The earliest subtypes were based on patterns of neuropsychological test performance. Usually, subjects were assigned to groups on the basis of various criteria, such as language retardation and verbal and performance I.Q. discrepancies. Their subsequent performance on neuropsychological tests was compared and interpreted.

Researchers described subtypes that could be distinguished on the basis of visual, auditory, and auditory-visual association problems (Johnson & Myklebust, 1967). Another system differentiated 'genetic dyslexia' from 'minimal neurological dysfunction' (Bannatyne, 1966). These typologies represent the initial explorations of the heterogeneity of LD, however, methodological weaknesses such as the absence of experimental manipulation and the failure to analyze data statistically may restrict their validity.

Some typologies used neuropsychological test patterns both to identify clusters and to infer cerebral substrates (Kinsbourne & Warrington, 1966). Subjects were selected on the basis of verbal and performance I.Q. score discrepancies. Subsequently, a neuropsychological battery was administered and the results were interpreted in terms of similarity to patients with various sites of cerebral damage. For Group I, the Language Retardation Group, performance was considered to be similar to that of patients with aphasic (speech) dysfunctions resulting from left hemisphere lesions. The deficits of Group II, the Gerstmann Group, were likened to those of patients with left angular gyrus lesions, including difficulty with calculations, form perception, and finger and right-left differentiation. There are several limitations to this study. Subjects were selected on the basis of I.Q. scores which may confound the test performance. In addition, statistical analysis of group differences has been described as inadequate (Fedorowicz & Trites, 1987).

LD subtypes have also been differentiated on the basis of memory performance. Subjects were assigned to subtypes on the basis of performance on a test of linguistic ability, and tests of memory skills were administered (Bateman, 1968). The subtypes were described as demonstrating either poor auditory and good visual memory, poor visual and good auditory memory, or problems with both. However, the data were not statistically analyzed.

Data from neurological, electroencephalographic, and psychological examinations has been used to classify specific as opposed to general LD (Ingram, Mason, & Blackburn, 1970). The specific LD subjects were selected on the basis of poorer reading and spelling relative to other academic skills, and general LD subjects were deficient in all academic areas. The specific LD group appeared to display less evidence of brain damage than did the general LD group, and two subgroups emerged from the specific LD category. One of these was characterized by auditory-phonic deficits, while the other displayed visual-spatial deficits. This is an interesting study, however, the absence of an adequate control group and the use of visual rather than statistical analysis of the data restrict its conclusions.

Several LD classification systems have been derived from academic achievement measures rather than neuropsychological performance patterns (Aaron, 1982; Boder, 1971; 1973). Boder identified three subtypes of LD based on patterns of reading and spelling errors. Dysphonetic dyslexics are considered to have difficulty with grapheme to phoneme conversion as a result of problematic auditory processing; dyseidetic dyslexics are considered to have primarily visual-spatial deficits; while the mixed dysphonetic dyseidetic dyslexics display difficulty with both types of processing. One study reported that subtype membership was stable (Boder & Jarrico, 1982) while another found that it was not (Felton & Campbell, 1985). Several researchers have observed that the subtypes could be differentiated from normal readers but not from each other (Felton & Campbell, 1985; Nockleby & Galbraith, 1984; Van den Bos, 1984). In addition, the absence of both statistical analyses and specific selection criteria in the initial typology construction have been criticized (Satz & Morris, 1981).

In general, typologies derived from subjective clinical impressions are criticized on several bases. Usually, subjects are assigned to subtype groups on the basis of performance on a task or set of tasks. Such a priori selection forces subjects into subtypes, which may result in subtype performance that is an artefact of the selection criteria. Other weaknesses include the absence of a theoretical basis from which to derive testable hypotheses, subjective rather than statistical data analyses, and the failure to validate typologies on independent criteria (Doerhing & Hoshko, 1977; Satz & Morris, 1981).

Objective Classification Techniques

Several classification systems have been developed using psychometric principles. While the clinical impression method is based on inference from the score patterns of subjects who were assigned to subtypes a priori, the objective method sorts the scores of non-grouped subjects.

The Q-technique of factor analysis has yielded several typologies. Doerhing and Hoshko (1979) used this method to sort subjects on the basis of reading skill test scores. The typology consisted of three subtypes: Type O, considered to have an oral reading deficit; Type A, with auditory-visual association deficits; and Type S, deficient in sequential relations. Positive aspects of this system include a theoretical model which identified the crucial tasks in reading skill acquisition (Laberge & Samuels, 1974), internal validation using cluster analysis (Doehring, Hoshko, & Bryans, 1979), and subsequent replication (Doerhing et al., 1981). In addition, neuropsychological characteristics of the subtypes were identified (Fiedorowitcz, Trites, & Doerhing, 1980).

Petrauskas and Rourke (1979) also used the Q technique in an examination of neuropsychological and Wide Range of Achievement Test (WRAT) data sets. The study has been commended for establishing reliability based on both a split-sample analysis and the application of the cluster technique. Three subtypes of reading problems were found to be reliable. Subtype 1 subjects showed the largest difference between verbal and performance I.Q, the latter being higher. Their reading and spelling test scores were lower than their arithmetic scores. Subtype 2 displayed a small discrepancy between verbal and performance I.Q., and poor performance on arithmetic, reading, and spelling tests. Subtype 3 displayed lower verbal than performance I.Q. For this subtype, verbal comprehension was average, but verbal production was deficient.

In a similar study, Fisk and Rourke (1979) identified impaired spelling and arithmetic performance in addition to reading deficits, applying the Q factor technique to sort a large sample on the basis of neuropsychological measures. An important aspect of these studies is that a neurophysiological basis was proposed by relating patterns of performance to those associated with brain lesion syndromes. They also reflect a focus on hemispheric lateralization or specialization during language acquisition.

Rourke and Finlayson (1978) used similar methods to derive a system of language impaired subtypes based on patterns of WRAT scores. The subtypes were also characterized by neuropsychological test performance. This WRAT - based typology has been studied relatively extensively. Performance on verbal and non-verbal memory measures differentiate the subtypes (Fletcher, 1985), as does auditory versus visual phonemic coding in short term memory (Seigel & Linder, 1984). An additional strength of the Rourke typology is the interpretation of subtype dysfunctions in terms of a neuropsychological model of hemispheric specialization during the acquisition of language (Rourke, 1982). Thus, the typology meets many of the criteria for classification systems research. It is based on a theoretical structure that enables hypothesis testing. Subject selection is based on performance as opposed to a priori identification. The reliability and internal validity of the typology have been established. Furthermore, the subtype-specific biological substrates were delineated using a task analysis method, in addition to neuropsychological performance patterns.

However, the validity of this schema has not been extensively explored. That is, the subtypes have not been differentiated by measures that are independent of those used to construct the system. For example, if a system was originally constructed using tests of visual-spatial and auditory-verbal skills, concurrent but not external validation would be provided by the differentiation of subtypes on the basis of visual and performance I.Q. discrepancies.

Direct measures of brain function can be utilized for purposes of validation (Benton, 1978; Fletcher, 1985; Rourke, 1991), especially for a system that proposes specific hemispheric and modality abnormalities. The present research aims to investigate the validity of modality - specific deficits for subtypes of Rourke's LD typology using ERP indices.

Rourke's Typology

The subtypes derived from Rourke's research are differentiated by patterns of academic achievement on the WRAT reading, spelling, and arithmetic subtests (Rourke & Finlayson, 1978). Children whose grade-equivalent scores on all three subtests were below the expected grade-placement were classified as Group 1. Poorer performance on the reading and spelling subtests relative to the arithmetic subtest described Group 2 children. The Group 3 children were selected on the basis of relatively better reading and spelling than arithmetic scores. All children completed a battery of neuropsychological tests of visual-perceptual and auditory-perceptual abilities. The results suggested that the performance of Group 3 children would be predictable given right hemisphere dysfunction. Both Group 1 and Group 2 subjects exhibited results that would be consistent only with impairment of left hemisphere systems. Rourke proposed that motor, psychomotor, and tactile - kinaesthetic performance may be more sensitive to differences between Groups 1 and 2.

A Developmental Neuropsychological Model of LD Subtypes

In order to discuss the developmental neuropsychological anomalies associated with the typology, Rourke adopted the Goldberg and Costa (1981) model of hemispheric specialization in the acquisition of language.

The model proposes that the left hemisphere is particularly efficient for unimodal and automatic routine functions, while the right hemisphere is required for intermodal integration and for processing novel or complex information. Children who will become skilled readers are thought to engage the specialized functions supported by each hemisphere at particular stages during language learning. The initial stage of reading instruction depends on an existing auditory language system: the child can comprehend and produce speech. The introduction of print is considered to invoke right hemisphere activity because the graphic units are novel stimuli. Additionally, the units must be associated with the existing auditory verbal units (grapheme-to-phoneme conversion), which is a complex, intermodal task. The degree to which such conversion becomes automatic depends on the development of left hemisphere routinized codes. Consequently, right hemisphere systems will not be engaged, as the graphic units are no longer novel, and the association between graphemes and phonemes is represented in left hemisphere codes. At this level, left hemisphere systems are considered to support the automatic processing of text while the right hemisphere systems are available for further processing such as synthesis of more complex associations.

Rourke (1982) suggests that specific language difficulties result from disruptions in the involvement of either left or right hemisphere systems. The reading and spelling disabled (RS) group, previously referred to as Group 2, are considered to indicate impaired left hemisphere activity. The absence of automatic verbal skills is evident in the slow, laborious reading exhibited by these children. Intact right hemisphere systems are suggested by their ability to use nonverbal cues for comprehension and their well-developed visual-spatial analysis and synthesis.

The performance of the arithmetic disability (A) group, comparable to the Group 3 children, suggests deficient right hemisphere involvement. Word recognition in terms of phoneme to grapheme matching is superior to word comprehension indicating the development of overly automatic systems. This may result from left hemisphere development in the absence of right hemisphere processing. Additionally, their difficulty with visual-spatial organization and synthesis supports the implication of impaired right hemisphere systems.

The Group 1 children originally described as deficient in reading, spelling, and arithmetic (RSA) were not specifically considered in terms of this neuropsychological model. However, Rourke and Finlayson (1978) found that their performance was indicative of left hemisphere dysfunction, as was proposed for the Group RS subjects. They suggested that comparisons of motor, psychomotor, and tactile-kinaesthetic performances between Groups RS and RSA may indicate differential hemispheric function and explain their disparate academic achievement patterns. However, the specific type or system of dysfunction within the left hemisphere may differ for Groups RSA and RS. For example, left frontal versus left parietal abnormality may underlie the inferior arithmetic performance of Group RSA subjects.

Summary of classification system research.

Two methods have been implemented to construct LD typologies. The subjective method selects LD subjects on the basis of various criteria, and compares their performance on other measures. Subtypes have been differentiated on the basis of I.Q. scores, neurospsychological performance, and academic achievement. The objective method does not pre-select subjects. Batteries of tests are administered. The data set is then analyzed using multivariate techniques to construct homogenous clusters of deficits.

Many classification systems have associated subtype deficit patterns with auditory-verbal or visual-spatial impairment (Bakker, 1979; Boder, 1971; Ingram et al., 1970; Johnson & Myklebust, 1967; Kinsbourne & Warrington, 1963; Pirozzolo, 1979; Rourke & Finlayson, 1978). The prevalence of this association indicates that modality of processing may be a salient aspect of LD subtype differences.

A number of typologies have reported that the deficit patterns of LD subtypes are consistent with those caused by lesions to certain areas of the brain. Possible neural substrates for LD subtype deficits have been derived from these analogies.

Research regarding the neurophysiological perspective of LD has been hampered by the lack of consensus on the definition and description of subtypes. This brief review illustrates the diversity of selection criteria and deficits that face researchers who attempt to identify specific LD substrates.

Biological Bases of LD

An important consideration in reviewing the biological bases of LD literature is that many of the criticisms of classification system research are applicable. The comparison of disabled with normal readers on any biological measure is constrained by the diversity of the LD sample.

Therefore the absence of a common definition and the use of exclusionary variables for subject selection are again fundamental problems. In most cases, a theoretical structure has not guided subject or task selection. A notable difference between classification and substrate research is the profusion of new typologies in the former (Satz & Morris, 1981), and the failure to acknowledge differential deficit syndromes in the latter.

The literature will be reviewed in two sections. The first will summarize evidence for a relationship between LD and structural factors. The second section will review evidence derived from indirect and direct measures of brain function.

Structural Evidence

Genetic Evidence

The proposal that a genetic factor exists for LD was made by Morgan (1896), based on the observation of a higher incidence of reading problems in children of LD parents. The proportions of LD children with LD parents have been cited as ranging from 37% (Ingram et al., 1970) to 90% (Hallgren, 1950) of the LD population. Many studies report proportions within this range (Finucci, Guthrie, Childs, Abbey, & Childs, 1976; Finucci, Whitehouse, Isaacs, & Childs, 1984;

Vogler, DeFries, & Decker, 1985; Zahalkova, Vrzal, & Kloboukova, 1972). The wide range of incidence rates may result from the use of different diagnostic criteria or from studying heterogeneous samples.

Twin study results have been more consistent: monozygotic twins indicating 70, 84, and 100% concordance while dizygotic rates have been cited as 31, 29, and 33% (Bakwin, 1973; Hermann, 1959; Pennington & Smith, 1983). However, other factors, including environment and shared characteristics such as intellectual ability, may confound twin study findings (Regehr, 1987). A study that compared LD in natural and adopted children to control for these possible confounds supports the heritability theory (Benton, 1975).

Further support for a genetic basis is evident in studies of gender differences. The incidence of LD is higher in males than in females, ranging from 2:1 to 8:1 (cf. Critchley & Critchley, 1978). This has been interpreted as evidence that LD is genetically dominant in males and recessive in females (Sladen, 1970).

<u>Physical Anomalies</u>

LD is characterized by a greater incidence of physical anomalies. Anomalous hand and foot structure, head size, and palate are more prevalent in LD than normal children (Taylor & Fletcher, 1983). The observation that many LD are left-handed has led to the proposal that left-handedness, LD, and autoimmune disorders may be related to abnormal left hemisphere and thymus gland development as a function of the production rate of, or sensitivity to, testosterone (Geschwind & Behan, 1982). This view has been partially supported in that adult LD demonstrated a higher incidence of autoimmune disease, hayfever and asthma. However, the relationship between LD and left-handedness was not confirmed (Pennington, Smith, & Haith, 1984). The incidence of soft neurological signs or Minimal Brain Damage Syndrome such as graphesthesia and finger agnosia have also been observed in LD children and interpreted as evidence of a biological basis of LD (Adamas, Koosis, & Estes, 1974).

Pre- and Peri-Natal Complications

Reading difficulties are often observed in children who experienced pre- or peri-natal complications such as low birthweight or anoxia (Landry, Fletcher, Chapieski, Zarling, Frances, & Denson, 1984). As these complications may result in intellectual and neurological damage, it is difficult to accept that the reading impairment of these children is equivalent to those of specifically LD children. The comparison is further restricted by the use of apparently normal neurological and intellectual functioning as diagnostic criteria for LD.

The relationship between physical anomalies, pre- and peri-natal complications and LD suggests that abnormal structural development may jeopardize the development of reading skills.

Autopsy Studies

Although autopsy studies are scarce, those that have been conducted have been quite informative (Hynd & Cohen, 1983). The autopsy of a 12 year old boy who suffered a cerebral hemorrhage was reported by Drake (1968). This child displayed problems with reading, writing, and arithmetic in the absence of identifiable neuropsychological, cerebellar, motor, or sensory dysfunction. The autopsy revealed several anomalies that were not related to the cause of death. The left and right parietal gyral patterns were unusually wide and the corpus callosum was atrophied. Microscopic investigations indicated that the cerebral cortex was thicker than usual, that cellular lamination was columnar and ectopic, and that neurons were embedded deep in the white matter. However, the child was also diagnosed with enuresis, asthma, hyperactivity, dizziness, 'blackouts', emotional disturbances, and left frontal headaches. These abnormalities may confound the diagnosis as specific LD.

The autopsy of a 20 year old man diagnosed as LD also revealed interesting abnormalities (Galaburda & Kemper, 1979). The man was left-handed, with a familial history of LD, and had shown late speech onset, reading and writing difficulties, seizure disorder, and EEG abnormalities including slowing over the right hemisphere. Gross neuroanatomy was normal in size and appearance, including an intact corpus callosum. However, microscopic observation indicated abnormal cytoarchitecture primarily in the area of the planum temporale. Molecular layers were fused and poorly differentiated, and unusual white matter and pyramidal cell size and structure were detected. Interestingly, these anomalies were evident in the left hemisphere only.

CT Scans

Computer assisted tomography (CT) scans of LD subjects indicated that many showed a reversed asymmetry, right greater than left, of the size of the planum temporale, relative to normal readers (Hier et al., 1978). A similar reversal has also been noted in parieto-occipital regions (Rosenberger & Hier, 1980). Thus, there appears to be an association between brain size and LD, but the nature of this association has not been elaborated.

<u>Summary of structural evidence</u>.

Overall, autopsy and CT studies indicate that structural abnormalities, particularly of posterior left hemisphere sites, are associated with LD. This evidence that refers LD to left hemisphere deficits complements observations of left hemisphere damage in patients with acquired language impairments (Geschwind & Galaburda, 1985).

<u>Evidence for Functional Differences</u>

The previous section reviewed evidence for structural differences in the brains of normal and disabled readers. Evidence that the brain function of LD individuals also differs from normal readers has been assembled from a number of research areas. Studies of acquired language deficits have contributed to the understanding of the neurophysiology of normal reading. This information has been used to generate hypotheses of the substrates of LD deficits on the basis of equivalent language loss. Behaviourial techniques aim to identify hemispheric dominance for particular tasks. In this case, stimuli are presented to one hemisphere at a time. Dominance is inferred by comparing the performance of each hemisphere. The development of electroencephalographic and ERP techniques has enabled the measurement of brain activity within as well as between the hemispheres.

Lesion Studies

The loss of a previously acquired ability to comprehend written words due to the occurrence of pathology or surgical intervention is referred to as alexia. Aphasia refers to acquired dysfunctions of the production and comprehension of speech. Observations of such deficits have engendered neurophysiological models of normal language processes that are relevant to an understanding of LD.

Since Broca's reports (1861; 1865) of impaired language function in conjunction with lesions of the third left frontal convolution, this brain region has been associated with the motor patterns for speech articulation. Subsequent observations by Wernicke (1874) indicated a relationship between lesion to the posterior portion of the first temporal gyrus and language comprehension. It is now known that Broca's and Wernicke's areas are joined by the arcuate fasciculus nerve fibre bundle (Geschwind & Galaburda, 1985). This cortical system has been incorporated in neurophysiological models of speech processing.

The brain localization of reading functions in particular have progressed on the basis of studies of alexia, the loss of the ability to read. Lesions of the left angular gyrus were observed to especially disrupt text comprehension (Dejerine, 1914). Visual-spatial processes such as word and letter perception appeared to be intact, as patients could perform word copying tasks. However, words were processed as visual patterns with no semantic or linguistic value. The fact that left angular gyrus lesions would disconnect the visual and auditory language centres has been interpreted as an indication that the visual pattern for a word requires conversion to its auditory form for comprehension.

The relationship between language deficits and brain lesions has been used to localize specific aspects of language processing (Geschwind, 1984; Geschwind & Galaburda, 1985; Geschwind & Levitsky, 1968). Comprehension of spoken words is thought to require the activation of primary auditory cortex and subsequently of Wernicke's area. Word reading is considered to depend on arousal in the primary visual cortex, projection to the angular gyrus where visual patterns are activated and then to Wernicke's area for activation of the auditory form. Pronunciation of words would require projection to and arousal of the articulatory form in Broca's area in order to stimulate the appropriate muscle movement patterns in motor areas.

The disconnection of the hemispheres has also resulted in language dysfunctions. Autopsy studies indicate that damage to the splenium, a nerve fibre bundle that connects the hemispheres across the corpus callosum, could result in an inability to recognize or comprehend letters or words, despite intact visual fields (Trescher & Ford, 1937). Subsequent animal split-brain studies indicated that the corpus callosum was necessary for learning and memory (Sperry, 1961). This evidence has been interpreted as supporting a model of language that requires intact right as well as left hemisphere systems, and an interaction between these. Human studies suggest that the right hemisphere has the capacity for some but not all language functions. A right-handed commissurotomized patient could not pronounce or write the name of stimuli presented to the left visual field or felt with the left hand (Gazzaniga & Sperry, 1967). However, verbal expression was possible when stimuli were presented to the right hand or right visual field. Furthermore, intact verbal comprehension was demonstrated when responses could be expressed by manual or non-verbal means. Thus the right hemisphere was considered to support the comprehension but not production of language (Sperry, Gazzaniga, & Bogen, 1969; Dimond, 1972). Right hemisphere language capacity has been further specified, using contact lenses that allow the exclusion of a hemi-field but preserve normal eye movement (Zaidel, 1976; 1977). The right hemisphere is considered to be specialized for perceptual and short term memory processes, while the left hemisphere is specialized for linguistic tasks.

Implications for LD.

There is a degree of correspondence between types of acquired and developmental language deficits (Aaron, Baxter, & Lucenti, 1980; Ellis, 1979; Holmes, 1978; Jorm, 1979; Wolf, 1978; 1982). However, such comparisons must be regarded with caution. The neurophysiological systems of these groups may not function comparably during critical stages of language acquisition, therefore a posteriori comparisons must be guarded (Kremin, 1982; Wolf, 1982).

Overall, there is compelling evidence that left and right hemisphere systems are not functionally equivalent and may be specialized for different aspects of language ability. This has contributed to the view that normal reading is related to left hemisphere dominance for language. Consequently, hemispheric dominance abnormalities, such as a reversal or the absence of dominance, have been considered as possible substrates of LD.

Behavioural Techniques

The hypothesis that abnormal hemispheric dominance is related to LD has been evaluated using visual hemi-field and dichotic listening tasks.

Visual hemi-field studies.

This technique is used to assess hemispheric specialization. Verbal and visual stimuli are presented to the left or right visual field using tachistoscopic techniques. Stimuli presented to the left visual field are processed by right hemisphere systems and stimuli presented to the right visual field are processed by left hemisphere systems. The speed and accuracy of responses to stimuli presented to each field are compared. Better performance for stimuli presented to a hemi-field is interpreted as evidence that the contralateral hemisphere is specialized for processing that type of stimulus. For normal readers, left hemisphere systems have been found to be specialized for the identification of words and letters, while right hemisphere systems are specialized for nonverbal stimuli such as shapes and faces (Kimura, 1966; Kimura & Durnford, 1974; Marcel et al., 1974; Pirozzolo, 1979; Pirozzolo & Rayner, 1979; Pirozzolo, Rayner, Hansch, & Hynd, 1983).

The hemi-field technique has been used to investigate hypotheses of abnormal lateralization in LD. Normal readers have shown a larger right visual field advantage for verbal stimuli than LD subjects, indicating a greater degree of left hemisphere specialization. (Kershner, 1977; Marcel et al, 1974; Marcel & Rajan, 1975; Pirozzolo & Rayner, 1979). However, the opposite effect has been reported. Larger right field advantages for LD than normal subjects during verbal recognition tasks have been observed (Yeni-Komshian, Isenberg, & Goldberg, 1975; Gross, Rothenberg, Schottenfeld, & Drake, 1978). Furthermore, some researchers have reported no differences in hemi-field advantage (McKeever & Huling, 1970; McKeever & VanDeventer, 1975).

There is an indication that left hemisphere processing of verbal stimuli presented to the right hemi-field differs with reading ability. However, the inconsistency of this effect may indicate that other factors besides laterality are involved in LD. In addition, a wide range of stimulus parameters, age, and selection criteria have been utilized in this research and may have contributed to the diversity of findings.

Dichotic listening tasks.

In the dichotic listening procedure, pairs of stimuli are presented simultaneously to each ear. Verbal stimuli, letters and words, are better identified when presented to the right than the left ear (Kimura, 1961a, 1961b). This has been interpreted as evidence that the left hemisphere is specialized for auditory language processing.

In studies of normal and LD dichotic listening performance, normal readers usually indicate a larger right ear-left hemisphere advantage than do LD subjects (Bakker et al, 1980; Bakker, Teunissen, & Bosch, 1976; Hynd et al., 1979; Satz, 1976; Witelson & Rabinovitch, 1972). This technique was used to test the laterality of Boder's LD subtypes (Obrzut, 1979). The auditory-verbal deficit group, the dysphonetics, demonstrated a poorer degree of lateralization than did the visual-spatial deficit group, the dyseidetics.

However, other studies have reported that normal and LD groups displayed equivalent left hemisphere lateralization for language (Abigail & Johnson, 1976; Bryden, 1970; Leong, 1976; McKeever & VanDeventer, 1975; Satz, Rardin, & Ross, 1971; Sparrow & Satz, 1970; Witelson, 1976). Furthermore, normal readers do not always display left hemisphere lateralization (Witelson & Rabinovitch, 1972).

The dichotic listening task technique has yielded interesting but discrepant results. In general, both normal and LD subjects demonstrate a right ear advantage, or left hemisphere specialization, for verbal material. However, the size of the advantage is much larger in normal than LD groups. This suggests that the hemisphere of specialization may be normal for LD subjects, but less efficient than for normal readers.

Summary of behavioural techniques and hemispheric lateralization.

Although results of studies of the auditory dichotic and visual hemi-field responses of LD subjects are somewhat inconsistent, the evidence tends to show that LD subjects demonstrate deficient lateralization for verbal tasks in both the auditory and visual modalities.

Classification system researchers have observed that auditory-verbal and visual-spatial deficits characterize different subtypes of LD. It would not be surprising if the auditory task was not sensitive to primarily visual-spatial abnormalities, or the visual task to those of LD subjects with auditory-based deficits. If the LD subjects were not subtyped appropriately, the heterogeneity of the groups across studies would contribute to the diverse findings. (Bryden, 1982; Obrzut, 1988).

Electrophysiological Studies of LD

LD subjects do not process linguistic stimuli as efficiently as normal readers, and this may be related to deficient lateralization. However, this evidence is indirect. Researchers report the relationships between lesions and LD, or infer hemispheric specialization from behaviourial measures. Investigators have utilized techniques that measure hemispheric brain activation more directly.

EEG Studies

EEG studies have addressed two issues regarding LD. One body of evidence addresses EEG abnormalities in brain electrical activity, and the second investigates hemispheric dominance differences.

The incidence of EEG abnormalities in LD groups has been cited as ranging from 36% to 75% (Ayres & Torres, 1967; Hughes, 1971; Hughes, Leander, & Ketchum, 1949; Hughes & Park, 1968; Kennard, Rabinovitch, & Wexler, 1952; Webb & Lawson, 1956). The nature of the abnormalities include the appearance of positive spikes, excessive occipital slowing, epileptiform sharp waves or spike discharge, and diffuse or generalized deviations. However, the functional significance of these results is not clear (Hughes, 1982). Indeed, Hughes

(1982) has stated that the presence of such a variety of EEG findings may indicate that the patterns are of no particular significance and may not be useful in the study of LD. Moreover, the percentage of abnormalities varies greatly from study to study. This high variability may result from heterogeneous subject selection. It has also been noted that EEG deviations are a function of task. Researchers reported that LD subjects displayed a decrease in the 16 - 32 Hz range activity during reading but showed a reverse relationship while resting (Sklar, Simmons, & Hanley, 1973). Thus, inconsistent findings may result from the use of different tasks as well as selection criteria.

EEG studies of LD using linguistic stimuli have provided some useful data (Duffy, 1981; Duffy, Bruchfield, & Lombroso, 1979; Duffy, Denkla, Bartels, Sandini, & Kiessling, 1980). Duffy and his associates observed no differences in resting EEG between LD and control groups. However, the groups were differentiated during the performance of linguistic tasks. Normal readers demonstrated desynchronization of rhythms in the 9 - 13 Hz frequency band in left parietal regions, while this effect was markedly reduced in LD subjects especially at the left angular gyrus. A similar study wherein EEG was recorded during visual flash, auditory click, and somatosensory wrist taps again demonstrated less desynchronization during the visual and auditory tasks for LD subjects (Sutton, Whitton, Topa, & Moldofsky, 1986).

Several EEG studies of normal readers indicate more desynchronization or lower amplitude of alpha over the left than the right hemisphere (Galaburda, LeMay, Kemper, & Geschwind, 1978; Galin & Ellis, 1975; Galin & Ornstein, 1973; Geschwind & Levitsky, 1968; Wadu, Clarke, & Hamm, 1975; Witelson & Pallie, 1973). Desynchrony of alpha power has been interpreted as an index of cortical activation (Galin & Ellis, 1975). Studies of LD subjects indicate hemispheric anomalies such as less alpha attenuation over the left hemisphere (eg. Duffy, 1981; Fuller, 1977) but results have been equivocal (Hughes, 1971; Muehl, Knott & Benton, 1965). Overall, some evidence exists that the left hemispheres of LD subjects are not activated to the same degree as are those of normal readers. However, this is not a consistent finding. Again, this may be due to the inadequate classification of LD subjects. In addition, the presence of hemispheric activation differences may be obscured by the presence of other EEG abnormalities such as those discussed previously.

<u>Summary of EEG studies</u>.

Several findings recur in the EEG and LD literature. LD groups tend to display less desynchronization over the left hemisphere, particularly at posterior sites. However, the clinical and functional significance of many of the parameters on which LD subjects differ are not known. Furthermore, the incidence of EEG abnormalities is extremely variable and the LD groups have not been homogeneous. Another issue that must be considered in electrophysiological studies of LD is that the impairment, by definition, is specific to a type or mode of processing. Therefore, static measures such as the size of brain structures or electrical brain activity may not be sensitive to salient neurophysiological abnormalities if the impaired systems are not engaged.

ERP Studies

The development of event-related potential techniques has enabled the exploration of specific processes and brain regions engaged during task performance. The concurrent measurement of brain activity during stimulus processing is especially important for the study of clinical groups. For example, behavioural studies usually measure change in overt responses. Thus, it is difficult to determine whether group differences occur during the processing of the stimulus, in the commission of the response, or both.

ERP methodology is based on the recording of EEG during stimulus presentation and averaging the resultant waveforms. The ERPs are described in terms of the latency, amplitude, and scalp distribution of particular deflections or peaks in the waveforms. Their utility is largely in the association of certain deflections with particular psychological processes. In addition, ERPs are unobtrusive, non-invasive measures which do not require overt responses to stimuli. Thus factors such as performance anxiety, a serious problem for LD subjects, may be diminished because they are not required to read aloud.

ERPs and LD

LD research using ERP methods has yielded interesting but conflicting results. The diversity may be due to the use of non-standardized subject selection criteria including homogeneity of deficits, age range, gender, I.Q., sensory, and neurological performance (Rosenthal, Boder, & Callaway, 1982). The tasks performed by subjects also vary, being cognitive or sensory, and active or passive, and presented in different modalities (Ollo & Squires, 1986). Technical aspects such as electrode type and placement, reference site, recording and averaging parameters also vary widely. In addition, researchers often focus on different peaks of the waveform. Those occurring early are considered to reflect physical characteristics of the stimulus and are termed exogenous, while later peaks are thought to index the cognitive processing associated with the task, and are termed endogenous. Thus, it may be misleading to compare studies that measure peaks of different latencies. Despite these difficulties, ERP research has contributed to the understanding of LD. This research will be reviewed in two sections. The first will consider ERP studies that aimed to distinguish between normal and disabled readers, using one LD group. Some of these are heterogeneous groups, and others have used selection criteria for one subtype of an LD typology. The second will review ERP studies that compared several LD subtypes with each other and with normal readers.

ERP studies of normal and one LD group

Sensory tasks.

Early studies aimed to discriminate between normal readers and heterogeneous LD groups on the basis of early latency peaks, usually in response to visually presented stimuli, such as light flashes. An increased latency for various components has been reported (Shields, 1973; Sobotka

& May, 1977; Symann-Louett, Gascon, Matsumiya, & Lombroso, 1977; Weber & Omenn, 1977). This has been interpreted as a reflection of slower information processing by the LD subjects. However, other researchers did not observe latency differences (Preston, Guthrie, & Childs, 1974; Shelbourne, 1978).

Amplitude differences have also been reported. Decreased amplitude in the visual ERPs of LD subjects to light flashes were observed in positive (P140) and negative (N200) peaks at left parietal sites (Conners, 1971). The results were replicated by a number of researchers (Preston et al., 1974; Symann-Louett et al, 1977). However, opposite effects were reported by Sobotka and May (1977), who observed larger amplitudes at P140-N200 parietally, and at N200-P280 occipitally for LD subjects. Larger amplitudes were also observed by Shields (1973). In addition, null effects on amplitude have been reported (Weber & Omenn, 1977).

Reports of hemispheric asymmetry differences in early latency ERPs between normal and LD subjects are similarly inconsistent. Reversed asymmetry, right greater than left hemisphere amplitude, has been observed (Conners, 1971; Sobotka & May, 1977). Null group differences have also been reported (Weber & Omenn, 1977). Differences over both hemispheres, which constrains decisions regarding asymmetry, have been noted in both EEG and ERP measures (Duffy et al., 1980).

Cognitive tasks.

Several ERP waves are elicited during cognitive tasks such as decision making, and are affected by factors such as difficulty of the decision. As LD difficulties are primarily evident during cognitive tasks, and they do not exhibit identifiable sensory dysfunction, ERPs have been recorded during the performance of cognitive tasks.

The P3 has been interpreted as an index of certain cognitive processes, such as decision making. In a decision making task, the easier the stimulus evaluation, the shorter the latency of P3 (eg. Donchin et al., 1978; Kutas, McCarthy, & Donchin, 1977). Shelbourne (1978) reported that LD subjects exhibited larger positive amplitude waves than controls at later than 300 ms latencies in a visual word/nonword discrimination task. However, smaller P250-600 ms amplitude waves were recorded from an LD group during a letter identification task (Dainer et al, 1981). ERPs recorded during word and symbol perception tasks indicated an absence of absolute differences between controls and LD, although LD children did display smaller P3 amplitude to words than to symbols (Holcomb, Ackerman, & Dykman, 1985). Similarly, smaller P200 and P3 amplitudes were observed for LD subjects than for controls during a reading task (Cohen & Breslin, 1984). Again, P3 amplitude was smaller, and N2 and P3 latencies were longer for LD subjects processing letters, syllables, and words (Taylor & Keenan, 1990).

In general, visual ERP studies have shown that LD subjects exhibit smaller amplitude and longer latency P3 waves. The amplitude of P3 has been shown to vary with factors such as difficulty, surprise, probability, unexpected deviation in a series, and decision-making (Donchin, 1981; Donchin et al., 1978; Duncan-Johnson & Donchin, 1977; Kutas et al., 1977; Pritchard, 1981; Ritter, Simson, & Vaughn, 1972; Squires, Wickens, Squires, & Donchin, 1976). As P3 amplitude is inversely related to task difficulty (eg., Brookhuis, Mulder, Mulder, & Gloerich, 1983; Kok & Looren de Jong, 1980), the smaller waves of LD subjects have been interpreted as evidence that these tasks are indeed more difficult for them. In addition, P3 latency has been used as an index of the speed of information processing, as it increases with stimulus discrimination difficulty (eg. Duncan-Johnson & Kopell, 1981; Squires, Donchin, Squires, & Grossberg, 1977) and the size of a stimulus set in memory tasks (eg. Ford, Roth, Mohs, Hopkins, & Kopell, 1979; Gomer, Spicuzza, & O'Donnell, 1976). Thus, the extended P3 latency for LD is considered to reflect slower information processing in these children.

Auditory ERP studies.

ERPs to auditory stimuli have not been studied extensively. However, longer N100 and P200 latencies to tones (Cohen, 1980) and smaller slow wave amplitudes for LD than controls during an auditory discrimination task (Ollo & Squires, 1986) have been reported. Auditory tones evoked smaller positive waves at about 300 ms for LD than control subjects in several studies (Holcomb et al., 1985; Lovrich & Stamm, 1983). Larger positivities during a "tight-tyke" discrimination task were observed with an LD group, and distinguished controls and LD more accurately than numerous other ERP and EEG measures (Duffy, Denkla, Bartels, & Sandini, 1980; Duffy et al., 1980).

An innovative method that combines auditory and visual tasks is termed the probe ERP technique. An irrelevant stimulus, usually auditory tone pips, is used as a probe of relative activation of brain areas while the subject performs another task. Responses to tone pips while reading indicate a greater left than right hemisphere asymmetry for normal readers, while the LD group showed the reverse asymmetry (Shucard, Cummins, & McGee, 1984). Another study implemented the probe technique during reading silently and aloud material of two difficulty levels (Johnson, Galin, Fein, Yingling, Herron, & Marcus, 1984). The LD group displayed increased left hemisphere activation during difficult tasks, and, compared to normals, a greater asymmetry during reading aloud than silently. Interestingly, these investigators reported that latency was shorter for early peaks and longer for later peaks for the LD group. These results are not consistent with those of Shucard and associates (1984); however comparison is difficult due to factors such as differences in subject selection, task, reference site, and peak analysis and interpretation differences.

Summary of one LD group ERP studies.

The most common electrophysiological correlates of LD are smaller amplitudes and longer latencies for the P3 wave to words. This effect has been interpreted as a reflection of increased task difficulty and slower information processing for these children. Hemispheric asymmetry differences are extremely inconsistent.

ERP Studies of LD Subtypes

The view that heterogeneity of the LD group may contribute to such diversity of results has led to ERP studies that aim to differentiate subtypes of LD. Some researchers have adopted a priori typology selection criteria, such as Boder's test, while others have proposed new a posteriori typologies based on measures such as ear advantage and identified ERP differences between subtypes (eg., Bakker et al., 1980).

The typology developed by Boder was used to group LD subjects for an ERP study. As previously summarized, Boder's typology consists of three subtypes termed dysphonetic, dyseidetic, and mixed (1971; 1973; Boder & Jarrico, 1982). The deficits of the dysphonetic subtype are considered to result from left hemisphere dysfunction, while the deficits of dyseidetics have been related to right hemisphere systems (Boder & Jarrico, 1982). In order to determine if abnormal left hemisphere systems do underlie the dysphonetic deficits, ERPs were recorded to auditory word (do/go) and musical chord discriminations (Fried, Tanguay, Boder, Doubleday, & Greensite, 1981). Dysphonetic subjects failed to display the left greater than right hemisphere asymmetry evident in the ERPs of normal and dyseidetic subjects.

These subtypes were also examined in another ERP study (Rosenthal et al., 1982). Subtyped LD adults were instructed to attend or ignore targets within series of light flashes and clicks. Four of eleven dyseidetic subjects displayed greater left than right parietal P3 amplitude, and four of twelve dysphonetics displayed the reverse effect. The remaining subjects did not demonstrate either asymmetry. These results differ from those of Fried and associates (1981). This may be due to the use of both visual and auditory stimuli in the Rosenthal experiment, whereas only auditory stimuli were presented in the Fried study. In addition, the auditory task presented word and music stimuli, which apparently require different processing than flashes and clicks. The use of linguistic stimuli may be more sensitive to the deficits of certain LD subtypes. This may also explain the low proportion of dyseidetics demonstrating a greater left than right hemisphere asymmetry in the Rosenthal study. Furthermore, the Fried study selected LD children while the Rosenthal study used LD adults. Thus, developmental differences may underlie the disparity.

Bakker and his associates have developed and tested a typology based on performance on a dichotic listening task

(Bakker, Moerland, & Goekoop-Hoefheno, 1981; Bakker et al., 1980). Normal and LD subjects were categorized according to ear preference in the dichotic task. Visual ERPs were recorded during a word pronunciation task. Two components were scored: a positive peak, P310, and a negative peak, N440, at bilateral parietal and temporal sites. Right ear preference normal readers indicated a right asymmetry in temporal P310, whereas right ear preference LD showed a reverse effect. The right ear preference normal readers also exhibited a greater left than right asymmetry in temporal and parietal N440 amplitude, whereas the LD consistently displayed symmetrical N440. Left ear preference normals displayed a left asymmetry in P310 amplitude and no lateralization of N440 amplitude. Left ear preference LD subjects demonstrated symmetry in both peaks.

These effects were replicated in a similar experiment wherein remediation techniques were evaluated using both direct tachistoscopic stimulation of specific hemispheres and indirect stimulation based on visually versus phonetically demanding texts (Bakker & Vinke, 1985). Direct stimulation affected the parietal P250 component and was correlated with effective remediation.

These complex but innovative studies succeeded in discriminating normal and LD subjects and left and right ear preference subjects. However, the discrimination of left and right ear preference LD subjects may relate to particular subtypes of LD, and may not be sensitive to deficits in systems other than auditory-verbal. For example, it would be interesting to examine subjects selected on the basis of visual field preference rather than ear preference. In addition, the integration of these studies with other ERP findings is restricted by the unique categorization criteria.

<u>Summary of ERP studies of LD subtypes</u>.

In general, ERP differences between normal and LD groups are evident at posterior sites, especially over the left hemisphere. Normal readers tend to display larger left than right hemisphere asymmetry for verbal stimulus processing. Hemispheric asymmetry differences have been observed in LD groups, but are inconsistent. No study has reported ERP effects that discriminate all the subtypes of a typology, although LD subjects as a whole, and individual subtypes, have been dissociated from normal readers. Furthermore, the deficit patterns of subtypes indicate impairment of either the auditory-verbal or the visual-spatial aspects of reading. Despite the prevalence of this view throughout LD research, differences in the ability to process visual-spatial and auditory-verbal information have not been determined electrophysiologically.

Psycholinguistic Research and ERPs

Psycholinguistic research implementing ERP methods has progressed quite rapidly over the past few years. The hemispheric asymmetries inferred from the behaviourial studies previously mentioned have been observed in ERPs elicited by language processing (Kutas & Hillyard, 1982; Neville, 1980; Neville, Kutas, & Schmidt, 1982a, 1982b; Rugg, 1983a, 1983b, 1984). Furthermore, specific waveform deflections have been shown to reflect particular sub-processes that are fundamental to skilled reading.

N400 and semantic incongruity

In the first of a series of experiments, Kutas and Hillyard (1980a) attempted to use P3 latency as a marker of the effects of contextual constraint on reading. If a context provides information about a target word, it may facilitate the stimulus evaluation of that word. As P3 latency varies inversely with task difficulty, it was anticipated that latency would be shorter to predictable targets and longer to unpredictable targets.

In the first experiment, a context was established by presenting a sentence, one word at a time. The terminal word of most of the sentences was expected and meaningful. One-fourth of the terminal words were unexpected (eg., "He shaved off his moustache and eyebrows."). A P3 was elicited by expected terminal words; however, unexpected terminal words elicited a centro-parietal negative wave in the same latency range as the P3. The effect was replicated (Kutas & Hillyard, 1980b) using terminal words that were semantically anomalous, rather than solely unexpected (eg., "I take my coffee with cream and dog."). Again, the incongruous words were characterized by the negative wave, the N400. Another experiment was conducted to determine if this wave was sensitive to deviation in general, or to semantic deviation specifically (Kutas & Hillyard, 1980c). In this case, terminal words were semantically congruent but physically deviant from the sentence context (eg., "She put on her high heel SHOES."). Physical incongruity elicited a series of positive waves, not the N400. Therefore, semantic incongruity and not physical incongruity elicits the N400. Furthermore, studies that manipulated grammatical deviance (Kutas & Hillyard, 1983) and expectancy (Kutas & Hillyard, 1984a) replicated the sensitivity of N400 to semantic processing.

As the utility of an ERP marker depends on its specificity to a type of cognitive process, the role of memory in the elicitation of N400 was explored. ERPs were recorded to terminal words that followed four-word phrases (Neville, Kutas, Chesney, & Schmidt, 1986). The subjects were instructed to push buttons to indicate whether the fifth word fit or did not fit the meaning of the previous phrase. A test of recognition memory for the terminal words was administered. The trials recorded during the initial recording were re-averaged to enable the comparison of ERPs to words that would be recognized to those to words that would be forgotten. The N400 was not associated with subsequent recognition. On this basis, the authors concluded that the N400 was not an index solely of memory processes, but rather appeared to reflect associations between terminal words and the preceding context.

The view that the N400 indexes the processing of word associations was also demonstrated in an experiment exploring violations of semantic knowledge. Subjects were instructed to identify sets of propositions as being true or false (Fischler, Bloom, Childers, Roucos, & Perry, 1983). Regardless of the validity of the proposition, N400 waves were elicited by incongruous relationships between the words that comprised the statement. For example, "a robin is not a bird" elicited smaller N400 amplitude than did "a robin is not a vehicle", despite the fact that it is invalid. This effect has been interpreted as supporting the N400 as an index of the strength of associations between words (Kutas & Van Petten, 1988).

A negative wave that is sensitive to semantic association has also been observed in word pair paradigms. Pairs comprised of a prime and a target, were used in a study of a lexical decision making and ERPs (Bentin, McCarthy, & Wood, 1985). The target words were real or pseudowords, and either semantically related to the prime or not. The subjects were required to indicate by a button press whether the target was real or not. The primed (related) targets elicited smaller N400 waves than did unprimed (unrelated) words. Thus, the semantic relationship between the primes and the targets resulted in N400 differences, despite the fact that it was irrelevant to the lexical decision. This may reflect an automatic aspect of semantic incongruity processing (Kutas & Van Petten, 1988). This is important to psycholinguistic research as automaticity is considered to be crucial for skilled reading (Goldberg & Costa, 1981), and is clearly absent in the laborious reading of some subtypes of LD, such as Group RS.

These studies have used sentence, phrase, and single word contexts to manipulate the semantic congruity between words. The facilitation for a response to a target that follows a related context is referred to as priming (Meyer & Schvaneveldt, 1974). However, the cognitive and neurophysiological processes that mediate such facilitation are unknown. Cognitive psychologists have proposed that semantic priming is the result of automatic spreading activation (Collins & Loftus, 1975) or of a combination of automatic and attentionally-mediated processing (Posner & Snyder, 1975a, 1975b). The effects of priming on response speed and accuracy when the subjects' expectancies and the interstimulus interval are manipulated suggest that there is an automatic aspect to incongruity processing (Fischler, 1977; Neely, 1977; Tweedy & Lapinski, 1981; Tweedy, Lapinski, & Schvaneveldt, 1977). If the N400 is a specific marker of incongruous linguistic associations, it should similarly be elicited automatically, regardless of task instructions. In order to explore automaticity and the N400, ERPs were recorded to targets during a letter search task (Kutas, 1985a). Congruous and incongruous word pairs were presented and followed by a letter. Subjects were instructed to indicate whether the letter had appeared during the previous word pair. Thus the relationship between prime and target was irrelevant to task performance. N400 waves were elicited by both types of targets, but amplitude was much greater to unprimed than primed words. The association between prime and target was processed, despite the fact that this was not necessary for task performance. Thus, the N400 appears to be elicited automatically by semantic incongruity, paralleling the behavioural effects of priming on response performance.

N400 and Episodic and Subjective Incongruities

It is clear that the N400 is sensitive to violations of semantic associations between words. Other research has reported that violations of episodic and subjective associations among words can elicit the N400 as well.

Sentences were used to explore the effects of violations of episodic knowledge (Fischler, Childers, Achariyapaopan, & Perry, 1985). Subjects memorized statements wherein a name was associated with an occupation (eg., "Matthew is a chemist."). Subsequently, subjects viewed these statements, some of which had been recombined to create false statements (eg., "Matthew is a lawyer.") The false statement elicited N400 waves, despite the fact that the information regarding names and occupations was episodic and not semantic. Thus, the N400 was indicative of violations of arbitrary associations that had been memorized by the subjects.

In a related experiment (Fischler, Bloom, Childers, Arroyo, & Perry, 1984), the effects of violations of personal knowledge were examined. Experimenters collected personal information from the subjects such as name, sex, and size. Subsequently, sentences were presented, wherein the validity of the terminal word was varied. False statements elicited an N400 whereas true statements did not. Thus, the N400 also indexes the processing of words that are incongruous with self-referential knowledge.

N400 and Orthographic and Phonological Incongruities

Words can be associated on the basis of semantic, episodic, or subjective knowledge, and violations of these relationships are characterized by a specific deflection in the ERP, namely the N400. In addition, the N400 wave is elicited by such deviations even when they are incidental to task performance. However, that is not to say that the N400 is automatically and consistently elicited to unprimed targets regardless of task instruction. Several researchers have observed that the N400 is affected by the type of analysis that is required for performance of the task (Polich, McCarthy, Wang, & Donchin, 1983; Rugg, 1984). In studies of analysis effect, subjects were presented with pairs of words wherein the target varied in terms of rhyming with the prime, or in terms of physical similarity of letter groupings. In the phonological processing condition, subjects were instructed to indicate if the target rhymed with the prime. In the orthographic condition, subjects judged the physical similarity between prime and target. Interestingly, orthographically dissimilar targets elicited an N400 regardless of instruction, that is, in both the phonological and orthographic modality conditions. However, the N400 was evident to phonologically dissimilar targets only during phonological analysis. This may indicate that orthographic processing is obligatory while phonological processing is optional (Kutas & Van Petten, 1988).

These studies have shown that the N400 is elicited by incongruity of various linguistic parameters. Further support that it is linguistically specific was provided by a study of incongruity to four types of contexts (Besson & Macar, 1987). In this study, ERPs were recorded to targets following visually presented sentences; well known melodies; geometric figures ordered in ascending size; and notes of the musical scale in ascending order. Only incongruous targets in the linguistic context, the visually presented sentences, elicited the N400.

N400 and Single Word Reading

The previous studies reported the effects of contextual constraint on N400 amplitude. A negative wave occurring within the same latency range but with a frontal electrode site maximum, is elicited under several other conditions.

Neville et al., (1982a, 1982b) observed that reading a series of single words elicited a frontally distributed negativity, termed the N410. A parietal negative wave was apparent but smaller than that elicited by incongruous stimuli. Thus, in the absence of incongruity, the parietal negativity was minimal. Another experiment reported similar effects of word reading on the ERP: a frontal negativity at 421 ms, labelled Ny (Stuss, Sarazin, Leech, & Picton, 1983). This same study also observed that Ny was elicited by mental rotation of geometric figures. In a later report, the authors suggested that the Ny may be an index of access to long term memory (Stuss, Picton, & Cerri, 1986). The distinctions between the processes indexed by N400 and N410 and Ny are unclear, however, they appear to reflect different processes.

Summary of the linguistic sensitivity of N400.

The N400 is an ERP wave that is especially sensitive to linguistic associations. These associations can be semantic, episodic, subjective, orthographic, or phonological. The incongruity must be linguistic; musical, graphic, and physical incongruities, such as type size, do not elicit the N400. In addition, frontally distributed negative waves appear to reflect aspects of reading that do not require the processing of association between words. These discoveries are extremely important to the study of reading and learning disabilities for several reasons. A fundamental task in learning to read is the development of linguistic associations between the sound of a word and the printed representation of that word (Goldberg & Costa, 1981). Secondly, text comprehension depends on the ability to integrate a word meaning with a previous context. Thirdly, some LD children display difficulty with information processing within or between specific modalities (eg. visual grapheme to auditory phoneme conversion). Finally, some LD children display difficulty with text comprehension and verbal memory retention, for which the ability to form and retrieve associations is of vital importance. An ERP wave that is sensitive to manipulations of word associations may be used to identify not only individuals with such difficulties, but may isolate the nature of the dysfunction as well.

N400 Studies of LD

A study was conducted to determine if the N400 could differentiate normal and LD subjects in a word reading and recognition memory task (Stelmack, Saxe, Noldy-Cullum, Campbell, & Armitage, 1988). The LD group was comprised of children selected according to criteria from Rourke's WRAT-based typology (1978). Their ERP waveforms evoked during the serial presentation of words were compared to a control group of normal readers. A fronto-centrally distributed negativity, maximal at 440 ms post-stimulus, was evident for controls but absent for the LD group in the recognition memory phase. The waveforms of the LD subjects were characterized by a distinct positive peak at about 250 ms that was minimal for controls. As the N400 reported by Kutas is elicited during linguistic tasks, it was considered that the absence of the negative wave in the LD group may reflect impairment in some process(es) subserving skilled reading.

In order to investigate this hypothesis, two studies were undertaken. The first study constitutes a pilot study for the research that will be presented in this thesis

(Stelmack & Miles, 1990). It was designed to exploit the sensitivity of parietal negativity to semantic incongruity processing. The parietal N400 reported in many investigations by Kutas and her colleagues was considered to be a potential index of dysfunctional linguistic processing. As demonstrated in numerous priming studies, this wave is a function of contextual constraint. Therefore, a priming task was selected to determine if the unprimed word processing indexed by N400 differed for LD and normal readers.

To ensure that the waveforms reflected the effects of priming on reading target words, rather than reading per se, it was necessary to select priming stimuli that could be utilized as well by the LD as by the controls. The subtype examined in this study, Group RS, is considered to process visual-spatial material relatively normally. Therefore, pictures rather than words were used as the first member of each stimulus pair. The second member,the target, was a word that named the picture, or was unrelated. The results indicated that while ERPs to the pictures were relatively equivalent, the groups differed in parietal negativity. To unrelated target words, normal readers demonstrated a large fronto-central and a smaller, but marked, parietal negative peak. LD subjects exhibited fronto-central negativity that was somewhat smaller than that of normal readers, but minimal parietal activity. Fronto-central negativity was interpreted as reflecting the ability of the LD group to utilize visual-spatial information to facilitate the orthographic decoding of a word. The absence of parietal negativity was considered to reflect difficulty in accessing long term memory for word meaning.

Non-random presentation of pairs of pictures and their names were used to provide as much facilitation as possible for the LD group to maximize the effects of priming. This study succeeded in differentiating the LD and normal subjects on the basis of N400 responses to unprimed words. However, the relationship between primed words and their preceding pictures was denotative not connotative. Thus, identification of unprimed words would require only that the words did not name the pictures. This could be based on the identification of a single letter or even the length of the word, rather than the semantic incongruity processing usually associated with N400. As reading is a difficult task for these children, once the decision that a word did not name the preceding picture was made, they may simply have stopped trying to read it. It is possible that the LD subjects may have not fully processed either primed or unprimed words. The identification of primed words could have been based on the same process as that postulated for unprimed word identification. In addition, the fact that primed and unprimed pairs were presented alternately as opposed to randomly, may have facilitated this type of identification. Furthermore, the knowledge that a word was not going to name a picture and would have to be read without facilitation may have resulted in the LD subjects not attempting to read the word at all. Thus, negative wave differences in these LD subjects' ERPs may not reflect abnormalities in accessing word meaning, and may instead reflect a failure to engage such processes. Information regarding the processing of word associations will require the presentation of semantically related and unrelated pairs.

Rationale For the Current Research

Classification systems research and biological substrate research indicate that visual-spatial and auditory-verbal processing ability varies with reading ability. Rourke's subtypes demonstrate different performance patterns on neuropsychological measures of auditory-verbal and visual-spatial abilities. Thus, the ability to process stimuli presented in the auditory and visual modalities may differ for normal readers and LD subtypes. Priming experiments have shown that the processing of a word that is related to a context is facilitated and that this is reflected in the attentuation of N400 amplitude. If primes presented in the auditory and visual modalities are processed equivalently, the effect of priming on N400 will also be equivalent. For LD subtypes, if visual-spatial and auditory-verbal information processing is deficient, the priming effect on N400 amplitude will also differ. The priming task will provide information on the cognitive process of extracting or utilizing linguistic information from auditory-verbal and visual-spatial stimuli, which is more salient to LD than the sensory processing of auditory and visual stimuli. This is especially important in view of the absence of identifiable sensory deficits in LD children. The use of ERPs to measure these effects rather than relying on subsequent recognition memory accuracy will avoid possible confounds such as group differences in memory span for words, which may be affected by linguistic experience or performance anxiety.

The focus of this study is to assess the validity of the characterization of a typology on the basis of auditory-verbal and visual-spatial processing deficits. Research has shown that these deficits may be related to left or right hemisphere dysfunction, and that skilled reading is associated with left hemisphere dominance for language. Therefore, group differences in the asymmetry of N400 amplitude are also of interest.

<u>The Priming Tasks</u>

Word comprehension is facilitated by priming or preceding the word with a semantically related stimulus to the extent that the required systems can process the prime. Thus a graphic prime, such as a picture, may enable word comprehension if systems for such processing are functional. Similarly, an auditory-verbal prime, such as a spoken word, may facilitate comprehension, given intact auditory processing systems. As previously discussed, the deficiencies of each subtype can be compared in terms of the ability to extract and utilize information from visual-spatial graphic or from auditory-verbal stimuli.

Thus, normal readers, for whom both visual-spatial and auditory-verbal processing are intact, would display priming effects when reading related target words, regardless of whether the prime is a picture or a word. This would be reflected in smaller negative waves to words primed by pictures or spoken words, than to unprimed words. On the basis of the association between left hemisphere dominance for language and skilled reading, normal readers are expected to exhibit larger left than right hemisphere amplitude.

Group A subjects have been described as displaying visual-spatial processing difficulty which may relate to right hemisphere abnormalities. Although at this age range the reading and spelling skills of this subtype are at least normal, visual - spatial processing problems may relate to the linguistic difficulties exhibited by such children during the early stages of language acquisition (Rourke, 1982). If visual stimuli are not processed as effectively as auditory stimuli, pictures will not facilitate the reading of related words to the same degree as would spoken words. As facilitation is indexed by smaller N400 amplitude, auditory priming will evoke smaller N400 waves than would picture priming. If right hemisphere systems are involved in Group A visual processing deficits, this may affect the magnitude of a left greater than right hemisphere asymmetry.

Group RS subjects are considered to exhibit auditory-verbal processing deficits that are consistent with left hemisphere dysfunction. If auditory stimuli are not processed normally, N400 amplitude to auditory primed words will not be reduced. If visual-spatial processing is intact, N400 amplitude to picture primed words will be reduced. If left hemisphere dysfunction underlies the deficits of this group, hemispheric asymmetry of the N400 amplitude will be absent.

Group RSA deficits are considered to result from left hemisphere dysfunction, as for Group RS. The arithmetic skill deficits of Group RSA may result from other or additional abnormalities within the left hemisphere. If auditory processing is abnormal for this group, the N400 amplitude will not be reduced to auditory primed words. If Group RSA has dysfunctional left hemisphere systems that are intact for Group RS, the distribution of the N400 wave may differ for Groups RS and RSA. If visual-spatial processing is related to the arithmetic deficit of this group, picture primes may not reduce N400 amplitude to target words. If left hemisphere systems are impaired for Group RSA, hemispheric asymmetry will be absent.

Hypotheses

Auditory and visual priming effects.

The presentation of words that are related to a preceding picture or spoken word are expected to elicit smaller N400 amplitude than will unprimed words in normal readers.

It is expected that priming effects in the auditory and visual sessions will be equivalent for normal readers but not for the LD subtypes. N400 amplitude differences between responses to primed and unprimed words are expected to be greater in the auditory than in the visual session for Group A. The reverse is expected to occur for Groups RS and RSA.

A related hypothesis is that session effects on priming will be a function of the ability to process the prime, as opposed to reflecting differences in other reading processes. If group differences are due to priming differences rather than other reading processes, N400 amplitudes to unprimed words should be equivalent. In addition, session effects on priming could result from dysfunctions in processing one type of prime, or from superior processing of another type. If visual-spatial or auditory-verbal processing deficits do contribute to subtypes of LD, each subtype will exhibit smaller priming effects than the normal readers in at least one session. This will establish that abnormally poor as opposed to abnormally superior processing underlies session differences.

In summary, if visual-spatial and auditory-verbal processing deficits are related to LD subtype deficits, priming effects on N400 amplitude will differ between auditory and visual sessions, for LD but not for normal readers. Furthermore, N400 amplitudes elicited by primed words, unprimed words, and the magnitude of the difference between these, will demonstrate that session differences are a function of specific processing impairment. Group differences may be evident in responses to these stimuli.

Hemispheric asymmetry.

The association between left hemisphere dominance for language and skilled reading may be reflected in larger left than right hemisphere N400 amplitudes for normal readers and not for LD subtypes.

Recognition memory performance.

Recognition memory performance is expected to reflect differences in both priming and reading ability. If reading is facilitated by primes in one session, these primed words may be better recognized by LD subtypes than those from the other session. However, difficulty with comprehension of the words presented for recognition may obscure any facilitation LD subjects may have experienced during the acquisition phase. The memory performance can also be used to infer task compliance if the score is greater than would occur by chance.

CHAPTER II

METHODS

The ability to utilize linguistic information to facilitate the processing of subsequently presented words is indexed by N400 amplitude. The deficits of LD subtypes have been associated with visual-spatial or auditory-verbal processing impairments. Thus, their ability to derive facilitation from stimuli presented in the auditory and visual modalities may not be as efficient as that of normal readers. In order to determine the validity of modality-specific processing deficits for LD subtypes, visual and auditory priming effects on N400 amplitude were compared. This chapter will describe the ERP recording and testing schedule, subject selection procedures, visual and auditory session methods, EEG recording parameters, and ERP scoring methods.

Subjects

Subject testing and ERP recording schedule.

ERPs to visually presented words were recorded during auditory and visual priming tasks in independent sessions on two different days. Each subject participated in both sessions. The order of the sessions was counterbalanced. Half the subjects from each of the groups attended the auditory priming session first and the visual priming session second. The reverse order was used for the remaining halves of the groups. The Weschler Intelligence Scale for Children - Revised (WISC-R) (1974), the WRAT subtests, and the Peabody Picture Vocabulary Test - Revised (PPVT) (1981) were administered on a third day following the ERP recording.

Subject selection.

The subjects were 36 males between the ages of 10 and 13 years. Ten children were normal readers (Group NR). These children were recruited from the families of university students and staff. The LD subjects were drawn from the Learning Disabilities Clinic at the Children's Hospital of Eastern Ontario and the special education classes of the Ottawa Roman Catholic School Board. Extensive personal and medical histories and psychological assessments were provided by staff psychologists at these institutions.

The following selection criteria were observed for normal and disabled readers: (1) normal intelligence (IQ$\geq$90) as determined by the WISC-R; (2) no identifiable auditory or visual deficits; (3) no evidence of brain damage or emotional instability; (4) right-handed; (5) no medication; (6) and English first-language. LD subjects were specifically selected on criteria defining Groups RSA, RS, and A (Rourke & Finlayson, 1978). Performance on the reading, spelling, and arithmetic subscales of the WRAT (Jastak & Wilkinson, 1984) was used to determine the subtype. The RSA group was comprised of 10 subjects who obtained reading, spelling, and arithmetic scores at least 1.5 standard deviations below age norms. The RS group was comprised of 8 subjects who obtained standard reading and spelling scores at least 1.5 standard deviations below both age norms and their individual arithmetic standard scores. The A group was comprised of 8 subjects who obtained arithmetic standard scores at least 1.5 standard deviations below age norms and below reading and spelling scores, and at least normal reading and spelling scores.

The normal readers scored within or above the average levels for their age group on the reading, spelling, and arithmetic subscales of the WRAT. The PPVT was administered to both normal and LD subjects to assess receptive auditory vocabulary. The mean PPVT and WRAT scores were significantly higher for normal readers compared to the LD groups. There were no significant differences between the four groups for age or IQ. The performance scores for all subjects are shown in Table 1. T-test results are presented in Table 2.

Visual Session Method

Visual stimuli.

Stimuli were semantically associated and non-associated picture-word pairs arranged such that a picture was followed either by a related word or by an unrelated word. The picture stimuli were chosen from children's colouring books and consisted of black on white photographic slides of unambiguous black line drawings (Stelmack, Plouffe, & Winogren, 1983). See Appendix 1 for examples of pictures. The word stimuli were black on white photographic slides of horizontally presented single concrete nouns typed in uppercase pica font. Words were selected by identifying synonyms for the names of the picture stimuli. Words were also chosen from the PPVT and WRAT reading and spelling tests within the range considered to be of average difficulty for the 10 - 13 years age group. See Appendix 2 for lists of related and unrelated pairs.

Stimulus presentation.

The stimulus slides were presented via a Kodak carousel projector (Model 850H) that was equipped with a tachistoscopic shutter. A second projector presented a clear interstimulus slide between stimulus presentations. A Lafayette timer was modified to control both stimulus duration (2 s) and the synchrony of the two projectors such that the offset of the stimulus slide would coincide with the onset of the clear interstimulus slide. This method was used to eliminate confounding ERPs generated by changes in light intensity at stimulus onset. The stimulus slides and the interstimulus slides were projected onto a blank wall in the main laboratory. A RCA video camera relayed the projected image to a 22 cm video monitor placed 1.5 m from the subject in a sound-attenuated chamber. Picture stimuli on average subtended a horizontal visual angle of 5°, and an average vertical angle of 3°. Word stimuli subtended an average horizontal angle of 4°, and a vertical visual angle of 1°. Stimulus onset was initiated every 5 s by a Sperry microcomputer. Thus, each trial consisted of a 2 s stimulus presentation, either a picture or a word, and a 3 s blank interval to allow electrical activity to return to baseline and blinking if necessary. The recognition memory series of words was presented on an IBM microcomputer.

Procedure.

Each subject was presented with two series of stimuli: the acquisition series and the recognition series. In the acquisition series each subject was shown 70 associated and 70 non-associated pairs of pictures and words. The pairs were presented in a computer-generated Bernoulli random sequence. Each subject was asked to look at each picture and to read each word silently and to remember as many words as possible for a subsequent memory test. The subjects were informed that in some pairs the word was related to the preceding picture and that in other pairs it was not. The subjects were asked to predict the word from the picture in order to encourage attention to the picture presentation. Prior to the experiment, a practice period presented slides of digits to familiarize the subjects with the procedure. The subjects were asked to refrain from blinking or moving while the stimuli were being presented. A five minute rest period was provided following the first seventy pairs in the acquisition series. Stimulus presentation was paused after every two pairs to allow blinking. A ten minute rest period preceded the recognition memory task.

The subsequent recognition memory series was conducted in two sessions with a five min rest period. In each session, the subject was asked to discriminate 35 target words that had been shown in the previous acquisition series from 35 distracter words that had not been shown. In one session the targets were primed words, and in the other session the targets were unprimed words. The order of the sessions was counterbalanced such that half the groups responded to the primed target session first and the other half responded to the unprimed target session first. The stimuli in each session were presented in a random sequence. Subjects were instructed to press one key on the IBM keyboard if the word was previously shown and another key if it was not. All subjects used their right hand to respond. Subjects were instructed to respond within the 2.5 s duration of the stimulus.

Auditory Session Method

Stimulus presentation.

The stimulus pairs were comprised of spoken word primes and visual word targets. The target word stimuli were produced and presented in the same manner as in session I. The auditory priming stimuli were single concrete nouns spoken by the experimenter who was seated in the sound-attenuated chamber with the subject. See Appendix 3 for lists of related and unrelated pairs. The pronunciation onset was initiated by an auditory cue indicating that the recording of the previous single trial was complete. A 3 s interstimulus interval was established by timing on a stopwatch after pronouncing the prime word. The experimenter triggered the presentation of the visual word on the television monitor by depressing a key on the Sperry computer keyboard. The duration of visual word presentation was 2 s, and was followed by a 3 s interstimulus interval, as in the visual session. A recognition memory series of words following the acquisition series was presented on the IBM microcomputer.

Procedure.

The session consisted of an acquisition and recognition series as in the first session. In the acquisition series, 70 pairs of associated words and 70 pairs of non-associated words were presented to each subject. The first member of each pair was spoken by the experimenter and the second member was presented visually on the television monitor. The pairs were presented in a computer-generated Bernoulli random sequence. Each subject was asked to listen to each priming word and to silently read each target word and to remember as many words as possible for a subsequent memory test. The subjects were informed that in some pairs the visual word was related to the spoken word that had preceded it and that in some pairs it was not. The subjects were asked to predict the visual word from the spoken word in order to encourage attention to the spoken words. Prior to the experiment, a practice period presented slides of digits to familiarize the subjects with procedure. A five minute rest period was provided following the first 70 pairs in the acquisition series. A ten minute rest period preceded the recognition memory task.

The recognition memory procedure was identical to that in the first experiment, except that the primed word targets had been preceded by spoken words rather than pictures.

Following the recognition task, subjects were asked to read a list of 20 randomly chosen words that had been presented during the acquisition phase in order to estimate a reading error rate.

EEG Recording

The EEG was recorded from 10 mm Beckman Ag/AgCl electrodes affixed to the scalp at F3,F4,Cz,P3,P4 and Oz according to the International 10-20 system (Jasper,1958). Each scalp electrode was referred to a balanced noncephalic sternovertebral site (Stephenson & Gibbs, 1951). The vertical electroculogram (V-EOG) was recorded from electrodes placed on the supraorbital and infraorbital ridges of the right eye. The horizontal electroculogram (H-EOG) was recorded from electrodes placed on the outer canthus of each eye. The ground electrode was affixed to the forehead. The skin was abraded with a sterile needle at each of the scalp, ground, and EOG electrode sites to minimize skin potential artifacts (Picton & Hillyard, 1972). Inter-electrode impedance was below 2 Kohms.

EEG and EOG signals were amplified using Nihon Kohden EU/5D polygraph amplifiers. For all channels, the time constant was set at 2 s and the high filter at 35 Hz. Analog-to-digital conversion was carried out at a 10 ms sampling rate. Signal averaging was performed off-line for 3 s beginning .5 s prior to stimulus onset. Trials during which a signal exceeded $\pm$150 uV within 1 s from onset on either V-EOG or EEG channels were rejected.

Scoring

For each subject, the ERPs to the target words were sorted into four categories: auditory primed words, auditory unprimed words, visual primed words, and visual unprimed words. The ERPs were grand averaged into four mean responses for each electrode site. T-tests were used to determine if the number of trials in each category varied by group or category. These analyses were not significant. The mean number of trials of all subjects was 59 for auditory primed words; 62 for auditory unprimed words; 64 for visual primed words; and 57 for visual unprimed words.

Latency windows for the N400 wave were derived from the morphological and topographical characteristics of the grand averaged waveforms. Peak amplitudes were measured relative to baseline using an automatic scoring routine. These values were subsequently checked by manual scoring. Separate channel analysis was used to score the wave as group differences in the site and category of amplitude maximum precluded the use of the reference channel method. The latter method may have yielded values that would not reflect the actual distribution of the negative wave in each group.

For the normal readers, a negative wave in the 300 - 600 ms range was evident to unprimed words in both the auditory (X=465) and visual (X=457) sessions. Amplitude was maximum at fronto-central sites. This wave was termed N400. The amplitude of the N400 was measured at each electrode site for each word category in the waveforms of all subjects.

CHAPTER III

RESULTS

The sensitivity of the N400 wave to semantic incongruity processing was used to test the validity of modality - specific deficits for LD subtypes. Thus, the analyses were designed to address several issues. Firstly, an analysis was conducted to identify the negative wave evident in the ERPs as N400. A second analysis was conducted for each session separately to identify group differences to primed words, unprimed words and the magnitude of the difference between these conditions. This will also determine if session differences are the result of deficient systems for processing primes in one session, or unusually proficient systems for processing primes in the other session. The typology characterizes the subtypes as deficient in auditory-verbal or visual-spatial processing deficits. Therefore, visual and auditory priming effects on N400 amplitude were compared within each group.

The neuropsychological developmental model of subtype deficits associates skilled reading with left hemisphere dominance for language. Thus, the asymmetry of N400 amplitude was also examined.

Recognition memory scores were analyzed to determine if priming condition or reading ability affected memory performance and to allow inferences regarding task compliance. Reading list errors were also compared.

Data Analyses

Comparisons made on the basis of previous research were conducted using one-tailed t-tests. More complex comparisons examined data using analyses of variance (ANOVA) BMDP programs. Greenhouse-Geisser correction probability values were used for repeated measures. The Scheffe post-hoc technique for multiple complex comparisons at $p<.05$ was applied. Mean N400 amplitudes to all words for all groups are presented in Table 3.

N400

The most prominent feature of the waveforms of Group NR subjects was a negative deflection that occurred between 400 and 600 ms post-stimulus. Scalp topography was examined using a two-way ANOVA: priming condition (primed, unprimed) by electrode site (F3, F4, Cz, P3, P4, Oz), within each session separately.

Priming condition and site interactions were significant for both the auditory and visual sessions. Amplitude was maximal frontally and smaller but evident at parietal sites. This effect was much larger in the unprimed than primed condition, in both the visual and auditory sessions: $\underline{F}(4, 18) = 7.52$, $\underline{p}<.003$,; $\underline{F}(4, 18) = 8.34$, $\underline{p}<.000$, respectively. Latency differences were also analyzed but were not significant. Mean latency in the auditory session was 465 ms and 457 ms in the visual session.

Group Differences in Priming Effects

The following section presents analyses of N400 amplitudes for the auditory and visual sessions separately. It was proposed that primed words would elicit smaller N400 amplitude than unprimed words, and that this would differ for normal and LD subtypes. Thus, N400 amplitudes of the groups to primed words were compared. To determine that these difference were the result of differences in the ability to process the prime, as opposed to differences in reading per se, the N400 amplitudes to the unprimed words were also compared. In addition, group differences in the degree of priming ability were analyzed by comparing the magnitude of the priming effect on N400 amplitude. Group comparisons are illustrated in Figures 1 and 2.

Auditory Session

This analysis assessed the effect of preceding a word with related or unrelated spoken words on N400 amplitude.

Two-way ANOVAs were conducted on N400 amplitudes at each electrode site separately: group (RSA, RS, A, NR) by priming condition (auditory primed word, auditory unprimed word).

Group and priming condition interactions were significant at fronto-central sites: F3, $\underline{F}(3, 32) = 4.19$, $\underline{p}<.001$; F4, $\underline{F}(3, 32) = 4.48$, $\underline{p}<.009$; Cz, $\underline{F}(3, 32) = 3.01$, $\underline{p}<.044$. Main effects of group and condition were significant at parietal sites: P3, $\underline{F}(1, 32) = 5.72$, $\underline{p}<.022$; $\underline{F}(1, 32) = 17.91$, $\underline{p}<.000$; and P4, $\underline{F}(1, 32) = 10.85$, $\underline{p}<.002$; $\underline{F}(1, 32) = 11.31$, $\underline{p}<.002$. Individual comparisons between means indicated that these results were due to the following effects.

Groups NR and A displayed smaller N400 amplitudes during auditory primed words than did Groups RSA and RS. The amplitudes of Groups NR and A were equivalent at all sites. Group RS displayed the largest amplitudes at all sites.

Group differences in N400 amplitude elicited by auditory unprimed words were not significant at F3, F4, Cz, and Oz. However, group differences were evident at left and right parietal sites, where Group RSA exhibited smaller amplitude than did Group RS.

Groups NR and A demonstrated marked and equivalent differences in N400 amplitude to primed than to unprimed words. Group RSA and Group RS differences were not significant.

Visual Session

This analysis assessed the effect on N400 amplitude when words were preceded by related and unrelated pictures. Two-way ANOVAs were conducted on N400 amplitudes at each electrode site separately: group (RSA, RS, A, NR) by priming condition (visual primed words, visual unprimed words). Condition by group interactions at all sites except Oz indicated that group membership affected changes in N400 amplitude during priming: F3, $F(3, 32) = 11.61$, $p<.000$; F4, $F(3, 32) = 6.79$, $p<.001$; Cz, $F(3, 32) = 5.38$, $p<.004$; P3, $F(3, 32) = 5.54$, $p<.003$; P4, $F(3, 32) = 6.65$, $p<.001$; Oz, $F(1, 32) = 2.63$, $p<.06$. Analysis of these interactions indicated group differences in the following effects.

Group NR displayed smaller N400 waves to primed words than the other groups. At P3 and P4, the N400 amplitudes of the LD groups were similar. However, Group RS exhibited larger amplitude than all other groups at F3, F4, and Cz. At Oz, Groups RS and A displayed smaller negative amplitude than did Groups RSA and NR.

For unprimed words, Group RS and Group A displayed smaller negative amplitude than did Group NR and Group RSA.

Only Group NR displayed smaller N400 amplitude to primed than unprimed words at all sites. Group A amplitudes were significantly smaller to primed than unprimed words, but only at frontal sites. The difference between primed and unprimed words at these sites was smaller for Group A than for Group NR. At all other sites, the LD groups did not display significant differences in N400 amplitude.

Session Effects on Priming

Auditory and visual session priming effects on N400 amplitude were compared. Difference measures were computed by subtracting N400 amplitudes to the unprimed words from those to the primed words for each electrode site. T-tests were computed to compare the difference measures in the auditory session to those in the visual session. Difference score means are presented in Table 4. Session effects on priming are presented in Figures 3 to 6. This analysis was used as differences in session priming effects were the primary a priori hypotheses and had been previously tested in part during the pilot study. In addition, the complexity of the group by priming condition by session interactions that would have been obtained with ANOVA would not have enhanced the interpretation of these data.

Groups NR, RS, and RSA results indicate no difference in priming effects on N400 amplitude as a function of session at any site.

Group A differences were significant at all sites; F3, $\underline{t}(7) = 2.27$, $\underline{p}<.03$; F4, $\underline{t}(7) = 2.02$, $\underline{p}<.04$; Cz, $\underline{t}(7) = 3.08$, $\underline{p}<.01$; P3, $\underline{t}(7) = 2.48$, $\underline{p}<.02$; P4, $\underline{t}(7) = 2.14$, $\underline{p}<.04$, and approached significance at Oz, $\underline{t}(7) = 1.39$, $\underline{p}<.10$. For this group, amplitude differences were larger in the auditory condition.

Hemispheric Asymmetry

Visual inspection of the waveforms indicated that asymmetry was affected by priming condition. Thus, the effect of auditory versus visual session priming on the asymmetry of the N400 wave was examined using four-way ANOVAs for the frontal and parietal lateral electrode sites separately: group (RSA, RS, A, NR) by session (auditory, visual) by priming condition (primed, unprimed) by hemisphere (left, right). These comparisons are illustrated in Figures 7 and 8.

A group, priming condition, and hemisphere interaction differentiated the asymmetry of the frontal N400 amplitude of the reading groups: $\underline{F}(3, 32) = 3.36$, $\underline{p}<.01$. Group NR exhibited marked left greater than right hemisphere N400 amplitude for unprimed words in both the auditory and visual session. Hemispheric differences were not significant at parietal sites.

Summary of N400 results.

Statistical analyses of the waveforms of normal and disabled readers indicated several areas of difference. Only normal readers exhibited equivalent and significant priming effects on the amplitude of N400 in both sessions, consistent N400 amplitude at frontal and parietal sites to unprimed words, and a markedly larger left than right hemisphere asymmetry at frontal sites during unprimed words. None of the subtypes showed all three effects.

Group A displayed larger priming effects on N400 amplitude in the auditory than in the visual session. Priming effects were significant in the auditory session at all sites. Visual priming effects were smaller than in the auditory session and only at frontal sites. Laterality was not evident.

At most sites, Group RS displayed larger amplitude waves to primed words than all other groups. Priming differences in N400 amplitude were not significant in either the visual or auditory session. A slight asymmetry to auditory primed words was not significant.

Group RSA did not display priming effects on N400 amplitude. They were differentiated from Group RS by displaying smaller amplitudes primarily to auditory primed words. They also differed at fronto-central sites to visual primed words. Asymmetry was not evident for this group.

All the LD groups were distinguished from Group NR in three effects. Firstly, all subtypes exhibited some degree of N400 amplitude during primed words. Secondly, none of the groups exhibited the consistent, discrete parietal negativity to unprimed words evident in Group NR waveforms. Finally, none of the LD groups displayed the frontal asymmetry in N400 amplitude to unprimed words that was evident for Group NR.

Recognition Memory Performance

The mean recognition memory scores (d') for each group are presented in Table 5. A group (NR, RSA, RS, A) by session (visual, auditory) by priming condition (primed, unprimed) ANOVA was computed. Main effects of group and priming condition were significant: [$F(1, 32) = 12.63$, $p<.000$; $F(1, 32) = 19.81$, $p<.000$]. A session by priming condition interaction was also significant: [$F(1, 32) = 12.01$, $p<.002$]. Individual comparisons between means indicated that these effects resulted from higher scores for Groups NR and A than for Groups RS and RSA, and for primed than unprimed targets. The interaction resulted from higher scores for visual than for auditory unprimed targets.

Reading List Errors

T-tests were conducted on the number of errors each subject from each group committed on the reading list test. Group NR (M = .1, SD = .316) and Group A (M = .38, SD = .518) committed few errors and did not differ; [$t(16) = 1.32$, $p<.214$]. Group RSA (M = 20.9, SD = 8.3) and Group RS (M = 33.3, SD = 8.7) produced more errors than did Group NR: [$t(18) = 7.93$, $p<.000$; $t(16) = 11.43$, $p<.000$], and more than Group A, [$t(16) = 7.01$, $p<.000$; $t(14)=11.32$, $p=.000$]. Group RS committed more errors than Group RSA, [$t(16) = 3.18$, $p<.006$].

CHAPTER IV

DISCUSSION

This research examined the validity of the characterization of LD subtypes on the basis of auditory-verbal and visual-spatial processing deficits (Rourke & Finlayson, 1978). The N400, an ERP wave that is sensitive to linguistic processing, is attenuated for primed words (eg., Fischler et al., 1983, 1985; Kutas & Hillyard, 1980a, 1980b, 1980c, 1983, 1984a; Kutas, Neville, & Schmidt, 1987; Neville et al., 1986). If a processing system is dysfunctional, primes presented in that system should not reduce N400 amplitude. Thus, the normal and LD subtypes were expected to exhibit different degrees of N400 attenuation. Furthermore, primes presented in the processing system that is considered to be intact for a subtype were expected to have a larger attentuation effect than primes presented to the deficient system. It was also expected that the substrates that underlie the different patterns of academic achievement exhibited by Groups RS and RSA would be evident in their ERP responses.

In the present study, the ERP waveforms clearly differ with reading ability, priming condition, and with the modality in which a prime is presented. This investigation of the validity of modality - specific deficits for LD subtypes will depend on the extent to which the ERPs support three hypotheses. Firstly, if changes in the amplitude of N400 to primed words are to be interpreted as reflecting the ability to process auditory or visual primes, it must be established that the N400 is sensitive to linguistic processing requirements in normal readers.

Secondly, visual and auditory session priming effects on N400 amplitude should differ according to the deficits proposed for each subtype (Rourke & Finlayson, 1978).

It must be determined that session priming differences result from impairment with one type of processing as opposed to proficiency with another, and that the ERPs reflect differences in semantic priming rather than other reading abilities. Therefore, a third section will interpret between-group differences to primed words, unprimed words, and the magnitude of the difference between these. Differences between Groups RS and RSA will also be considered in this section.

As the typology has been discussed in terms of a developmental model of hemispheric specialization during language acquisition (Goldberg & Costa, 1981), N400 asymmetry differences will also be interpreted. Finally, considerations for future research will be proposed.

The Linguistic Sensitivity of N400

It has been established that the amplitude of the parietal N400 wave is sensitive to violations of semantic associations between words (cf. Kutas & Van Petten, 1988). Thus, N400 varies with some aspect of semantic processing. It has also been shown that fronto-central negativity is elicited by word reading tasks (Neville, 1985) and by the mental rotation of geometric figures and picture naming (Stuss et al., 1983; Stuss et al., 1986). This may reflect some aspect of the visual-spatial or orthographic analysis of words. In children, it has been shown that words that are incongruent with a context elicit both fronto-central and parietal negativities in the 300 to 500 ms latency range, and that these waves are attenuated to primed words (Stelmack & Miles, 1990). For normal readers, then, priming may serve to facilitate aspects of both the orthographic and semantic processes involved in reading.

The present research replicated the effect of picture priming on reading related words for normal readers (Stelmack & Miles, 1990). The amplitude of the N400 wave at both fronto-central and parietal electrode sites was larger to unprimed than to primed words in both the auditory and visual sessions. If fronto-central N400 reflects orthographic analysis and parietal N400 semantic analysis, it follows that, for normal readers, a prime serves to facilitate both the reading or orthographic analysis of a word and its semantic analysis, regardless of the modality in which the prime is presented.

As no overt responses were required during the sessions, the subjects were informed that a recognition memory test would follow in order to encourage task compliance. The analysis of recognition memory scores indicates that performance was better than chance. In order to achieve this level, the subjects must have been attempting to read the words (Green & Swets, 1966). Therefore, the ERPs may be considered to have functional significance as indices of processing activity differences.

Session Effects on Priming

For normal readers, the difference in N400 amplitude between primed and unprimed words was equivalent in the auditory and visual sessions at all sites. Thus, picture and spoken word primes enabled equivalent facilitation for the reading of target words. If fronto-central and parietal negativity are indicative of orthographic and semantic activity, it may be concluded that, for normal readers, both processes were equally facilitated by auditory and visual priming.

Similarly, there were no differences in the change of N400 amplitude in the auditory or visual sessions for Groups RSA and RS. It was predicted that these groups would exhibit smaller priming effects in the auditory than in the visual session, due to indications of deficiencies in left hemisphere systems, which may impair auditory-verbal processing. Although, it appears that auditory priming did not differ from visual priming, on the basis of this analysis it cannot be determined that these systems are equally impaired or equally efficient. The interpretation of between - group differences will address this issue. However, it can be concluded that although left hemisphere systems for auditory-verbal processing are considered to be impaired for both Groups RSA and RS, visual processing does not appear to be functionally different.

Group A subjects exhibited larger priming effects on N400 in the auditory than in the visual session. This result was predicted on the basis that Group A is characterized by visual-spatial processing deficits (Rourke, 1982) and therefore that visual priming would be ineffective in reducing N400 amplitude. In the auditory session, N400 amplitudes were smaller to primed than to unprimed words at fronto-central and parietal sites, as was evident for normal readers. Thus, the visual-spatial processing of related targets appears to have been facilitated by spoken word primes despite the impairments these subjects exhibit with visual-spatial processes. Semantic processing seems to have been similarly affected. As predicted, picture priming did not have the same effect on N400 amplitude. Thus, the ability to extract or utilize information from visual stimuli may be a salient variable in the learning difficulty that is associated with Group A subjects during the early stages of langugae acquisition. It cannot be determined from this analysis if the magnitude of the priming difference in the auditory session is similar to that in normal readers. Nor can it be ascertained whether the session differences are due to deficient visual-spatial processes or to proficient auditory-verbal processes. This will require the interpretation of group responses to words within each session.

In summary, visual and auditory priming effects provided support for the modality - specific deficit hypothesis associated with Rourke's LD typology. Certainly the LD subtypes were differentiated by ERP patterns. Auditory priming was more effective than visual priming for Group A. Groups RS and RSA did not exhibit differences in auditory or visual priming. The predictions regarding the nature of the subtype differentiation were not entirely accurate. Only Group A exhibited larger attentuation of N400 amplitude to primed words than to unprimed words in the session considered to engage their intact processing skills.

Group Comparisons

Group responses to primed and unprimed words and the magnitudes of difference in N400 amplitude between primed and unprimed words were compared to address three issues. The first was the source of session differences (proficiency or deficiency), the second whether these resulted from reading or priming ability differences, and finally, to examine the distinctions between Groups RS and RSA.

N400 to Unprimed Words

It was considered that session differences in N400 amplitude could only be interpreted as priming ability differences if the group responses to unprimed words were equivalent. Differences did occur to auditory unprimed words, but between Groups RSA and RS, not between these groups and normal readers. As these LD groups did not exhibit priming effects, interpretation of the results is not affected. Similarily, differences were evident to visual unprimed words at Oz, in that Groups RS and A displayed smaller amplitude responses than Groups NR and RSA. Again, session differences in the priming effect on amplitude were not significant at this site.

However, this does distinguish Group RS from Group RSA. Both are considered to have left hemisphere dysfunctions that impair auditory-verbal processes (Rourke & Finlayson, 1978). The amplitude differences at parietal sites suggest, however, that semantic processes may not be equivalent. The additional arithmetic difficulties of Group RSA may relate to an inability to associate visual-spatial symbols with semantic concepts, whereas for Group RS this deficit may be more specific to linguistic symbols. Thus, for Group RS auditory-verbal processing impairment may be primarily verbal, while for Group RSA more general auditory information processing may be problematic.

Group A responses to auditory unprimed words were equivalent to those of Group NR. Therefore, interpretation of differences to primed words as an effect of priming rather than reading ability is justified.

<u>Magnitude of the Priming Effect</u>

If normal readers exhibited larger priming effects than each LD subtype in at least one session, then differences in session effects on priming could only be attributed to impairment with a particular type of processing rather than abnormal proficiency with another. The magnitude of the auditory priming effect was equivalent for Group A and normal readers. The magnitude of the visual priming effect was larger for normal readers than all other groups at all sites. Group A indicated significant differences only at frontal sites and to a much smaller degree. Thus, it can be concluded that Group A does not process visual-spatial stimuli as efficiently as auditory stimuli, nor as efficiently as normal readers. However, not only are auditory stimuli processed more effectively than visual stimuli, they are processed relatively normally. This is consistent with the neuropsychological characteristics of this group.

Differences that are associated with session effects can be interpreted as resulting from deficiencies with one or more types of processing. This would seem to be an obvious and perhaps unnecessary conclusion. However, as the major hypothesis of this research concerned differential session effects on priming, and as Group A subtype exhibits very rapid processing of certain types of information (Rourke, 1982), the analysis was considered crucial to further interpretation.

<u>N400 to Primed Words</u>

Visual and auditory primed words elicited different N400 amplitudes for normal readers and LD subtypes. In the visual session, normal readers exhibited smaller N400 amplitude to primed words than all the LD subtypes. This suggests that generally normal readers derive more facilitation from visual primes than all other groups. This effect occurs at fronto-central and parietal sites. Thus, for normal readers, preceding a word with a related picture may serve to facilitate both the visual-spatial and semantic processes required for reading.

In the auditory session, normal readers also displayed smaller N400 amplitude than Groups RS and RSA, but Group A amplitudes were relatively equivalent to normal readers. Both Group A and normal readers exhibited smaller amplitude responses than Groups RS and RSA. This suggests that auditory-verbal primes were processed as efficiently by Group A as by normal readers, and that this facilitated the processing of the targets in terms of orthographic and semantic processing.

As Group A readers display better word recognition than comprehension (Rourke, 1982; Rourke & Finlayson, 1978), it follows that their orthographic ability would be superior to semantic processing. Interestingly, this group displayed priming effects on frontal but not parietal N400 amplitude. This may reflect that, for Group A, visual-spatial information can be used to facilitate orthographic analysis but not semantic processing. This interpretation is supported by Rourke's view that right - hemisphere deficits are related to the development of extremely automatic but deficient left - hemisphere systems for reading in the absence of adequate semantic associations. Reading may be facilitated by visual primes, but the systems for processing visually presented words may not incorporate semantic information. If auditory-verbal processes are intact, semantic information may be accessed by spoken words and may be reflected in the parietal N400 effects in the auditory session.

Groups RS and RSA, which were considered to have deficient auditory-verbal processing, appear to have not been able to extract or utilize information from either spoken or visual primes. As intact auditory comprehension is considered to be a prerequisite for the normal acquisition of reading skills (Goldberg & Costa, 1981), impairment with auditory-verbal systems may have precluded the development of neural systems for visual word patterns that are considered to subserve reading (eg., Geschwind, 1984; Geschwind & Galaburda, 1985). Although these groups display intact visual-spatial processes (Rourke & Finlayson, 1978) picture priming did not affect the processing of target words. It may be that they have difficulty with visual linguistic information in addition to their auditory processing deficits. However, it may be that these children are not deficient in the extraction or utilization of information from visual stimuli, but that neural systems for word pattern processing do not exist, or are so impaired that they cannot function adequately despite facilitation.

In the previous study, Group RS subjects displayed smaller N400 amplitude to picture - primed words at fronto-central but not parietal sites (Stelmack & Miles, 1990). In this study, picture primed words did not elicit smaller negativities for the same subtype. This may be due to the relationship between pictures and primed targets in the first study being denotative, while this experiment established connotative or semantically related associations. Group RS may be able to derive enough information from pictures to identify their names, but this may not be sufficient to enable the reading of related words. Perhaps the reading of names is performed on the basis of identification of one or several letters and does not require complete processing of the entire word. However, this suggests that the absence of superior visual priming effects evident in this study is due to deficits with the processing of the target words, as opposed to the systems for processing visual-spatial stimuli.

The sessions effects did differentiate the LD subtypes from each other as well as from normal readers. However, inspection of the waveforms indicates two anomalous findings. Firstly, Group RS exhibited unusually large N400 amplitude to primed words in both sessions, particularly at fronto-central sites. This may indicate difficulty with visual-spatial as well as auditory-verbal processing, as previously discussed, However, several other interpretations are possible. If auditory-verbal processing is deficient for this group, it is feasible that motor patterns for articulation, usually associated with Broca's area, a frontal system, have not developed normally. The larger amplitude at frontal sites may reflect additional activation of such systems that have been impaired due to auditory-verbal dysfunction. Many of the Group RS and Group RSA children demonstrated great difficulty in not repeating the spoken word primes, and especially in not pronouncing the target words aloud. It was necessary for the experimenter to place a finger in front of the lips of these children for several trials several times over the course of the session to prevent this behaviour. As tongue movement can result in 100 microvolt amplitude waves at central electrode sites (Picton & Hink, 1974), the large fronto-central amplitude may reflect this rather than any cognitive function. However, it is also possible that the children could not completely inhibit the activation of articulation motor patterns, and that this was reflected by frontal amplitudes. It may also be that the neurophysiological model that proposes that access to auditory representations is required for full visual word pattern comprehension explains this anomaly.

An additional caution in interpreting these data is that of assuming that the target stimuli are processed as words. The fronto-central negativity has been interpreted as reflecting the visual-spatial processing of words. This referred to the orthographic analysis of visual-spatial letter or letter-group patterns, not solely of a visual shape per se. However, it is impossible to ascertain that subjects, especially those of LD groups, were not processing these stimuli on the basis of word length or shape, as opposed to that of the actual information represented by words.

Previous LD Studies

The ERP studies of LD subjects that were previously reviewed implemented tasks that were designed to elicit the P3. This wave is associated with factors such as difficulty of decision making and memory set size, but not specifically linguistic processing (eg., Donchin, 1981; Donchin et al, 1978; Pritchard, 1981). Thus, it is difficult to integrate the results of the current study with those findings. However, the most commonly observed effect was that amplitude differences between normal and LD groups occurred at parietal sites (eg. Bakker et al, 1980, 1981; Conners, 1971; Duffy et al, 1980; Preston et al, 1974; Rosenthal et al., 1982). In this study, several parietal differences were also evident. None of the LD groups displayed parietal priming effects on N400 in the visual session. While frontal differences were also absent for Groups RS and RSA, parietal abnormality is certainly implicated. Therefore, the P3 and

N400 are elicited by different tasks but the parietal distributions of both are unusual for LD subjects.

It has been suggested that the role of hemispheric dominance for language may not be the only salient issue in LD. The development of frontal to posterior systems has been suggested as a possible focus for research (Rourke, 1982). The unusual frontal activity of Group RS and the parietal abnormalities of all the LD groups indicate that intrahemispheric as well as interhemispheric functions may be biological determinants of LD deficits.

Hemispheric Asymmetry

Group NR subjects exhibit left greater than right hemisphere asymmetry in frontal N400 amplitude during both auditory and visual unprimed words. The LD groups did not display this effect. Similar results have been observed during a number of ERP studies (Bakker et al, 1980; Fried et al, 1981; Rosenthal et al, 1982; Schucard et al, 1984) and was not surprising for Groups RS and RSA, who are considered to display left hemisphere deficits. However, the association of asymmetry with skilled reading is clearly supported by Group A ERP patterns. Despite relatively normal priming effects in the auditory session, Group A did not display normal asymmetry. This may reflect a lack of automaticity in the visual analysis of words. As left hemisphere dominance for language is considered to result from or support such automaticity, it is possible that the processes that underlie the ERP differences between these groups are primarily left hemisphere systems. The deficits of this group are considered to indicate abnormalities primarily of right hemisphere systems. However, such deficits may affect the development of left hemisphere systems for reading (Rourke, 1982). Thus, while the original deficit for Group A may be in right hemisphere systems, left hemisphere systems could also be expected to be abnormal.

An interesting aspect of this interpretation is that the left hemisphere asymmetry evident in the ERPs of normal readers cannot reflect solely the activation of systems for word comprehension. Normal readers display this effect to unprimed words but not to primed words, despite the fact that they are reading in both conditions. In addition, Group A subjects display normal reading list error rates, auditory priming effects and word recognition performance. Thus, the asymmetry may reflect some aspect of semantic incongruity processing, such as a shift of semantic category searching (Posner & Snyder, 1975a, 1975b). This type of processing may not occur for Group A if their left hemisphere systems for reading do not include normal semantic associations.

Recognition Memory Performance

The absence of differences between normal readers and Group A recognition memory scores for auditory primed word targets supports the interpretation of the N400 wave data that priming was effective for this group. The recognition memory performance of Group A supports the ERP data indicating that auditory but not visual priming is effective. The scores for auditory session words were equivalent to those of Group NR, while visual session scores were lower.

Recognition memory performance comparison supports the interpretation of ERP results that Groups RSA and RS did not process words normally. Priming does not appear to have facilitated recognition memory for these groups. This is consistent with description of word memory skills for children with left hemisphere system dysfunction as being of very short duration (Rourke & Finlayson, 1978; Rourke, 1982). However, the scores of all groups are greater than if responses were random. This implies that the subjects complied with instructions to attempt to read the targets. Furthermore, it justifies the interpretation of waveforms as a function of processing differences. If responses had been random, it could be suggested that subjects were not attempting the task and that their ERPs were not of functional significance.

Conclusions

Rourke's LD typology of children selected on the basis of academic achievement patterns and characterized by visual-spatial or auditory-verbal deficits patterns has been supported to some extent. Especially for Group A, priming in the system proposed to be intact was effective. Groups RS and RSA did display similar difficulty with auditory-verbal processing as predicted, however, visual-spatial priming was also ineffective. This may be due to the difficulty with word reading in general, as opposed to impairments with both visual and auditory processing.

The priming paradigm appears to be sensitive to the deficiencies of these groups, but may not relect their intact abilities. In view of the number of classification systems that identify visual-spatial or auditory-verbal deficits with subtype performance patterns (Bakker, 1979; Boder, 1973; Ingram et al., 1970; Kinsbourne & Warrington, 1963; Pirozzola, 1979), it is not surprising that at least one of the subtypes displayed session effects on priming. It may be useful to manipulate the mode of processing required for targets, rather than, or in addition to, that for primes. Specifically, if pictures or spoken words were used as targets rather than visually presented words, ERPs may be as sensitive to the processing abnormalities of Groups RS and RSA as they are to those of Group A.

In addition, the association of left hemisphere dominance for language with skilled reading has been clearly demonstrated. The fact that it is only evident for normal readers in the unprimed condition may explain the diversity of findings regarding hemispheric dominance.

Considerations for future research

This research provided evidence of modality - specific deficits for a LD typology that was based on a model of hemispheric specialization during language acquisition. The sensitivity of ERP waves to specific processes, especially those subserving language, lends this technique to further elucidation of LD.

The issue of hemispheric dominance for language is fundamental to this and other classification systems. Many studies, including the one reported in this thesis, attempt to identify laterality differences between normal and disabled readers on the basis of theoretical models of language acquisition. However, as in Goldberg and Costa's model (1981), the hemispheric specialization may be crucial during acquisition, not necessarily after reading becomes skilled. Thus, it may be informative to study ERPs during such acquisition to determine if hemispheric dominance changes during normal language learning, and if this differs for LD subtypes. As basic reading skills are acquired when children are too young to comply with task instructions, the acquisition of a new symbolic set by older children could be utilized. Words could be presented in other languages that use a different alphabet, such as Russian, in order to avoid confounds with existing lexical knowledge. It may be interesting to use idiographic systems, such as Japanese Kanji, to determine if such a visual-spatial based system evokes subtype-specific ERP differences. These results would have implications for remediation, as well as identifying hemispheric activation during learning.

Another comparison between the reality of language acquisition and research is that of stimulus presentation. The basis of language acquisition is the development of associations between the child's experience of an object, the sound of its name, and the sight of its printed name. An important factor in the integration of these events is that they must occur simultaneously. In laboratory experiments stimuli are usually presented serially. Certainly most ERP experiments present stimuli in this manner in order to average trials on a time-locked basis. However, ERP studies in our laboratory are implementing the Stroop method of simultaneous stimuli presentation to identify the automatic and attentional aspects of picture and word processing. This may prove to be an extremely useful tool in the study of LD and remediation strategies.

Another aspect of language acquisition and LD models is the role of memory. Subtypes may exhibit memory problems for specific types of information. ERPs have been recorded during performance of the Sternberg task (1966) where subjects are instructed to decide whether a target or probe stimulus was previously presented in an array. By varying the nature of the stimuli, using numbers and shapes, and perhaps modality, and comparing auditory and visual memory abilities, ERPs may be used to dissociate memory processes from linguistic deficiencies.

This research has shown that ERPs are sensitive to differential processing abilities of normal readers and LD subtypes. One goal of LD research is to identify reading problems as early as possible. Usually, such difficulties are only evident when formal reading instruction begins. However, children watch cartoons and listen to nursery rhymes years before instruction begins. If ERPs are sensitive to the information processing systems that subserve these activities, early identification of potential difficulties may be possible, particularly in children at risk due to familial prevalence.

The illiteracy rate in this and most countries is alarmingly high. While programs exist to teach illiterate adults, it is very difficult to determine if their inability to read results solely from a lack of education, or if LD is a factor. The development of ERP indices of specific reading problems may enable rapid and accurate identification of adults who require different teaching methods than other illiterate individuals. This may have implications for the individual, in terms of program compliance and success, and for the financial resources of such education systems.

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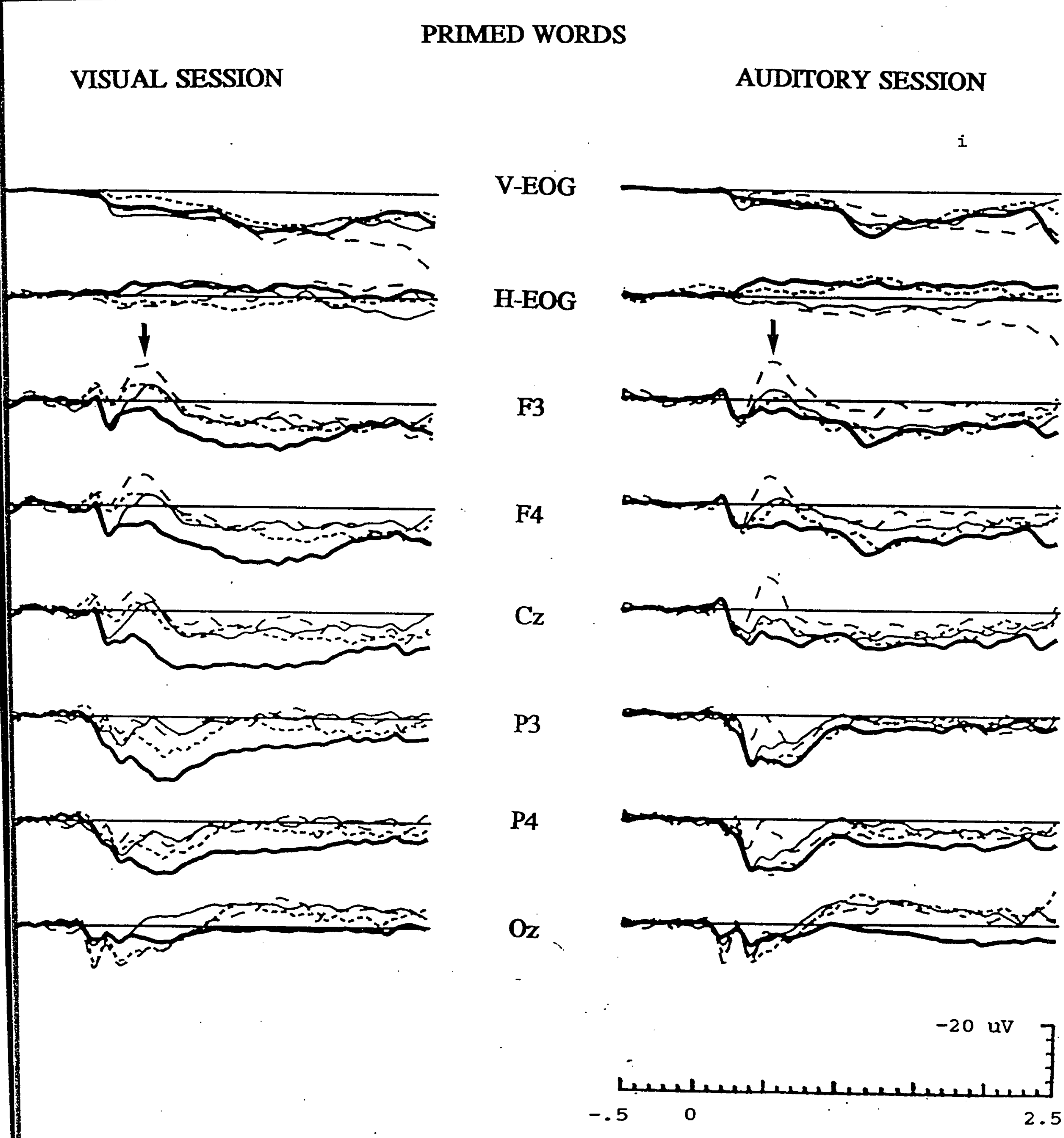


NORMAL READERS
READING/SPELLING/ARITHMETIC DISABLED
READING/SPELLING DISABLED
ARITHMETIC DISABLED

Figure 1. Group responses to primed words.

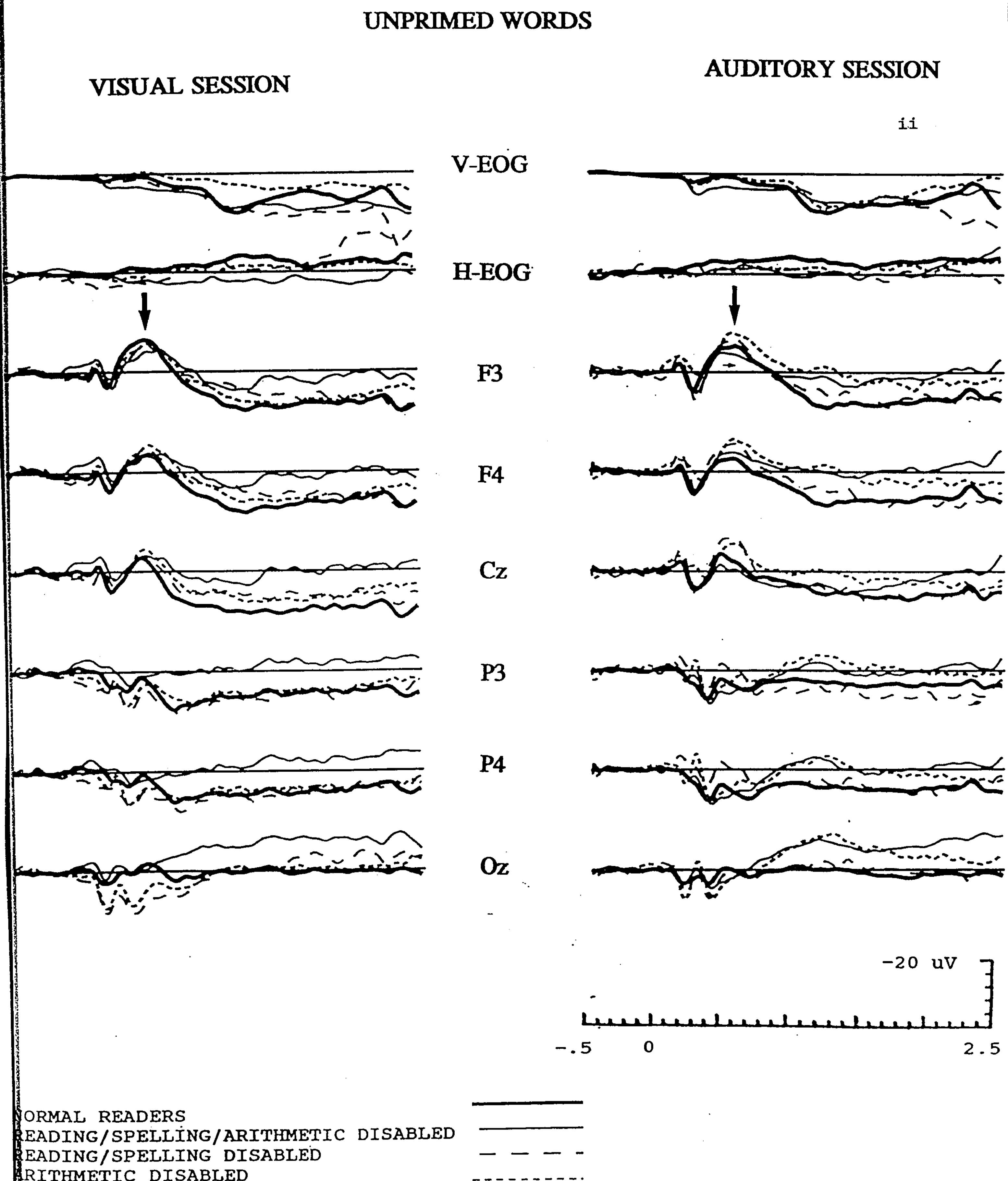


Figure 2. Group responses to unprimed words.

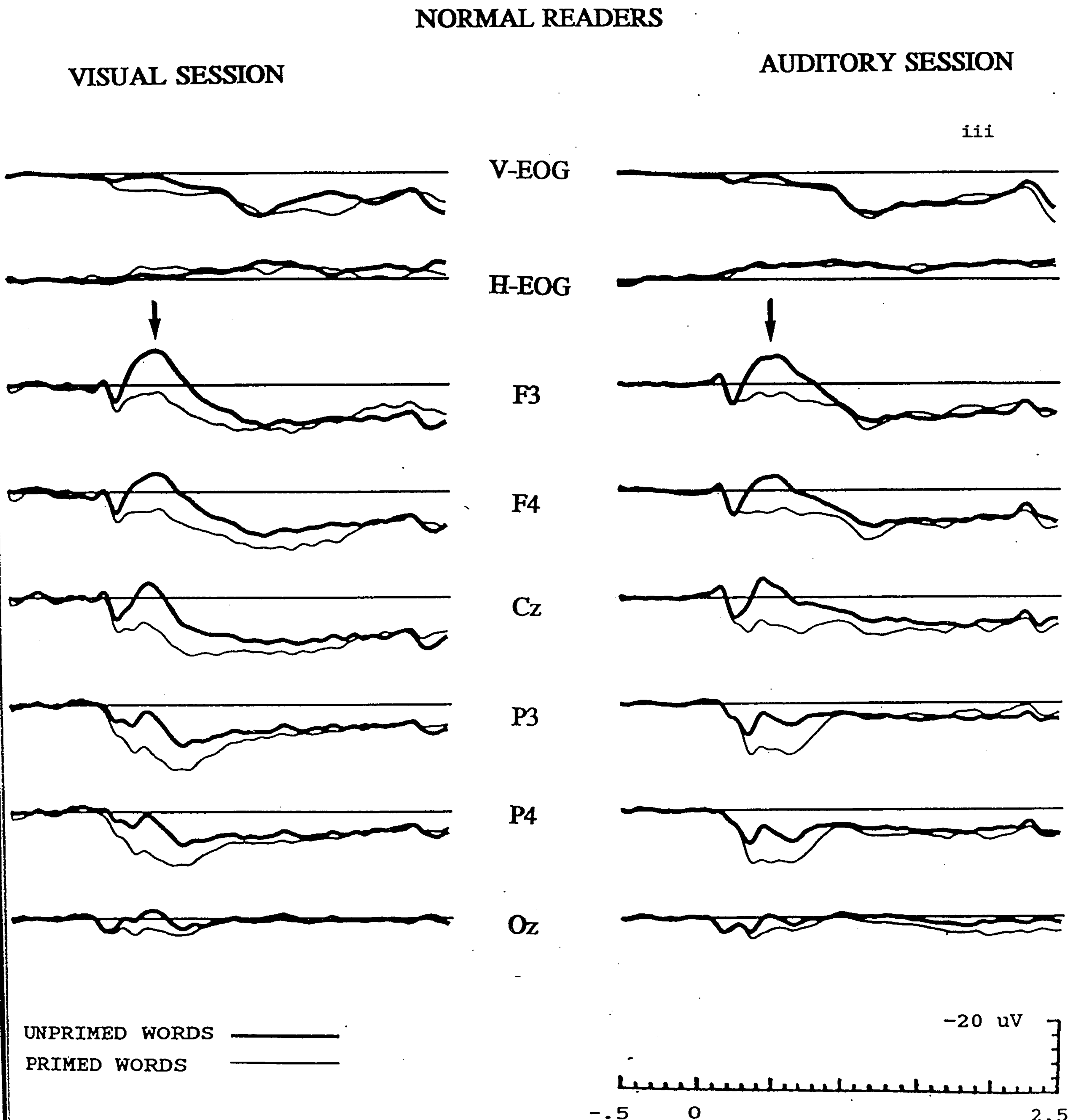


Figure 3. Visual and auditory priming effects for Group NR.

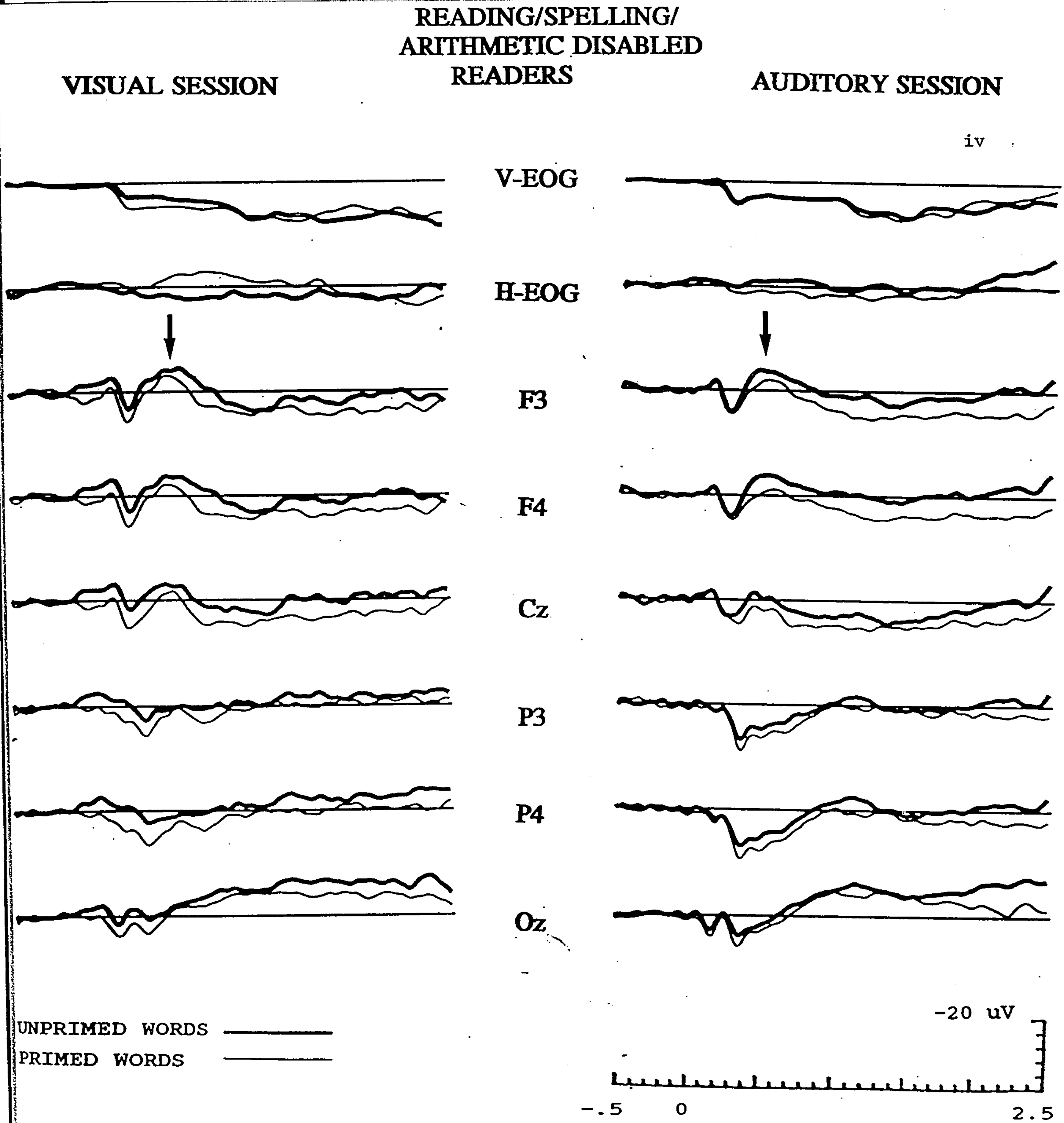


Figure 4. Visual and auditory priming effects for Group RSA.

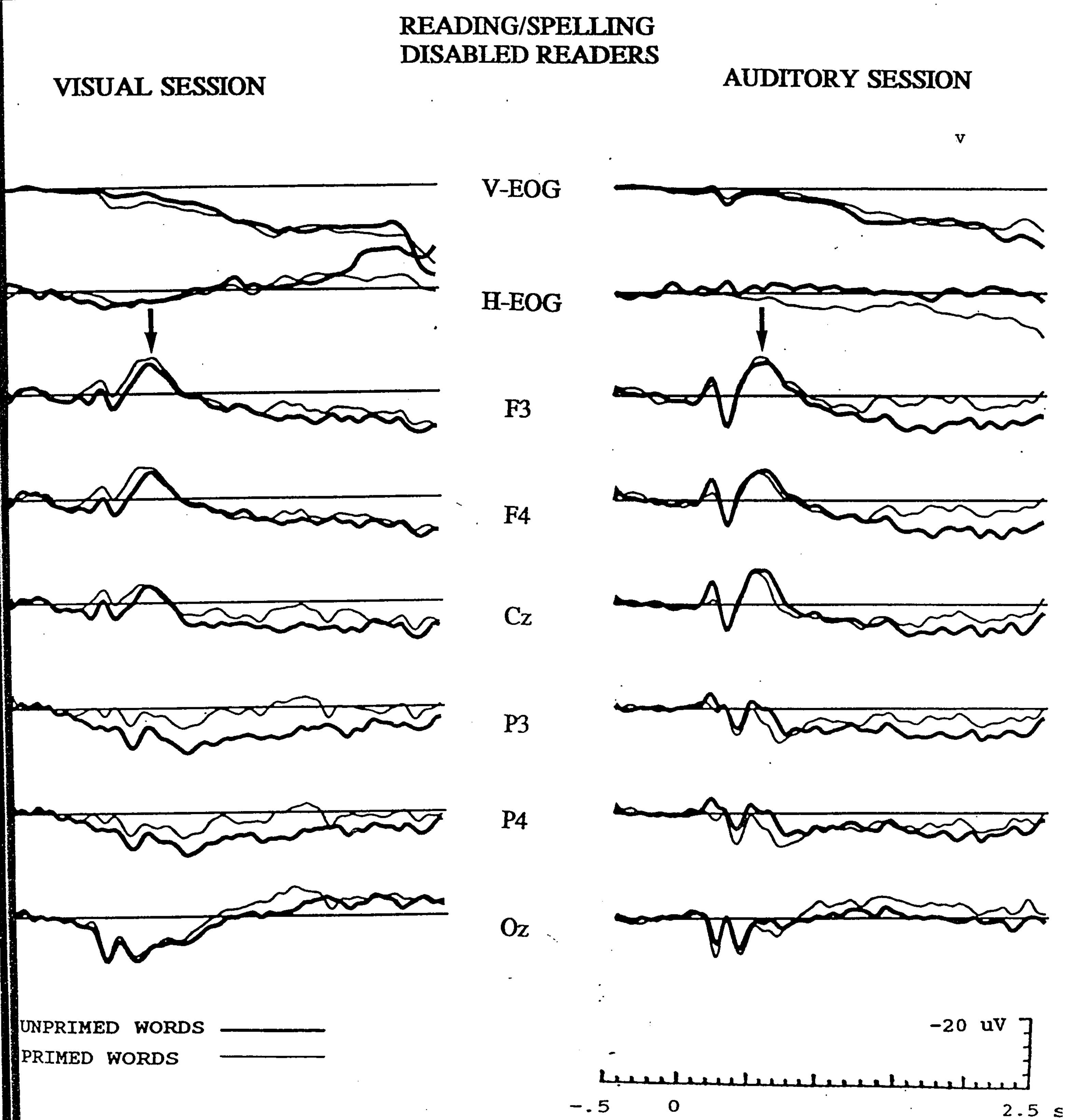


Figure 5. Visual and auditory priming effects for Group RS.

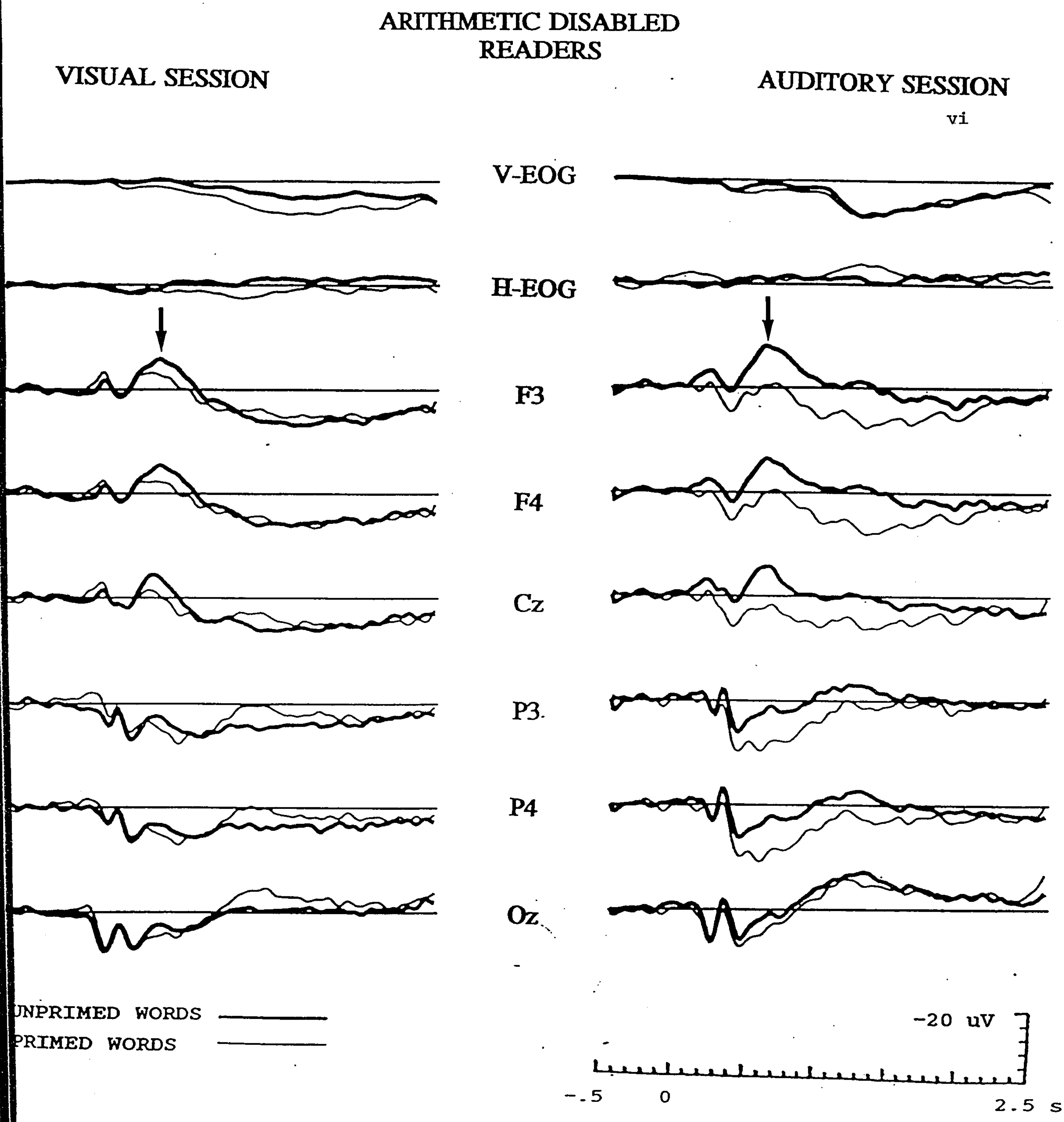


Figure 6. Visual and auditory priming effects for Group A.

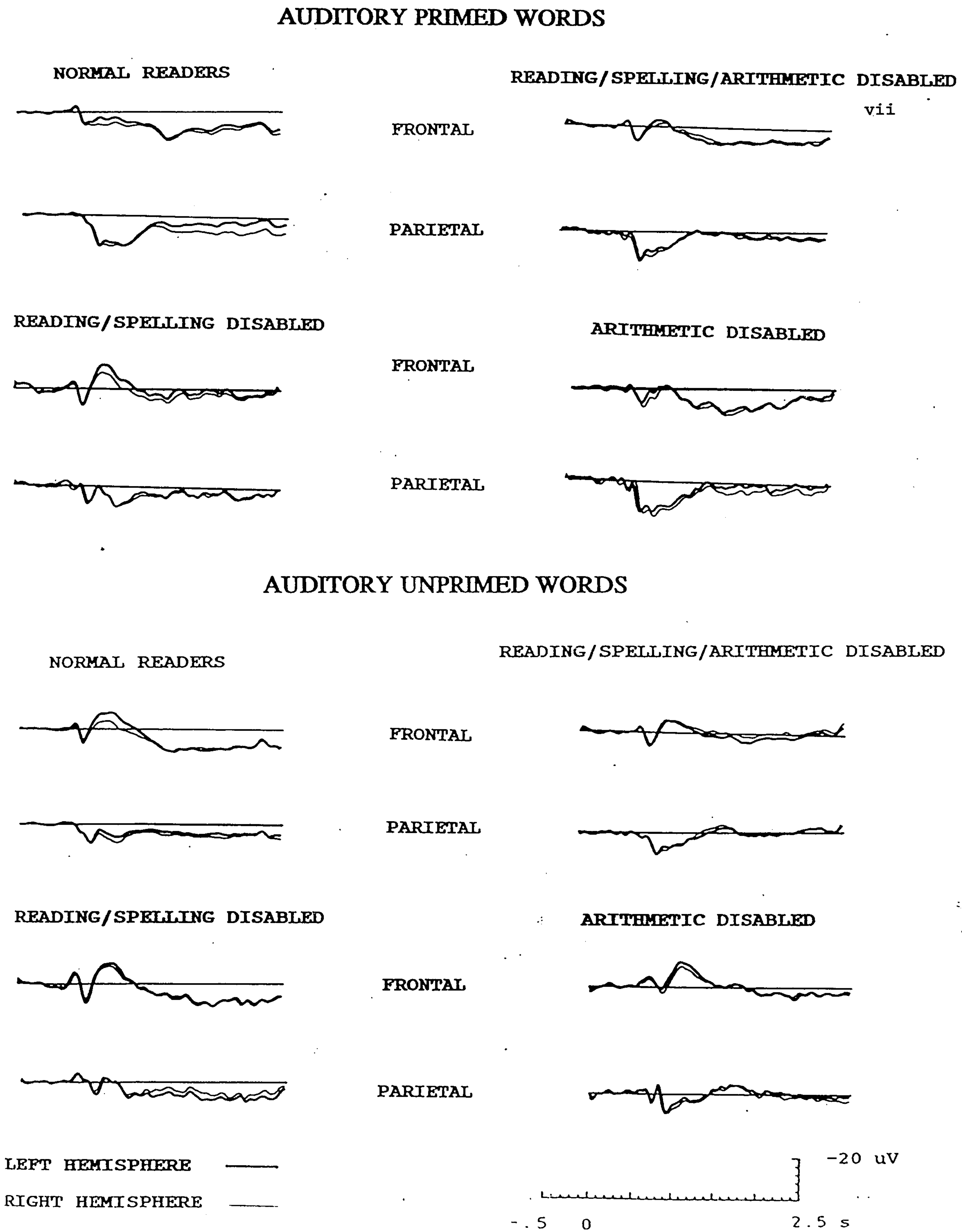


Figure 7. Hemispheric asymmetry of N400 in the auditory session.

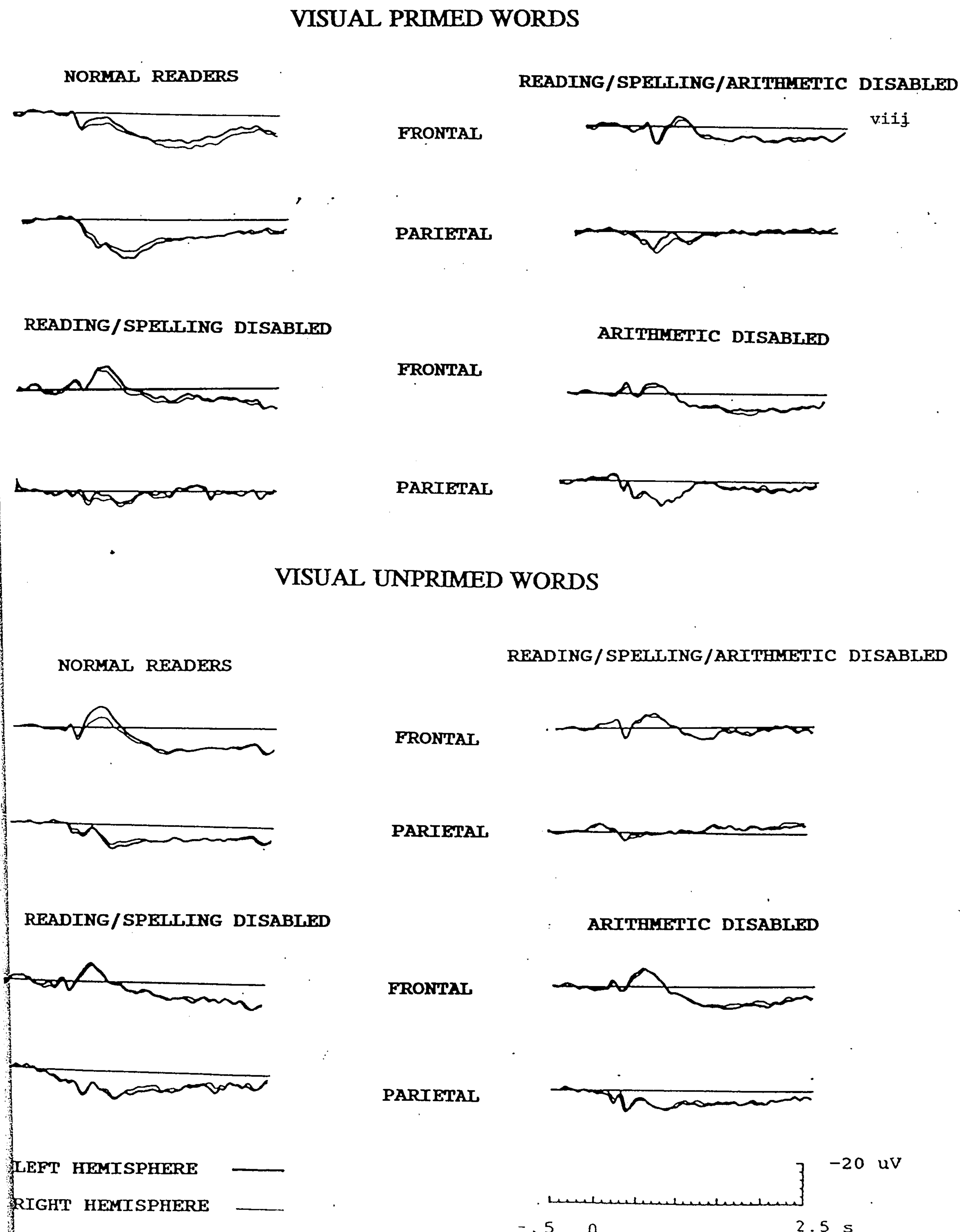


Figure 8. Hemispheric asymmetry of N400 in the visual session.

Table 1

Mean Values on Selection Criteria Measures

Measure	NR (n=10)	RSA (n=10)	RS (n=8)	A (n=8)
Years	11.7 (1.0)	10.8 (1.2)	11.2 (1.3)	10.8 (0.9)
WISC-R	113 (11.6)	103 (7.7)	95 (35.3)	112 (7.1)
PPVT	14.3 (1.9)	10.2 (1.7)	11.6 (1.9)	13.1 (3.5)
WRAT Reading SS	108.1 (8.8)	71.2 (9.8)	76.6 (20.3)	108.8(9.7)
PS	67.8 (16.2)	3.5 (2.9)	13.5 (13.9)	68.5 (18.7)
GE	8.2 (1.7)	2.2 (0.7)	2.7 (1.8)	7.5 (2.5)
Spelling SS	107.2 (6.6)	73.5 (5.6)	61.1 (27.9)	106.5 (6.5)
PS	67.3 (15.7)	4.7 (3.0)	8.3 (12.9)	65.8 (15.6)
GE	8.1 (1.8)	2.1 (0.5)	2.4 (1.4)	6.8 (1.8)
Arithmetic SS	117.0 (18.1)	73.9 (5.5)	89.9 (34.6)	88.8 (11.5)
PS	76.2 (19.8)	5.2 (4.5)	47.6 (33.9)	28.3 (17.9)
GE	9.1 (2.4)	2.8 (0.7)	5.3 (3.4)	4.6 (1.8)

Note: Mean age, I.Q., PPVT and WRAT standard scores (SS), percentile scores (PS), and grade equivalent scores (GE) on the Reading, Spelling and Arithmetic subtests for Group NR (normal readers), Group RSA (reading, spelling, arithmetic disabled), Group RS (reading spelling disabled), and Group A (arithmetic disabled). (SDs in parentheses).

Table 2

Statistical Comparison of Group Means on Selection Criteria

Groups	Years	PPVT	I.Q.	Reading SS	Reading PS	Reading GE	Spelling SS	Spelling PS	Spelling GE	Arithmetic SS	Arithmetic PS	Arithmetic GE
NR v. RSA	ns	*	*	*	*	*	*	*	*	*	*	*
NR v. A	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	*	*
NR v RS	ns	*	ns	*	*	*	*	*	*	ns	ns	*
RS v. RSA	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	*
RS v. A	ns	ns	ns	*	*	*	*	*	*	ns	ns	ns
RSA v. A	ns	*	*	*	*	*	*	*	*	*	*	*

Note: T-test results comparing groups on age, PPVT, I.Q., and WRAT subtest standard scores (SS), percentile scores (PS), and grade equivalent (GE). t(18) or t(16) values are significant at the .01 level.

Table 3

N400 Amplitude Means (uV) and Standard Deviations

Site	GROUP			
	NR	RSA	RS	A
Auditory Condition				
F3 primed	1.7(7.7)	-3.9(7.1)	-11.0(11.1)	-0.6(8.3)
unprimed	-10.0(7.2)	-6.3(8.5)	-8.9(10.4)	-12.1(7.5)
F4 primed	5.5(8.2)	-1.7(7.1)	-9.9(11.3)	-0.2(5.5)
unprimed	-6.1(9.1)	-5.8(8.1)	-7.7(14.2)	-10.4(6.3)
Cz primed	5.5(10.3)	1.5(7.5)	-8.9(10.9)	2.9(4.9)
unprimed	-6.1(7.6)	-2.5(8.7)	-10.5(12.8)	-8.2(7.1)
P3 primed	10.5(8.9)	7.5(11.0)	-0.5(15.4)	11.1(6.9)
unprimed	1.6(8.7)	6.3(9.6)	-4.4(16.2)	0.1(7.7)
P4 primed	12.0(9.2)	9.8(10.5)	0.6(14.3)	11.4(9.3)
unprimed	3.3(7.5)	7.7(11.1)	-4.2(18.3)	2.6(8.4)
Oz primed	3.5(8.7)	4.2(8.7)	1.2(15.0)	7.2(6.1)
unprimed	-0.8(7.5)	2.0(8.1)	0.2(11.4)	-0.5(9.5)
Visual Condition				
F3 primed	-2.3(8.1)	-4.9(7.2)	-10.8(12.3)	-5.0(8.5)
unprimed	-9.9(8.9)	-6.6(7.8)	-8.8(13.3)	-9.1(9.7)
F4 primed	5.8(8.6)	-3.7(7.8)	-8.9(13.9)	-3.5(6.4)
unprimed	-5.1(9.5)	-6.0(7.9)	-7.9(12.6)	-8.4(6.4)
Cz primed	6.5(7.7)	-2.5(7.1)	-5.9(16.0)	-2.9(8.8)
unprimed	-4.7(9.8)	-4.6(9.3)	-4.6(12.1)	-6.7(7.2)
P3 primed	11.1(4.2)	-1.6(8.5)	2.5(5.5)	4.0(6.9)
unprimed	1.4(6.8)	0.4(8.4)	4.4(7.7)	2.0(7.4)
P4 primed	11.5(7.7)	-2.0(8.7)	2.0(5.5)	4.4(10.3)
unprimed	1.1(9.5)	-1.9(8.7)	4.4(8.3)	3.6(8.5)
Oz primed	2.8(3.4)	-2.6(8.7)	8.9(10.5)	7.0(10.5)
unprimed	-2.2(3.3)	-1.3(8.5)	7.2(15.4)	3.2(9.3)

Table 4

Differences in mean N400 amplitude to primed and unprimed words in the auditory and visual sessions

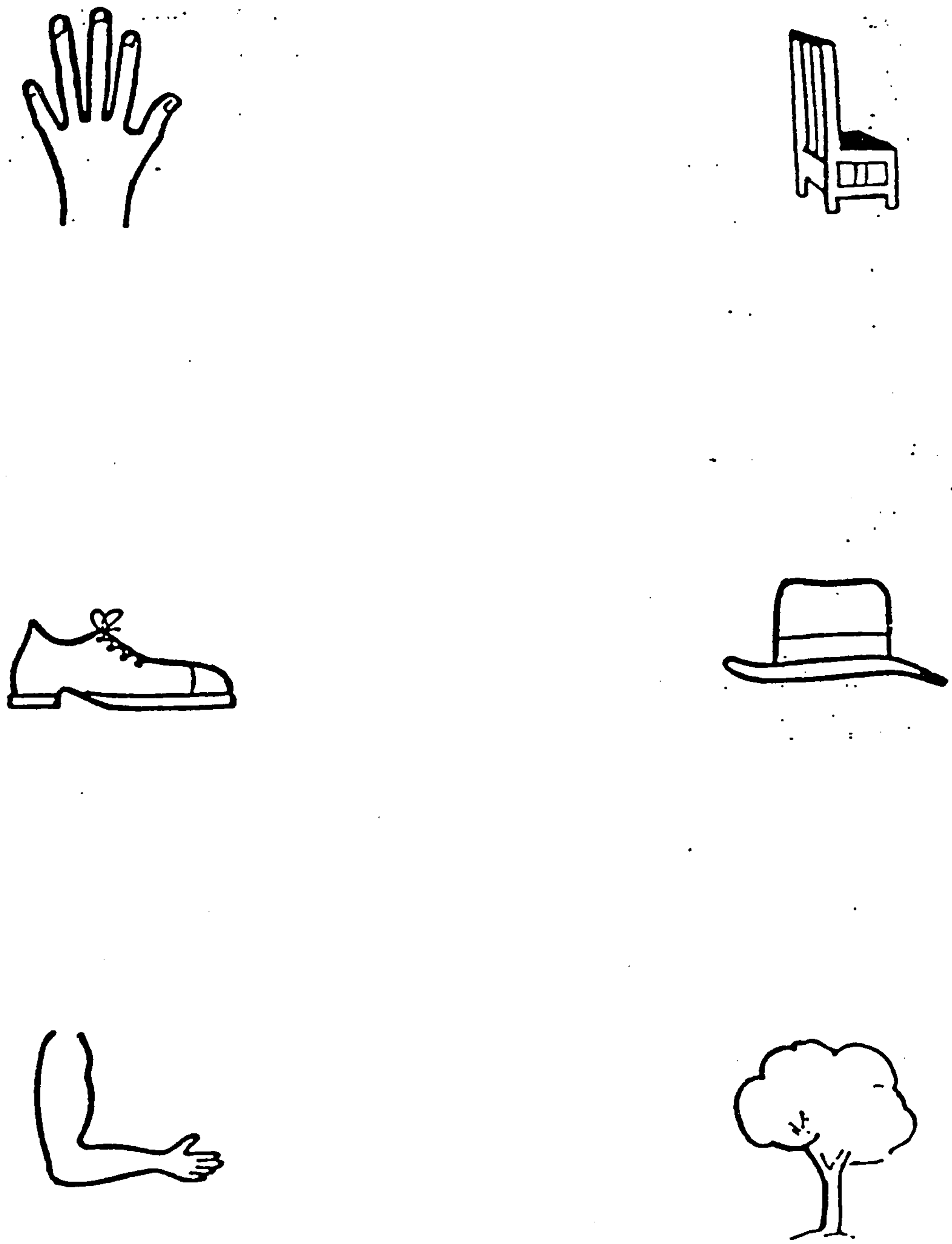
	Group			
Electrode Site	NR	RSA	RS	A
F3				
auditory	-11.7	-2.9	2.2	-11.5
visual	-12.2	-1.7	2.0	-4.1
F4				
auditory	-11.5	-4.1	2.2	-10.2
visual	-10.9	-2.3	1.1	-4.9
Cz				
auditory	-11.6	-4.0	-1.5	-11.1
visual	-11.2	-2.1	1.3	-3.8
P3				
auditory	-8.8	-1.2	-3.9	-11.1
visual	-9.7	2.0	2.0	-2.0
P4				
auditory	-8.7	-2.1	-4.9	-8.8
visual	-10.3	0.1	2.4	0.7
Oz				
auditory	-11.1	-2.2	-0.9	-7.6
visual	-5.0	-1.4	-1.6	-3.7

Table 5

Mean Recognition Memory Scores (d') and standard deviations

target	Group			
	Group NR	Group RSA	Group RS	Group A
Auditory				
primed words	2.42 (1.0)	1.50 (0.5)	1.24 (1.0)	1.67 (0.6)
unprimed words	1.94 (1.0)	0.67 (0.4)	0.59 (0.6)	1.39 (0.4)
Visual				
primed words	2.59 (0.8)	1.04 (0.7)	0.89 (0.9)	1.39 (0.8)
unprimed words	2.66 (0.6)	0.77 (0.7)	1.01 (0.5)	1.30 (0.7)

Appendix 1



Examples of pictures used in the visual session.

Appendix 2

Names of pictures and word targets used in the visual session.

1. noose - hang
2. shoe - camera
3. snake - giraffe
4. bird - wing
5. foot - bow
6. truck - van
7. kettle - tea
8. sofa - hat
9. sled - snow
10. anchor - feather
11. camel - desert
12. trunk - cage
13. cat - dog
14. gate - mouse
15. whale - fish
16. glass - sword
17. harp - stamp
18. star - sky
19. mermaid - sea
20. daisy - whistle
21. fan - moon
22. chair - sit
23. parrot - crow
24. shamrock - case
25. pencil - eraser
26. pig - farm
27. cigar - boat
28. dress - frog
29. horse - flag
30. cherries - peach
31. rooster - hen
32. pear - banana
33. fish - lake
34. teepee - indian
35. heart - love
36. snowshoe - winter
37. compass - bed
38. skate - ice
39. club - castle
40. clown - metal
41. paw - penguin
42. ladder - step
43. well - water
44. tricycle - bike
45. watch - clock
46. net - line
47. carrot - radar
48. mushroom - bin

49. birdhouse - gun
50. nail - train
51. bathtub - ball
52. mitten - guitar
53. basket - apple
54. shell - turtle
55. octopus - squid
56. horn - window
57. nest - fly
58. sailboat - dice
59. cap - jar
60. mop - grapes
61. tunnel - racoon
62. tree - igloo
63. kangaroo - hop
64. button - thread
65. jacket - cigarette
66. crib - parachute
67. plane - rabbit
68. skirt - dress
69. owl - wise
70. wig - radio
71. whip - scale
72. bottle - statue
73. doghouse - kitten
74. stool - stick
75. crown - throne
76. diver - ocean
77. pail - fork
78. cow - pumpkin
79. castle - puck
80. lock - key
81. ring - mill
82. phone - call
83. house - violin
84. slide - snowman
85. camera - picture
86. cake - sweet
87. chain - link
88. hand - foot
89. diamond - ruby
90. rat - stair
91. saw - wood
92. barrel - drum
93. bicycle - bug
94. cane - football
95. skiis - sponge
96. rocket - space
97. spectacles - ride
98. hotdog - mustard
99. clothesline - tractor
100. stump - log

101. crocodile - wheel
102. car - bone
103. umbrella - rain
104. comb - brush
105. bus - staple
106. shirt - sleeve
107. square - triangle
108. boy - girl
109. trumpet - music
110. drum - nose
111. boot - bridge
112. magnet - bottle
113. socks - butter
114. bed - book
115. sweater - needle
116. belt - key
117. ghost - spook
118. cup - drink
119. hanger - closet
120. bear - piano
121. axe - wood
122. hook - worm
123. apron - cook
124. crib - baby
125. lightbulb - fist
126. tulips - rose
127. ashtray - snake
128. pelican - bush
129. canoe - film
130. jug - milk
131. zebra - mouth
132. sun - moon
133. rectangle - circle
134. television - cabbage
135. pie - slice
136. cactus - desert
137. lion - tiger
138. eye - blink
139. lamb - fly
140. wagon - volcano

Appendix 3

Word pairs used in the auditory session.

1. beetle - bug
2. trap - ham
3. seed - ankle
4. tadpole - turtle
5. beak - desk
6. door - boot
7. church - cross
8. lane - tent
9. street - curb
10. hall - cotton
11. maple - leaf
12. sip - lid
13. mall - store
14. doll - butter
15. lemon - sour
16. bat - fort
17. jam - plank
18. cord - plug
19. knee - rope
20. pond - sheet
21. song - paste
22. washer - dryer
23. bee - sting
24. rack - cartoon
25. chicken - hen
26. telephone - dial
27. pill - egg
28. path - steel
29. pole - sign
30. soda - straw
31. window - ledge
32. field - farm
33. lamp - light
34. saucer - cup
35. navy - ship
36. win - lose
37. battle - snail
38. pen - ink
39. rock - plan
40. elbow - pal
41. bead - orange
42. grin - laugh
43. lettuce - tomato
44. flame - match
45. splash - toast
45. plant - salt
46. button - lime
47. stew - pants

48. curl - glove
49. mole - rug
50. stack - peanut
51. frown - tear
52. hammer - nail
53. world - map
54. lips - kiss
55. bag - mask
56. scratch - cut
57. woods - forest
58. cape - pea
59. tape - face
60. wall - land
61. neck - head
62. bean - track
63. lobster - crab
64. peel - cast
65. soup - flash
66. paint - mast
67. police - badge
68. bank - money
69. hip - wheel
70. elephant - zipper
71. prince - brick
72. scar - scab
73. tank - purse
74. baseball - glove
75. spider - web
76. sole - lamb
77. pan - eel
78. pack - fork
79. towel - bath
80. sack - run
81. penny - dollar
82. squirrel - cookie
83. rest - post
84. steam - iron
85. robber - safe
86. balloon - party
87. thread - sew
88. dentist - teeth
89. doll - bacon
90. comb - hair
91. seal - spoon
92. can - rice
93. shrub - bush
94. pop - box
95. seat - cheese
96. river - lake
97. man - tray
98. lawn - grass
99. goat - weed

101. loaf - roast
102. birthday - candle
103. water - tap
104. skin - cone
105. army - war
106. storm - cloud
107. calf - bull
108. medal - prize
109. vine - gift
110. mouse - trap
111. corn - flap
112. cart - pool
113. chief - dog
114. park - star
115. mast - sled
116. fish - hook
117. school - book
118. palace - boy
119. dish - plate
120. socks - shoes
121. saddle - pony
122. arm - leg
123. duck - saw
124. student - pupil
125. dock - crust
126. monster - rink
127. flip - goose
128. knit - sweater
129. handle - toe
130. zebra - stripe
131. queen - king
132. street - spot
133. snow - shovel
134. jewel - pearl
135. hive - wasp
136. ape - monkey
137. card - bite
138. barn - wand
139. candy - gum
140. jet - pilot