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An examination of the neurophysiological and cognitive components underlying developmental dyslexia

BY

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

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Dedication

This thesis is dedicated to my parents whose constant support and understanding allowed the completion of this Degree

Abstract

Event-related potentials (ERPs) were recorded in 11 dyslexic and 11 normal control children concurrent to a visual search task. ERPs were elicited by an irrelevant auditory stimulus delivered over headphones while the subject performed the search task. Electrical activity was recorded from bilateral frontal, central, and parietal scalp sites for 500 msec following stimulus presentation. ERP analyses were done comparing dyslexics and controls on the amplitude of the P1, N1, and P2 components; and latency of the P1, N1 components. The dyslexics exhibited a smaller amplitude P1 at the left central site compared with controls. No differences between groups were observed on latency. The search task required the subject to cancel occurrences of either a verbal or nonverbal target distributed throughout a random array. Search performance was evaluated according to several time, accuracy, and strategy parameters. Dyslexics compared with controls had longer distances and times between targets. The groups did not differ on measures of accuracy and strategy. Dyslexics were characterized into one of three subgroups defined by Boder: dysphonetic, dyseidetic or mixed. ERP and search measures on the verbal search task were described among groups. The mixed group appeared to have an aberrant ERP from dysphonetic and dyseidetic dyslexics but analysis of these subgroups on the ERP and search parameters was not possible. The dyslexics participated in a larger study of cognitive assessment. Ten tests were characterized according to processing strategy and performance was evaluated among groups for each test. Dyseidetic dyslexics remembered fewer items than the other two subgroups on the Posner but not Stroop test of selective attention. Dysphonetic compared with dyseidetic and mixed type subgroups recalled fewer matrices on a test of matrix identification. The mixed subgroup took longer to find a target located in an array than did the other two subgroups. No other differences were found among groups. Possible factors accounting for the lack of significant results and implications for future research are discussed.

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List of Abbreviations and Symbols

AC	alternate current
ANOVA	Analysis of Variance
CAS	Cognitive Assessment System
CCAT	Canadian Cognitive Abilities Test
cm	centimetres
cm^2	squared centimetres
C3	left central electrode site
C4	right central electrode site
dB	decibels
D	distance in pixel units
D_i	individual distance in pixel units within a set
DE	dyseidetic type dyslexic
DP	dysphonetic type dyslexic
EEG	electroencephalogram
ERP	event-related potential
F	Fisher's F-test
F3	left frontal electrode site
F4	right frontal electrode site
Hz	Hertz
ITT	Inter-target time
IQ	intelligence quotient
Kohms	Killi-ohms
M	mean
msec	milliseconds

List of Abbreviations and Symbols (cont'd)

MX	mixed type dyslexic
_n_	number of subjects
N1	negative going ERP component observed about 100 msec after stimulus onset
N2	negative going ERP component observed about 200 msec after stimulus onset
No.	number
_p_	probability
P1	positive going ERP component observed about 100 msec after stimulus onset
P2	positive going ERP component observed about 200 msec after stimulus onset
P3	positive going ERP component observed about 300 msec after stimulus onset
P3	left parietal electrode site
P4	right parietal electrode site
_r_	statistical correlation
_R_	Multiple Regression coefficient
_S_	estimate of computed search strategy
_SE_	estimate of the standard error of the mean
S07	subject 7 who participated in the ERP/Search
S15	subject 15 who participated in the ERP/Search
SAS	Statistical Analysis System
_t_	Student's t
T_i	individual inter-target time within a set
TSQUARE	Multivariate Analysis of Variance for two groups
VC3-P1	P1 component amplitude observed at the

List of Abbreviations and Symbols (cont'd)

	C3 electrode site on the verbal task
vs.	versus
<u>W</u>	Kendall's Coefficient of Concordance
WISC-R	Weschler Intelligence Scale for Children-Revised
μV	microvolts
Σ	addition of terms

An examination of the neurophysiological and cognitive components underlying developmental dyslexia

A variety of studies have attempted to identify the neurophysiological correlates underlying dyslexia in an effort to confirm possible brain dysfunction as an important etiological factor in dyslexia. The focus of these studies has been the affirmation of neurological processing differences between normal and dyslexic readers found in numerous psychological evaluations (Hynd, Semrud-Clikeman, Lorys, Novey, & Eliopulas, 1990).

Dyslexia is a specific learning disability characterized by a pervasive difficulty in acquiring the skills for reading, despite adequate opportunity for learning, and in the absence of neurological and behavioural impairments (Hooper & Hynd, 1985). It has been suggested, however, that an underlying neurological dysfunction is etiologically significant in the development of dyslexia although the behavioural evidence to support this assumption has largely been correlative (Hynd et al., 1990).

Event-related potential (ERP) recording is a neurophysiological technique which measures electrical brain activity; it is well suited for the assessment of continuous cognitive functioning at the cerebral level independent of behavioural performance (Hunt, 1985). These attributes are especially appealing for studying the neurophysiological bases of dyslexia in relation to the dysfunctional cognitive performance characteristic of the disorder.

Typically, ERPs are generated by presentation of a novel stimulus within sets of repetitive stimuli; ERPs appear as peaks on the otherwise static baseline of resting activity (Hansen & Hillyard, 1980). Event-related potentials are typically recorded from one of two basic sensory modalities and are measured, relative to baseline, according to amplitude and latency of particular components (McCallum, 1986). Although amplitude and latency are task specific, positive components are generally elicited at 100, 200, and 300 milliseconds post-stimulus (P1, P2 and P3, respectively); negative components typically occur about 100 (N1), and 200 (N2) milliseconds post-stimulus. Visual ERPs are reliably elicited from all locations of the scalp with the largest amplitude ERPs being evoked from the occipital regions (McCallum, 1986). Auditory ERPs are also evoked at all scalp areas but elicit greater amplitude peaks from more anterior, especially central, locations (McCallum, 1986).

Each component is thought to relate to a particular cognitive phenomenon: N1, P1, and P2 to selective attention, N2 to arousal, and P3 to the attentional attributes of novelty and surprise (Karrer, Cohen, & Tueting, 1984).

Recent studies have employed ERPs as a technique for studying the visual and auditory processing differences between dyslexics and normal controls. Generally, dyslexics exhibit smaller amplitude visual ERPs compared with normal controls (Long & Murray, 1982). In parallel studies, Harter and his colleagues have examined the relationship between visual stimuli and reaction time in dyslexic versus normal and attention deficit disorder control groups (Harter, Anllo-Vento, Wood, & Schroeder, 1988; Harter, Deiring, & Wood, 1989). In all these studies, dyslexic children were identified as having at least a 1.5 year discrepancy between the expected and actual level of reading achievement. These investigators found that the dyslexics had decreased amplitudes of P2 and P3 components primarily at the left central electrode site. Negativity and P1 were not measured. These authors concluded that, relative to normals, dyslexics employ a dysfunctional brain mechanism that is different from that used by the attention-deficit disorder group.

Decreases in amplitude of the P3 component in dyslexics compared to normal controls have also been observed in a letter/symbol discrimination task (Taylor & Keenan, 1990). These investigators operationally defined the dyslexic child as being 1.3 years below average in reading level. Dyslexics were reported to have significant increased latencies of the N2 and P3 components relative to controls on this task.

In a similar word recognition task, dyslexics were observed to exhibit larger amplitude N1 and P2 components than normal control subjects (Stelmack, Saxe, Noldy-Cullum, Campbell, & Armitage, 1988). Although these results are in direct opposition to those observed by Harter and his colleagues, the procedure of ERP collection and behavioural tasks were somewhat different between the two studies. Furthermore, the dyslexic children were drawn from a hospital remedial program and thus may have represented a slightly different dyslexic population.

There also appear to be differences in the processing of target and nontarget stimuli regardless of modality. Generally, when target information is processed, the amplitude components of the ERP increase relative to the processing of non-target information (Hansen & Hillyard, 1980). It has been observed that dyslexics, in comparison to normal controls show a significantly larger general enhancement of ERP amplitude for the N1 component elicited by processing of visual target information (Harter, Anllo-Vento, & Wood, 1989). Enhancement of the P3 component on this task, however, was significantly smaller between groups.

Auditory ERPs have not been as extensively studied in dyslexic populations as visual ERPs. Lovrich and Stamm (1983) observed that dyslexic children, defined as being significantly retarded on several psychological reading tests, have smaller P3 amplitudes on a reaction time auditory selection task when compared with normal children; no group differences were found to exist between the attention-related components of N1 and P2 amplitude. These authors suggested that the dyslexics were less efficient than normal children in processing target information but that this difference was not related to attention.

Similarly, Holcomb, Ackerman, and Dykman (1986) found that dyslexics significantly differed from normal and attention deficit controls on an auditory discrimination task of detecting a low probability nonsense syllable. Specifically, dyslexics, characterized as being at least two years behind normal controls on tests of reading, exhibited a significantly smaller P3 amplitude which occurred significantly later than in attention deficit disorder and normal control children. Groups, however, were undifferentiated according to task and did not significantly differ on the N2 amplitude component.

It has also been reported that dyslexics, identified as being at least two years behind normal children on tests of reading, have smaller overall slow wave activity when compared with normal children on tests of auditory discrimination (Ollo & Squires, 1986) suggesting that dyslexics do not fully process incoming auditory information.

This observation was further tested by presenting auditory stimuli of words or music and measuring ERP processing components of dyslexics and normal controls (Fried, Tanguay, Boder, Doubleday, & Greensite, 1981). Dyslexics were identified as being at least two years delayed on the Jastak Wide Range Achievement Test. Waveform differences between hemispheres were computed by a cross-correlational comparison of each ERP waveform elicited by each stimulus type (words or music). Dyslexics, in one particular subgroup, were observed not to possess the normal shift from left to right hemispheric processing that occurs when stimuli change from words to music. No group differences were observed in discrete measures of amplitude or latency suggesting that the individual attentional components of the ERP were not as important as identifying overall shifts in processing. The authors concluded that this particular group of dyslexics did not acquire a left hemispheric specialization for language.

In summary, dyslexics and controls are generally found to differ on measures of visual and auditory

ERPs although such differences appear to be task specific. Reading disabled children exhibit significantly smaller amplitude visual ERP components of N1, P2, and P3. It has also been reported that dyslexics have marked increases in visually evoked N2 latency.

Dyslexics compared with normal control children appear to have a generally slower morphology of the auditory ERP waveform. Although dyslexics have been reported to have significant decreases in P3 amplitude, they have not been found to differ on the ERP attention-related components (N1, P1, and N2). It appears that dyslexics differ from normals in the morphology of the overall waveform rather than in individual components.

Since behavioural performance in ERP studies is usually restricted to measuring reaction time or simple discriminations, traditional ERPs may not adequately assess complex cognitive differences between dyslexics and controls. For example, ERP components of attention are based on the processing of simple stimuli and may therefore be inadequate measures of cognitive ability (Johnstone et al., 1984). Furthermore, ERP amplitudes increase when elicited by target stimuli, developing a confound between stimulus feature and response set. The probe paradigm (Papanicoulau & Johnstone, 1984) is an ERP technique that records ERPs elicited by task-independent stimuli, thereby eliminating the confound between stimulus relevance and response. The technique involves recording ERPs to a task-irrelevant, repetitive stimulus while the subject performs a cognitively complex task (Papanicoulau & Johnstone, 1984). Inferences about cortical activity can then be made by comparing variations in ERP components in response to the irrelevant stimulus. The theory hinges on the notion that information processing is of finite capacity (Posner, Inhoff, Friedrich, & Rafal, 1987) and that ERP features will vary according to the amount of cortex involved in the cognitively attended task. That is, as a particular cognitive system is employed, the ability to process additional sensory information is reduced, producing a smaller amplitude ERP. This amplitude reduction has been found to inversely relate to the amount of resources allotted to the task (Freisen & Jutai, 1990; Papanicoulau & Johnstone, 1984). The technique has been used for almost 30 years to successfully attenuate task-related ERPs and is becoming more popular as a method for establishing functional relationships between higher-level cognitive processes and external stimuli (Shucard, Cummins, Thomas, & Shucard, 1981; Federico, 1985). Auditory probe ERP methods are particularly useful in the study of attentional processes (Papanicoulau & Johnstone, 1984; Shucard et al., 1981; Shucard, Shucard, & Thomas, 1977).

Johnstone et al. (1984) employed a visual probe ERP paradigm to evaluate differences between dyslexic and normal control children during various complex cognitive tasks, including reading. These investigators recruited children through public and private special education centers; each participant underwent a rigorous behavioural and neurological screening procedure. The reading disabled group was operationally defined according to performance measured on the Gray Oral Reading Test and a reading test given by the experimenters themselves. Dyslexic children were comprised of children at least two years behind normal controls on each of these tests. The probe consisted of an illuminated checkerboard located at each side of a table of which the centre panel formed a working surface. Stimuli were presented for 12 msec, at one-sec intervals during several spatial and language related tests. Cognitive tests included mirror drawing, block design, silent and oral reading of easy and difficult text, and passive listening of tape recorded stories. Electrical activity was recorded bilaterally from central and parietal sites; and from midtemporal regions. Data were subjected to Principal Component Analysis which extracted 10 pertinent factors corresponding to latency. Included amongst these factors were the N1, P1, N2 and P2 components. All factors were then submitted for analysis of variance.

Significant group differences emerged for the factors corresponding to the P1, N1 and N2 components with consistently smaller factor loadings being observed in the dyslexic group. In particular, the largest differences between groups were revealed by factors measured from the central electrodes. Specifically, dyslexics exhibited smaller factor loadings corresponding to N2 than the control group. The reading disabled compared with the control group also had a significantly smaller factor loading which fit the P1 component. The N1 corresponding factor revealed a significant group by site main effect difference, with the dyslexics having a smaller component only on the left side and specific to central and parietal sites. The authors conclude that the probe paradigm is a sensitive technique that can identify fine differences between dyslexics and controls while engaged in cognitively complex tasks.

In summary of Johnstone et al. (1984), dyslexics, relative to controls, exhibited significantly smaller factor loadings corresponding to the attention-related ERP components of N1, P1, and N2 in response to irrelevant visual stimuli presented during various reading related tasks. Furthermore, dyslexics had consistently more negative right than left site factors corresponding to the P1 and N1 components which revealed a significant group by side interaction.

The present study will use an auditory probe ERP paradigm to examine attentional components associated with a concurrent task of visual exploration. It has been reported that ERPs are successfully attenuated across sensory modalities (Papanicoulau & Johnstone, 1984). That is, attention to the relevant visual stimuli is expected to decrease ERP attention related components to irrelevant auditory stimuli. The probe consisted of binaural tone pips delivered over headphones while the subject engaged in a visual search task of either letters or nonverbal stimuli.

The search tasks were modified computer versions of the pencil-and-paper cancellation tasks developed by Weintraub and Mesulam (1985). By examining the number of errors of commission and omission, these investigators have successfully used the tests to characterize the spatial distribution of attention in neurologically damaged patients (Weintraub & Mesulam, 1985; Weintraub & Mesulam, 1988). Furthermore, hypothetically psychosis-prone college students have been observed to have abnormal patterns of spatial attention on these tests when compared to normals (Jutai, 1988). Schizophrenic and normal populations have also been differentiated by analyzing patterns of attention measured on these search tasks (Tomer & Flor-Henry, 1989).

Similar types of cancellation tasks have also revealed developmental differences in processing strategy between children and adults (Ruskin & Kaye, 1990) and in directing of attention between young and old adults (Nebes & Madden, 1983). It appears that visual cancellation tasks are useful indicators of spatial attention in children and adults.

In a study by Eskenazi and Diamond (1983) dyslexic and normal children were compared on exploration times and eye movement features when engaged in a nonverbal search task (objects or symbols). Dyslexic children, chosen from child development centres, performed as well as controls on most stimulus arrays. Only if stimuli were unfamiliar and presented in a crowded and tilted manner did the dyslexics show aberrant eye movement features. When eye movement features were measured on a reading task, however, the dyslexics showed increased number of eye fixations and regressions, and tended to dwell at the beginning of a new sentence suggesting that dyslexics have abnormal eye movement patterns on scanning of verbal material. It appears dyslexics have little problem with searching nonverbal material but have significant difficulty in the scanning of verbal information.

Das and his colleagues (Das, Mensink, & Mishra, 1990) have also examined exploration times between good and poor readers on verbal and nonverbal search tasks. Poor readers were defined as those children two or more years behind normal controls on locally administered elementary reading test. These investigators observed that reading level of the high IQ group was significantly discriminated by the visual search task.

In the present study, the visual search tasks are presented concurrent with the auditory probe. According to the theory underlying the probe ERP paradigm, the more cognitive resources allotted to the primary task (visual search) the fewer resources left to process the tone pips. Since it has been demonstrated that dyslexics have difficulty processing verbal but not nonverbal information (Eskenazi & Diamond, 1983), it is proposed that this group compared with normal controls will show significantly poorer performance on the verbal but not nonverbal search tasks employed here. Indeed, the defining characteristic of dyslexia is the inability to process verbal information. Search performance is measured according to several parameters but in general it is expected that search times will increase and strategy will be more erratic in the dyslexic than control group only on the verbal search task.

Furthermore, all three of the ERP attention-related components are hypothesized to significantly decrease in amplitude in the dyslexic compared with normal population in a manner similarly observed by Johnstone et al., (1984). Latency of the N1 and P1 components are expected to increase in the dyslexic relative to control group as has been observed in several studies of ERP attention (Taylor & Keenan, 1990; Harter et al., 1989). It is expected that the largest differences between the groups will be observed on the left-sided electrodes and particularly at anterior sites (frontal and central).

It appears dyslexics are differentiated from controls on a variety of neurological and cognitive tests. Although suggestive of a homogeneous entity, inconsistent empirical results and lack of a diagnostic unity, have led to the awareness of the heterogeneity of the classification and etiology of dyslexia (Flynn & Deering, 1989a). One approach to classifying reading disabled children into subgroups is that of Elena Boder (Boder, 1973; Boder & Jarrico, 1982).

Boder's diagnostic system (Boder, 1973) is based on the assumption that reading and spelling are interdependent functions which when assessed, are capable of distinguishing three different types of dyslexia and one type of nonspecific reading retardation. The first of these subgroups is the dysphonetic child who is characterized by an inability to decipher individual phonemes. The main reading strategy of the dysphonetic, therefore, is to recognize words by sight. Spelling patterns are consonant with this primary deficit; dysphonetic children can spell familiar words by recognition but they can not phonetically derive the spelling of new words.

The converse of the dysphonetic is the dyseidetic child, described by Boder as initially lacking the ability to recognize phonemes but once having done so, is able to apply the rules of phonetic analysis. The dyseidetic child, however, having learned individual phonemes may still have difficulty recognizing whole words, therefore, he reads all words as if seeing them for the first time. His spelling ability is poor but phonetically logical, unlike the dysphonetic child's strategy. That is, the dyseidetic child spells by sound and typically misspells words that are phonemically decipherable (e.g., 'hows' for house).

An amalgamation of the dysphonetic and dyseidetic deficiencies comprises the third of Boder's subgroups. The mixed type dyslexic child is characterized by poor phonemic awareness as well as the inability to apply phonetic analysis. These children have the poorest prognosis and often can not learn to identify or spell simple words.

The nonspecific type of reading disorder is comprised of children who are poor readers but whose spelling ability is essentially normal. Although Boder (1973) did not describe performance of this group in relation to the other three groups, one study found no significant differences between an identified nonspecific subpopulation and normal controls on several tasks involving both sequential-analytic and simultaneous-gestalt types of processing (Nockleby & Galbraith, 1984). The authors concluded that nonspecific dyslexics perform similarly to normal controls on tests other than reading.

Since Boder's initial formulation of these subgroups almost 30 years ago, numerous studies have investigated the validity and usefulness of this classification system in distinguishing dyslexic categories (c.f., Hooper, 1988). It appears that the Boder Diagnostic Screening Procedure (Boder, 1973) is successfully able to discriminate specific reading disability from more general dysfunctions such as attention deficit disorder (Levy & Hobbes, 1989) and neurological impairment (Dorman, 1987).

A wide range of neuropsychological tests have been assessed according to the Boder subgroups. Obrzut (1979) investigated differences in memory capacity of the three Boder subgroups on a dichotic listening task. He observed that the dysphonetic and mixed subgroups were less able to attend, store and recall information of both auditory and simultaneously presented visual-auditory stimuli than dyseidetic and normal children. These results suggested that both auditory and visual representations of words are not efficiently processed by the dysphonetic child. Similarly, dysphonetic children have been observed to be deficient in the phonetic discrimination of spoken as well as written language (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981). The spelling of dysphonetics has also been confirmed to be phonetically inaccurate when compared with head-injured and normal controls (Horn, O'Donnell, & Leicht, 1988). Collectively, the results of these studies demonstrate that dysphonetic children are poorer on tasks requiring the attending, processing and subsequent recall of phonetic type stimuli, supporting Boder's initial description of this subgroup.

Boder's description of the dyseidetic subgroup has also been supported by the literature. Bauserman and Obrzut (1981) observed that dyseidetic children were better able than dysphonetic and mixed subgroups to match temporal information on a memory matching test but were significantly poorer on a similar task requiring matching of spatial information. These authors concluded that dyseidetic children may exhibit a different memory pattern than the other subgroups when processing spatial information. Similarly, in a comprehensive neuropsychological evaluation, dyseidetic children were differentially identified from the other subgroups by an increased slow wave brain activity measured by EEG during tests of spatial ability (Flynn & Deering, 1989a). This difference was further affirmed by analysis of computer topographic brain mapping (Flynn & Deering, 1989b).

It is generally agreed that the mixed subgroup is poorer at most cognitive tasks (Hooper, 1988). Impairment, however, is often related to a second subgroup's dysfunctional performance depending upon the type of task (Nockleby & Galbraith, 1984). For example, members of the mixed subgroup perform as poor as the dysphonetic group on tasks requiring phonetic analysis (Horn, O'Donnell, & Leicht, 1988).

In conclusion, the classification system described by Boder (1973) appears to provide three potentially valid subgroups of developmental dyslexia which may serve as useful categories for diagnostic and research purposes (Flynn & Deering, 1989a). In addition, the system appears able to distinguish a fourth group that has problems with reading but not spelling. Flynn and Deering (1989a; 1989b) suggested that the Boder classification system may be particularly useful in neurophysiological research studying specific reading disability.

The Boder Diagnostic Screening Procedure (Boder, 1973) is used here to classify the group of reading disabled children who participated in the ERP/Search study described above, into the three dyslexic subgroups. Since the dyseidetic and mixed type subgroups have been observed to have aberrant electrical brain activity (Flynn & Deering, 1989a), it is expected in this study, that these subgroups will exhibit an overall aberrant waveform with the individual ERP components smaller in amplitude and longer in latency than those observed in the dysphonetic group.

Search performance is also anticipated to differ between Boder subgroups. It is expected that the dysphonetic and mixed subgroups will be less efficient on the verbal search task and that the dyseidetic and mixed subgroups will be less efficient on the nonverbal search task.

The dyslexic group who participated in the ERP/Search study formed part of a larger group of dyslexics who were tested on a variety of cognitive tests described by Das et al. (1990). Differences between groups was evaluated according to performance on these cognitive tests, divided into four types of processing strategy. It is hypothesized that the dyseidetic compared to the dysphonetic group will perform poorer on tasks of planning as well as on tasks involving selective attention. Planning strategy is tested on visual search and number matching abilities; attention is assessed by performance on the Posner and Stroop tests. It is hypothesized that the dysphonetic subgroup will perform poorer relative to the dyseidetic group on tasks involving successive processing skills which include tests of word recall, and sentence repetition/question. It is proposed that the dyseidetic group will perform poorer than the dysphonetic group on tests of simultaneous processing. Simultaneous tasks include figure memory, matrix identification and letter naming. It is expected that the mixed dyslexic group will show an overall performance deficit across all tasks.

In summarizing the hypotheses set forth in each part of this study it is expected that dyslexics in comparison with normal controls will exhibit: (a) smaller N1, P1 and P2 amplitude ERPs in response to the irrelevant tone pips delivered during the verbal search task; (b) later latency peaks of the N1 and P1 components; and (c) poorer search performance on the verbal search task but not on the nonverbal task.

Furthermore, it is expected that the Boder defined subgroups of dyslexics will differ between categories such that dyseidetic and mixed type dyslexics in comparison with dysphonetics will exhibit: (a) smaller N1, P1, and P2 amplitude ERP components as defined above; (b) later latency peaks of the N1 and P1 components; (c) poorer performance on the nonverbal search task; and (d) different performance patterns on the verbal search task with the dyseidetic performing superior to the dysphonetic and mixed subgroups.

Finally it is expected that on tasks of cognitive performance: (a) dysphonetics will be poorer than dyseidetics on tasks requiring successive processing; (b) dyseidetics will be poorer than dysphonetics on visual-spatial tasks including tests of selective attention, simultaneous processing and planning; and (c) mixed type children will perform as poor as dysphonetics on successive processing tasks and as poor as dyseidetics on the visual-spatial tasks.

Methodology

Subjects

A total of 22 subjects (male = 14) participated in the ERP/Search study. All were recruited on the basis of age, sex, reading ability and overall school achievement from the Edmonton Catholic School District. Five schools participated in this study. The reading disabled children (n = 11; M age = 9.3, SE = 0.380) were selected according to placement in a remedial school program. All reading disabled children were of normal intelligence (full scale IQ M = 101; SE = 1.99) as assessed on the Weschler Intelligence Scale for Children--Revised (WISC-R). Elemental word attack strategies were tested using the Woodcock Johnson Reading Battery, Basic Skills Cluster; all children scored below the 25th percentile on this scale (M = 15.5; SE = 1.6). No criterion was imposed on the level of comprehension. The control group was comprised of 11 age matched (M = 8.3; SE = 0.38) children from the same school. Since intelligence scores were not available for children of the control group, school achievement was considered an appropriate substitute of aptitude. The Canadian Cognitive Abilities Test

(CCAT) is a standard battery of tests given to elementary children in the third grade that effectively assesses school achievement; scores on this test were matched to Full Scale IQ of the dyslexic children (Achievement scores, $\underline{M}$ = 106; $\underline{SE}$ = 1.85). No child had a history of head injury, was on medication or had been diagnosed with a behaviour disorder.

Based on the classification of Boder Diagnostic Screening Procedure (Boder, 1973; Boder & Jarrico, 1982) a larger group of reading disabled children ($\underline{n}$ = 20) who participated in a cognitive assessment part of this study were divided into three subgroups. Seven children were identified as being dysphonetic, six as dyseidetic, and four as mixed.

Procedure and Data Collection

Event-related potentials. EEG was recorded with gold disc electrodes (Grass E5GH). Electrodes were placed at frontal left and right (F3, and F4 respectively), central left (C3) and right (C4), and parietal left (P3) and right (P4) using the 10-20 International System. All scalp locations were referred to linked earlobes. Eye movements and blinks were recorded using electrodes placed supraorbitally and over the outer canthus of the right eye. Inter-electrode impedance was maintained below 5 Kohms for each subject. Once the electrodes had been applied, the subject was seated in a dimly illuminated room in a padded chair with a headrest. It was explained to the subject that tones would be presented in each ear while he played a "game" with the computer. The subject was instructed not to attend to the tones but to concentrate on accurately performing the task.

Binaural tone pips (98 dB, 1000 Hz) were delivered through headphones at a rate of 1.3 per second while the subject performed the visual search task. All channels were sampled on-line at a rate of 256 Hz beginning 100 msec before each tone pip and continuing 500 msec post-stimulus onset. Physiologic signals were amplified using bandwidths of 0.1 Hz to 30 Hz (6 dB down) on Grass AC amplifiers. Data were collected in response to 75 pips and were stored on disk.

Visual search task. The Weintraub and Mesulam (1985) paper-and-pencil cancellation tasks were modified to allow presentation on a Zenith 27 cm colour monitor. Stimulus displays (see Figure 1)

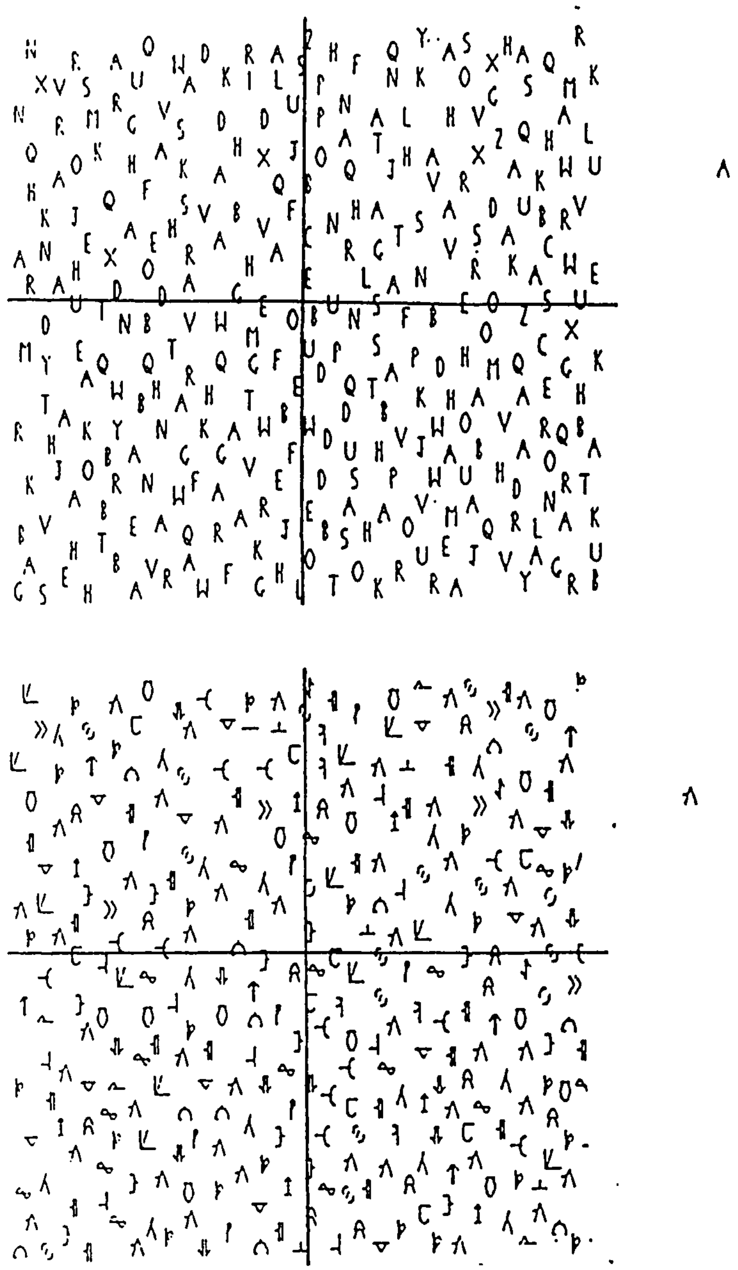

Figure 1. The verbal and nonverbal search arrays as depicted on the computer. Lines represent the separation of the screen into four quadrants. The verbal search task was adapted from Weintraub and Mesulam (1985) and was comprised of 306 capital letter stimuli. Subjects were to cancel instances of the target letter "A" with a light sensitive pen. The nonverbal search array consisted of 306 rearranged capital letter stimuli adapted from the verbal array. Subjects were to identify instances of the target " ʌ " and cancel them with a light sensitive pen.

consisted of a verbal visual search task (capital letters) and a nonverbal visual search task (re-arranged capital letters). Each task was a random array presented on the monitor 50 cm from the subject's resting head. The purpose of the nonverbal re-arrangement of letters was to facilitate lower verbal association of the stimuli while maintaining the same features as the verbal stimuli. The efficacy of this manipulation was observed by increased latencies of naming responses to these stimuli (Freisen & Jutai, 1990). The 306 stimuli contained in an array, each occupied approximately 0.6 cm^2 of space and were presented in white against a black screen. Cancellation of the 48 equally distributed targets was accomplished by using an FTG Data Systems (FT-156) electronic light sensitive pen. When this pen was pushed to the screen, a white 0.6 cm^2 rectangle replaced the stimulus hit. Targets as well as nontargets were replaced in this way.

The subject held the pen in his preferred hand and was allowed to practice using the pen on a linear set of digits. After effective use of the pen was demonstrated, the subject was informed that he was to use the pen and cancel only a specific target which would be shown to him. After ensuring that the subject understood the directions, the target appeared on the screen and the subject was asked to memorize it and to cancel only those instances of the target on the subsequently presented array. The subject was reminded not to attend to the ear tones and to work as quickly and as accurately as possible until all targets were cancelled. The subject was asked to reproduce the target from memory after completing the task to ensure proper encoding. Presentation of array type was counterbalanced across subjects. The data were stored on disk and analyzed by computer.

Cognitive assessment. The reading disabled group described above, comprised part of a larger group of 20 dyslexic children administered several assessment tests. Ten selected tests constituted this battery and were chosen from the Cognitive Assessment System (CAS). These tests were divided into four categories according to underlying theoretical processing strategy (Das, Snart, & Mulcahy, 1982). A brief description of each test within each category is given below. Children were administered these tests at their own school according to the procedure outlined in the manual.

A description of the ten cognitive tests according to type of strategy follows: planning tasks include visual search and matching numbers; attentional tasks consisted of Posner and Stroop tests; successive tasks were comprised of word recall, sentence repetition and question while figure memory, matrix identification, and the Simultaneous Verbal Test made up the simultaneous processing tasks.

The visual search task required the child to identify either a target letter, digit or object in an array of either similar (Control type) or dissimilar (Automatic type) stimuli. Time to locate the target in the array was measured.

Matching numbers required the subject to identify two identical strings of numbers among a set of differing sequences. Sequences varied in length from three to seven digits; number correct and time to complete all sets were recorded. A time constraint of two minutes was imposed.

A subject was to identify letter pairs on the Posner selective attention task. Two conditions of two trials each, outlined pairs of letters on the basis of physical duplication (e.g. NN but not Nn; Test 1) or name match (e.g. Nn but not Nt; Test 2). Number correct and time to complete 100 letter pairs per set constituted the dependent variables. A time limit of 180 seconds existed for each set.

The Stroop task consisted of three timed naming tests. Firstly, the child was to read the names of colours (red, yellow, green and blue) in black ink; the second test required the subject to name boxes of colours (colours as above) while the third test consisted of naming the colour of ink of a word inconsistent with the ink (e.g. the word blue written in red ink would be correctly identified as red). Time to complete each word, colour and interference test was recorded.

On the word recall test, the child's objective was to repeat a series of words read to him by the experimenter. A trial was marked as correct only if the exact order of the series was maintained.

Sentence repetition tests consisted of nonsense sentences, read by the experimenter which the child was to accurately recall. Questions concerning these sentences were then asked of the child; number of correct answers was scored.

The simultaneous verbal task required the subject to identify a particular picture among several related pictures according to verbal (and written) instructions (e.g. Which picture shows the ball on the table? -- required the child to identify this picture among various pictures of a ball, a plant, and a table). Number correct as well as time to discriminate among pictures were measured.

Figure memory tests consisted of 20 drawings briefly shown to the subject and then drawn from memory. After five consecutive errors, the test was discontinued and the number of correctly recalled drawings recorded.

The matrices test was comprised of 20 sets of four matrices each. The subject was required to identify a particular target matrix among a set of four similar test matrices. Performance on this test was assessed by the number of correct identifications of the target stimulus.

Data Analysis

Event-related potential components. Averaged ERPs were computed off-line, with artifact epochs rejected using Paradigm Scientific EEG Analyst

(Freisen & Jutai, 1990) computer software.

An automatic peak detection program was used to determine amplitude and latency as follows: (a) P1 amplitude, the most positive voltage between 100-150 msec post-stimulus (b) N1 amplitude, the most negative voltage between 100-250 msec post-stimulus; (c) P2 amplitude, the most positive voltage between 120-250 msec occurring subsequent to N1; (d) P1 and N1 latency, time associated with the apex of voltage within the appropriate time range. Amplitudes were measured relative to a baseline of 100 msec pre-stimulus; latencies were measured relative to stimulus onset (time 0).

Search performance parameters. Initial statistical analysis of the search data was done using Statistical Analysis System (SAS) microcomputer programs (Harrop & Velicer, 1990); total time, mean inter-target distance, number errors of commission and omission, mean inter-target time and a measure of search strategy were calculated. Since the data on the inter-target time were skewed, these data were submitted to a log transformation.

An estimate of search strategy (S) was calculated by the following formula:

$$\underline{S} = \frac{\sum_{\underline{i}=1}^{\underline{n}} [(\underline{D}_{\underline{i}} \times \underline{T}_{\underline{i}}) / 100]}{\underline{n}}$$

The intent of this measure was to provide a quantitative measure of search strategy dependent upon inter-target distance ($\underline{D}$; in pixel units), inter-target time ($\underline{T}$; in seconds) and total number of detections ($\underline{n}$).

Pilot work in this laboratory has indicated that these scores are normally distributed, ranging from 1-10. Furthermore, this index is representative of systematicity; low scores are indicative of systematic, linear-type search and high scores of erratic, scattered-type search. Since the search for the last few targets commonly occurred during rechecking of the array this resulted in atypical inter-target distances and search times. In order to eliminate this distortion, the last 3 inter-target times and distances were arbitrarily removed prior to analysis.

In addition to the SAS analysis, a <u>search</u>

systematicity rating was acquired. Two independent raters classified each individual's search performance of the verbal search task along a scale of 1 to 5, with 1 being the most unsystematic. These analyses were based on reproductions of the subject's search pattern on the array with coloured sequential numbers indicating the order of targets hit (see Figure 2 for examples of systematic and unsystematic ratings of these arrays). Inter-rater reliability was assessed by Kendall's Coefficient of Concordance (W). Raters did not significantly differ between themselves ($W = 0.026$ $p > .10$). Ratings were not done on the nonverbal task.

Search strategy on the verbal search task was also evaluated by calculating an uncertainty score for each subject (Frick & Miller, 1951; Loh & Beck, 1989). These scores indicated the degree of predictability of the location of a target based on sets of previous target locations. The location of a target was defined as the quadrant of the screen in which the target appeared. High uncertainty scores indicated unpredictable search patterns among quadrants and hence less predicability in assessing the location of a subsequent target. Figure 3

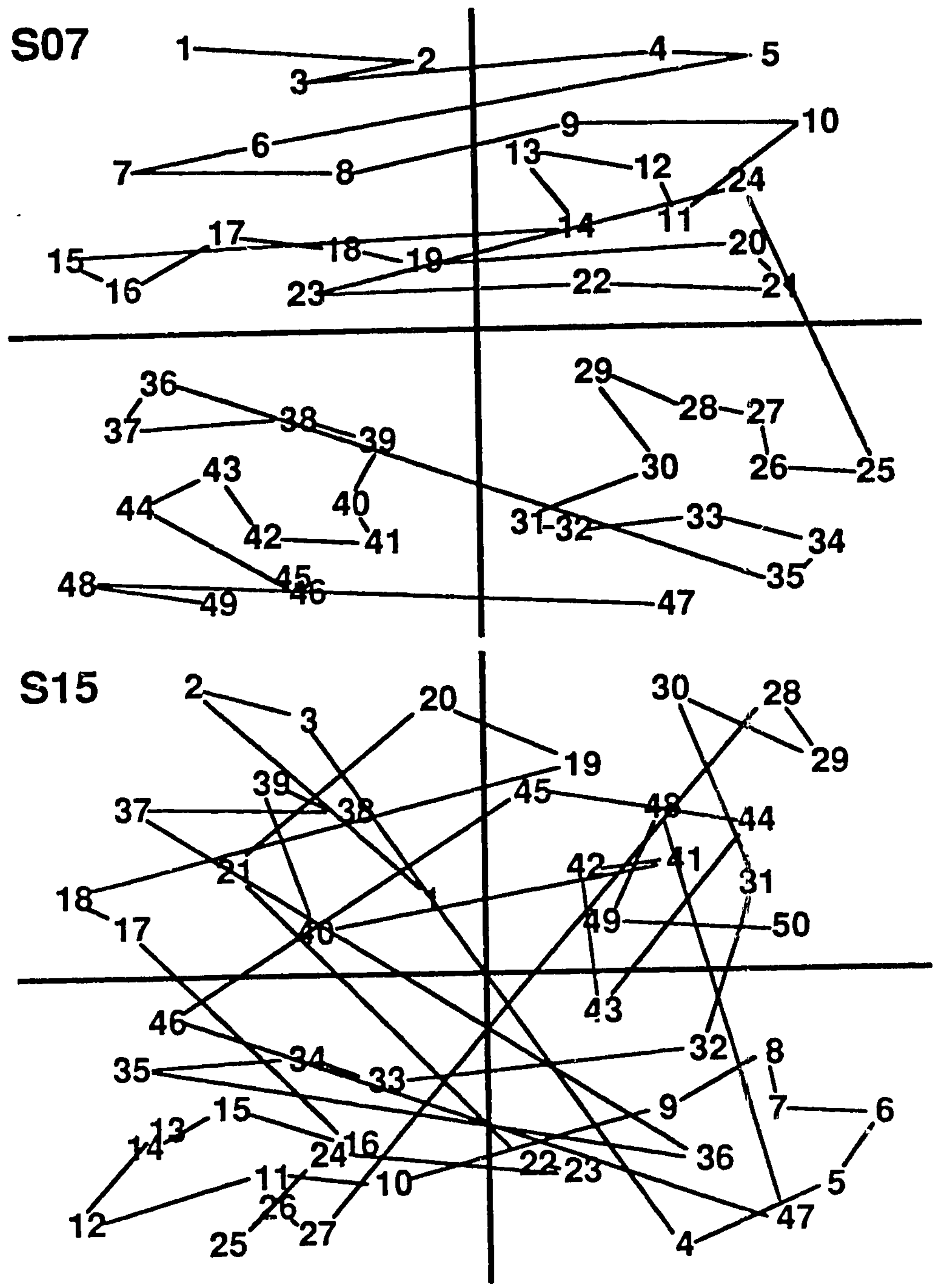

Figure 2. Examples of the reproductions of search pattern on the verbal array given to two independent raters for classification of systematicity. Quadrants are divided into four sections by the heavy solid line. Numbers represent sequential target his with successive targets joined by a line. The unsystematic search pattern is easily recognized by the erratic path (S15) followed in the identification of targets whereas the systematic search (S07) is characterized by movements of a more consistent orientation.

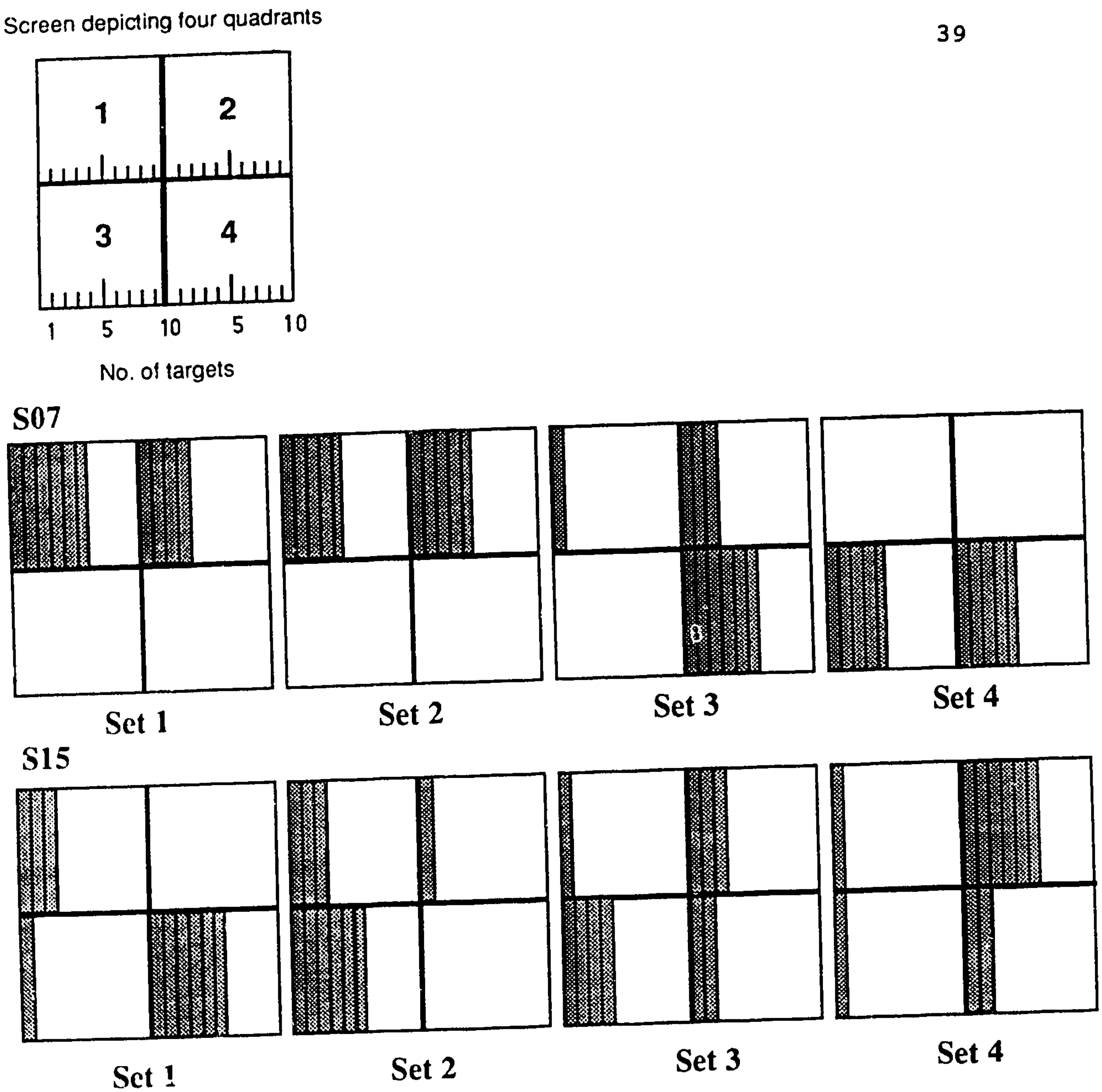

Figure 3. Diagrammatic representation of number of identified targets in each of the four screen quadrants across four successive sets of ten targets located. Quadrants are numbered left to right. For example, subject S15 identified targets 30-39 by locating 1 target in quadrant 1, 3 targets in quadrant 2, 4 targets in quadrant 3, and 2 targets in quadrant 4.

illustrates the difference between erratic and systematic searchers by showing number of targets identified within each quadrant for successive blocks of ten targets located. Systematic searchers typically found more targets within one or two quadrants per set.

Assessment of the uncertainty of search path on the nonverbal search task was not attempted.

Cognitive evaluation of Boder subgroups. Depending upon task, total time and/or number correct were measured on each of the ten cognitive tests within each subgroup.

Visual inspection of waveforms. Grand-averaged ERPs were calculated across subjects in each group according to task. These averages are presented in Figures 4 & 5.

Statistical Analyses

ERP/Search performance of dyslexics and normal controls. Descriptive statistics were calculated for each of the ERP and search performance data sets. Frequency histograms revealed relatively normally distributed data for each set. The ERP data was submitted to TSQUARE analysis (Morrison, 1990). Amplitude and latency for the P1, N1, and P2

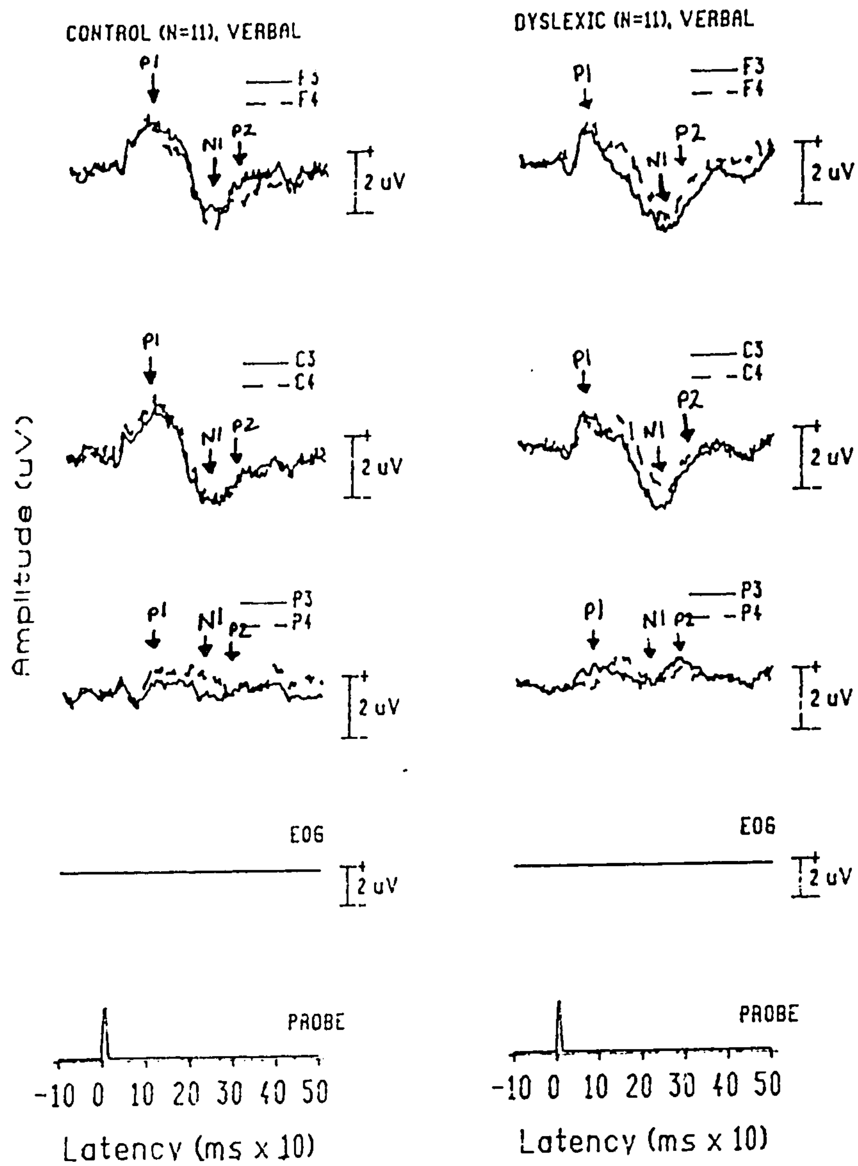

Figure 4. Amplitudes in μv of the grand-averaged ERPs of the normal control group (n = 11; left column) and dyslexic group (n = 11; right column) recorded from bilateral frontal (F3, F4), central (C3, C4), and parietal (P3, P4) sites during presentation of the auditory probe on the verbal search task. Eye movements appear as a straight line along the bottom of each column since artifacts have been removed. Solid lines represent ERPs recorded from the left hemisphere; dotted lines represent ERPs recorded over the right hemisphere.
Arrows indicate P1, N1, and P2 latencies.

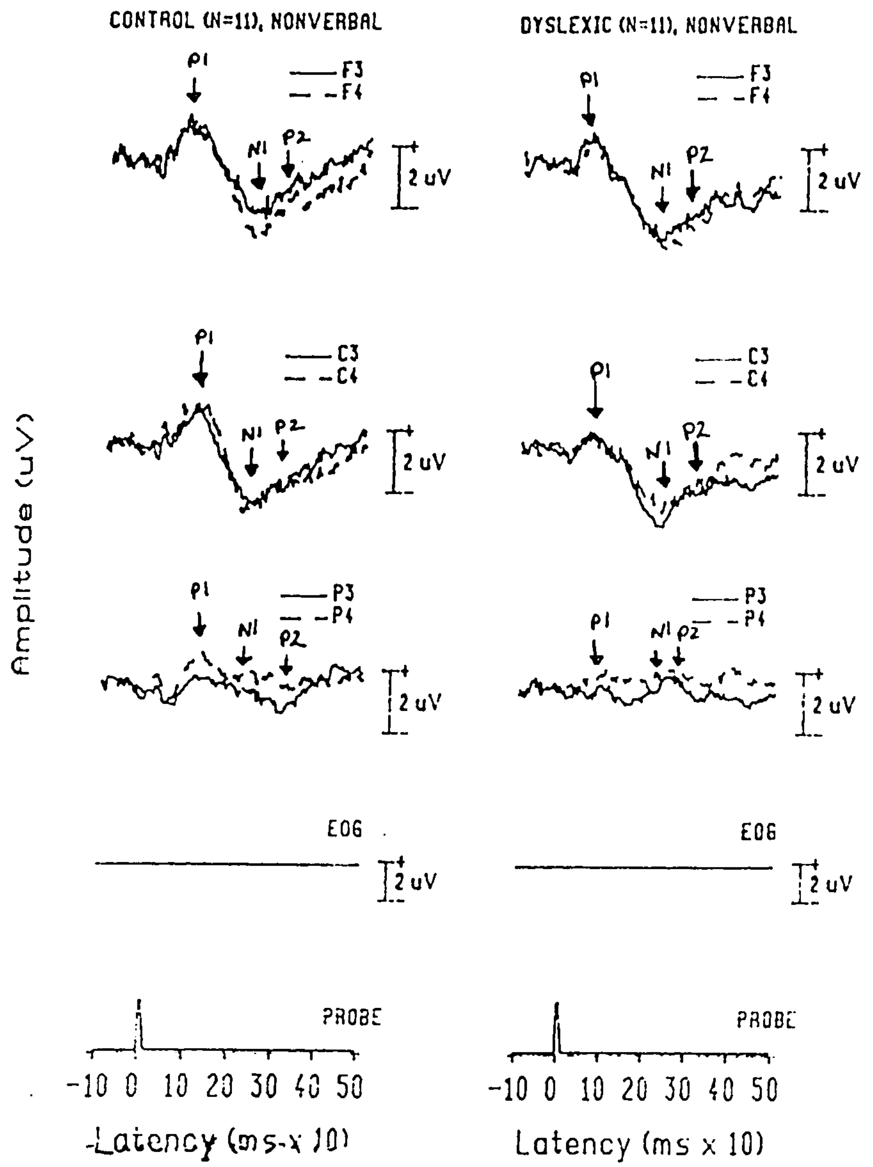

Figure 5. Amplitudes in μ v of the grand-averaged ERPs of the normal control group (n = 11; left column) and dyslexic group n = 11; right column) recorded from bilateral frontal (F3, F4), central (C3, C4), and parietal (P3, P4) sites during presentation of the auditory probe on the nonverbal search task. Eye movements appear as a straight line along the bottom of each column since artifacts have been removed. Solid lines represent ERPs recorded from the left hemisphere; dotted lines represent ERPs recorded over the right hemisphere.
Arrows indicate P1, N1, and P2 latencies.

components were subjected to this inquiry. In order to increase the statistical power, two-sample *t*-tests were also completed on the P1 and N1 components. These two components were chosen for theoretical reasons. Each performance variable was evaluated by a two-sample *t*-test as were the bilateral central and parietal P1 amplitude components appraised during only the verbal task. Although the application of multiple *t*-tests likely increased the probability of finding a false positive result, this error was compromised for the sake of increased power.

In addition, relationships between the variables of inter-target time on the verbal task and the associated central and parietal P1 amplitudes were examined. Scatterplots of these combinations were completed. Statistical correlations were also performed between the inter-target time observed on the search task and P1 or N1 amplitude.

ERP/Search performance of Boder subgroups. Mean P1 and N1 amplitude components and search performance scores were calculated for each of the three Boder categories.

Cognitive evaluation of Boder subgroups. Finally, means and standard errors of the mean were calculated for each cognitive test according to Boder subgroup followed by one-way analyses of variance for each of the ten tests. Post-hoc comparisons (Scheffe *F*-test) were calculated for significant main effects. Correlations were calculated between individual Boder subgroups and IQ for significant main effects.

Results

Descriptive statistics and TSQUARE

ERP measures. Means and estimates of the standard error of the mean for the amplitudes of P1, N1, and P2 at each site are presented in Tables 1 - 4. The *F*-value realised by the TSQUARE analysis is also shown. Given that the critical value of $F_{.05}(3, 18)$ is 3.16, it is apparent that no *F*-value approaches significance, that is, there are no significant main effects of amplitude between groups.

These same statistics were calculated, as above, for the latency components. Tables 5 - 8 list these values. No significant results were found between dyslexics and controls by the TSQUARE for $F_{.05}(2, 19) = 3.52$ for a group main effect of amplitude.

From observations of the grand-averaged ERP figures and Tables 1 - 8, it was determined that the P2 component was not yet developed in this age group; this is consistent with previous work on developmental changes of ERP components (Kurtzberg et al., 1984). This component, therefore, was not subjected to further statistical analysis.

In summary, it was established that dyslexics did not significantly differ from controls on amplitude

Table 1. Means and standard errors of amplitude (μv) of P1, N1, & P2 ERP components from the frontal, central, and parietal areas of the left hemisphere of dyslexics and normal controls during the verbal search task. The *F*-values and associated probability levels are given for the between group comparisons.

		Component				
		P1	N1	P2		
Location	Condition	*M*(*SE*)	*M*(*SE*)	*M*(*SE*)	*F*	*p*
Frontal						
	Dyslexic	0.482(0.642)	-3.15(0.382)	0.276(0.302)	1.77	.19
	Control	1.91(0.492)	-2.43(0.274)	-0.307(0.855)		
Central						
	Dyslexic	0.835(0.640)	-3.00(0.513)	0.375(0.162)	1.80	.18
	Control	1.92(0.346)	-2.31(0.259)	-0.300(0.398)		
Parietal						
	Dyslexic	1.12(0.508)	-1.25(0.456)	0.680(0.298)	1.88	.17
	Control	1.07(0.268)	-1.09(0.266)	-0.170(0.282)		

Table 2. Means and standard errors of amplitude (μv) of P1, N1, & P2 ERP components from the frontal, central, and parietal areas of the right hemisphere of dyslexics and normal controls during the verbal search task. The *F*-values and associated probability levels are given for the between group comparisons.

		Component				
		P1	N1	P2		
Location	Condition	*M*(*SE*)	*M*(*SE*)	*M*(*SE*)	*F*	*p*
Frontal						
	Dyslexic	1.56(0.744)	-2.72(0.580)	0.623(0.330)	0.50	.69
	Control	1.63(0.356)	-2.61(0.273)	-0.239(0.640)		
Central						
	Dyslexic	1.60(0.608)	-2.31(0.400)	0.440(0.185)	0.53	.67
	Control	2.22(0.373)	-2.29(0.341)	-0.098(0.441)		
Parietal						
	Dyslexic	1.52(0.409)	-0.797(0.263)	0.517(0.140)	0.56	.65
	Control	1.23(0.204)	-0.549(0.270)	0.247(0.266)		

Table 3. Means and standard errors of amplitude (μv) of P1, N1, & P2 ERP components from the frontal, central, and parietal areas of the left hemisphere of dyslexics and normal controls during the nonverbal search task. The *F*-values and associated probability levels are given for the between group comparisons.

		Component				
		P1	N1	P2		
Location	Condition	*M*(*SE*)	*M*(*SE*)	*M*(*SE*)	*F*	*p*
Frontal						
	Dyslexic	0.311(0.423)	-3.44(0.500)	-1.03(0.444)	2.9	.07
	Control	1.30(0.624)	-2.52(0.639)	0.725(0.583)		
Central						
	Dyslexic	0.492(0.384)	-3.28(0.594)	-0.870(0.509)	1.9	.17
	Control	1.53(0.374)	-2.78(0.501)	0.476(0.520)		
Parietal						
	Dyslexic	0.322(0.393)	-1.64(0.319)	-0.194(0.336)	0.55	.66
	Control	0.812(0.456)	-1.57(0.496)	0.424(0.524)		

Table 4. Means and standard errors of amplitude (μv) of P1, N1, & P2 ERP components from the frontal, central, and parietal areas of the right hemisphere of dyslexics and normal controls during the nonverbal search task. The F-values and associated probability levels are given for the between group comparisons.

		Component				
		P1	N1	P2		
Location	Condition	$M(SE)$	$M(SE)$	$M(SE)$	F	p
Frontal						
	Dyslexic	0.218(0.506)	-3.70(0.586)	-0.421(0.570)	0.88	.47
	Control	1.25(0.581)	-3.25(0.408)	0.283(0.497)		
Central						
	[illegible]	0.469(0.456)	-2.74(0.503)	-0.348(0.457)	2.2	.13
	[illegible]	1.88(0.481)	-2.86(0.507)	-0.0764(0.324)		
Parietal						
	Dyslexic	1.02(0.359)	-0.859(0.342)	0.146(0.229)	0.57	.64
	Control	1.62(0.295)	-0.566(0.207)	0.184(0.268)		

Table 5. Means and standard errors of latency (msec) of P1, N1, & P2 ERP components from the frontal, central, and parietal areas of the left hemisphere of dyslexics and normal controls during the verbal search task. The *F*-values and associated probability levels are given for the between group comparisons.

		Component			
		P1	N1		
Location	Condition	*M*(*SE*)	*M*(*SE*)	*F*	*p*
Frontal					
	Dyslexic	131.4(4.18)	213.4(8.69)	0.11	.90
	Control	133.5(3.20)	216.6(9.77)		
Central					
	Dyslexic	136.7(3.69)	220.5(6.15)	0.28	.76
	Control	132.8(4.31)	223.1(6.20)		
Parietal					
	Dyslexic	133.5(4.34)	189.3(11.7)	0.16	.85
	Control	134.6(4.66)	199.2(12.4)		

Table 6. Means and standard errors of latency (msec) of P1, N1, & P2 ERP components from the frontal, central, and parietal areas of the right hemisphere of dyslexics and normal controls during the verbal search task. The *F*-values and associated probability levels are given for the between group comparisons.

		Component			
		P1	N1		
Location	Condition	*M*(*SE*)	*M*(*SE*)	*F*	*p*
Frontal					
	Dyslexic	137.4(3.98)	226.9(6.34)	0.49	.62
	Control	133.2(4.26)	230.5(3.69)		
Central					
	Dyslexic	140.3(3.51)	228.3(7.15)	0.71	.51
	Control	134.2(3.62)	225.1(5.73)		
Parietal					
	Dyslexic	141.0(3.83)	211.9(11.6)	1.6	.24
	Control	135.3(3.54)	189.6(14.8)		

Table 7. Means and standard errors of latency (msec) of P1, N1, & P2 ERP components from the frontal, central, and parietal areas of the left hemisphere of dyslexics and normal controls during the nonverbal search task. The *F*-values and associated probability levels are given for the between group comparisons.

		Component			
		P1	N1		
Location	Condition	*M*(*SE*)	*M*(*SE*)	*F*	*p*
Frontal					
	Dyslexic	130.7(3.74)	207.0(10.0)	0.55	.59
	Control	128.9(3.37)	221.2(8.85)		
Central					
	Dyslexic	130.7(3.66)	205.6(10.6)	0.83	.45
	Control	127.5(3.22)	217.7(7.71)		
Parietal					
	Dyslexic	132.5(3.39)	177.6(9.59)	0.71	.50
	Control	132.5(4.06)	196.0(11.9)		

Table 8. Means and standard errors of latency (msec) of P1, N1, & P2 ERP components from the frontal, central, and parietal areas of the right hemisphere of dyslexics and normal controls during the nonverbal search task. The *F*-values and associated probability levels are given for the between group comparisons.

		Component			
		P1	N1		
Location	Condition	*M*(*SE*)	*M*(*SE*)	*F*	*p*
Frontal					
	Dyslexic	129.6(3.97)	214.8(10.4)	0.25	.78
	Control	126.4(4.05)	220.9(10.1)		
Central					
	Dyslexic	130.7(3.43)	216.3(10.3)	0.25	.78
	Control	127.1(4.29)	219.1(5.83)		
Parietal					
	Dyslexic	133.9(3.08	182.5(10.4)	1.1	.36
	Control	130.0(3.50)	199.2(8.39)		

or latency measures of the P1 and N1 components; it was ascertained that neither population exhibited a P2 component.

Search performance measures. For each group, means and estimates of the standard error of the mean were computed for each of the 9 performance parameters of the verbal search task (7 for the nonverbal). Table 9 contains these values along with the t-value calculated by a two-sample t-test comparing group means. The appropriate critical value for a two-tailed $t_{.05}(20)$ is 2.086. The dyslexic compared to control group was observed to have a significantly larger pixel-unit distance between targets on only the verbal search task.

In summary, analysis of two-sample mean differences between dyslexic and control groups on visual search performance measures revealed only a significantly larger inter-target distance in the dyslexic population.

Other Statistical Analyses of ERP and Search Performance

Two-sample t-tests. Analysis of the P1 component at bilateral central and parietal sites revealed a significant difference between dyslexics and

Table 9. Means, standard errors and associated *t*-values of performance measures on verbal and nonverbal search tasks

Task	Measure	Group: Dyslexic *M*(*SE*)	Group: Control *M*(*SE*)	*t*	*p*
Verbal	Total time (sec)	220.2(23.5)	196.6(24.4)	0.70	.49
	Inter-target distance (pixel)	123.8(3.77)	105.7(5.51)	2.7	.01
	No. Omissions	1.09(0.992)	0.364(0.137)	1.3	.23
	No. Commissions	1.45(0.443)	2.09(1.11)	0.93	.36
	Inter-target time (sec)	4.25(0.715)	3.28(0.497)	1.6	.13
	log (ITT)	0.604(0.0069)	0.489(0.0076)	1.7	.10
	Search score	8.49(4.97)	6.11(2.66)	1.6	.13
	Uncertainty (H2)	81.1(1.82)	80.1(2.26)	0.35	.73
	Rating	1.64(0.363)	1.82(0.325)	0.37	.71
Nonverbal					
	Total time (sec)	255.3(19.3)	256.5(24.0)	0.04	.97
	Inter-target distance (pixel)	134.9(7.95)	113.7(6.37)	2.1	.05
	No. Omissions	3.82(12.3)	[illegible].73(7.24)	0.04	.97
	No. Commissions	4.45(19.9)	1.18(5.91)	1.3	.20
	Inter-target time (sec)	4.34(0.149)	4.30(0.279)	0.12	.91
	log (ITT)	0.644(0.0019)	0.624(0.0028)	0.52	.61
	Search score	9.50(2.13)	7.77(1.63)	1.6	.12

controls at C3 P1 amplitude (t = 2.29; p < .05) during the verbal search task. The dyslexic group had a significantly lower amplitude, relative to control, at this site. No other group differences emerged significant.

MAD analysis. This analysis provides an estimate of the variability between groups based on median, rather than mean scores and is a more appropriate analysis when the data contains some extreme scores (Hogg, 1977). Only the inter-target time was subjected to this analysis since these data did contain two extreme data points. Once the MAD estimate of variability was obtained a t-test for differences between group medians was performed. Dyslexics were observed to have significantly higher verbal but not nonverbal median times than the control group (t = 2.204; p < .025).

Analysis of variable relationships. Figure 6 depicts the relationship of inter-target search time and left central P1 amplitude for the verbal task. This was the only scatter plot which appeared to discriminate between the two groups.

Correlational comparisons between groups failed to reveal a significant association between the

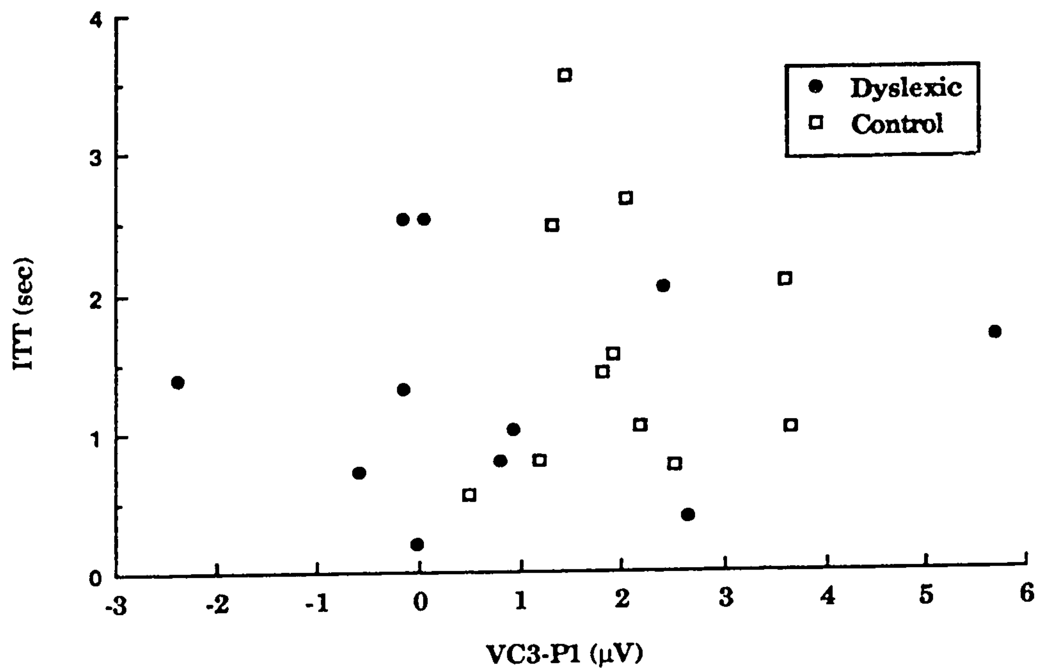

Figure 6. Scatterplot of the relationship of inter-target time (ITT; sec) and P1 amplitude recorded from the left central electrode site (VC3-P1; μv) for control (open squares) and dyslexics (filled circles). Both variables were measured during the verbal search task.

variables of inter-target search time and P1 amplitude (*r* = -.14 for both groups between search and P1-left central amplitude; *r* = -.01 for the reading disabled group, *r* = -.33 for the control group). Since it is evident from Figure 6 that there were two extreme data points which possibly affected the correlations above, a similar correlation was conducted for the dyslexic population with these points removed (*r* = -.26). It is apparent, that the control group had a stronger relationship between these variables than did the reading disabled group although no correlations were statistically significant.

ERP and Search Performance as a Function of Boder Classification

Several differences emerged between groups on performance of the cognitive tasks. To assess whether similar differences could be found on the ERP and search performance measures, means and standard errors of the mean for the search performance variables and the ERP N1 and P1 components according to Boder categories were calculated. Table 10 contains these values for the ERP measures; Table 11 shows the Search means and

Table 10

Means and standard errors of P1 and N1 amplitudes (μv) of ERPs recorded from the left hemisphere in Boder subgroups

	Group		
	DP	DE	MX
Measure	*M*(*SE*)	*M*(*SE*)	*M*(*SE*)
Frontal P1	0.571(1.39)	0.649(0.575)	-0.070(0.992)
Central P1	0.802(1.33)	0.863(0.634)	-0.309(0.278)
Parietal P1	1.31(1.04)	1.47(0.494)	-0.080(0.370)
Frontal N1	-2.48(0.513)	-3.50(0.705)	-4.16(0.171)
Central N1	-2.09(0.711)	-3.14(0.756)	-5.00(0.191)
Parietal N1	-0.393(0.711)	-1.14(0.895)	-2.78(0.478)

Note. DP = Dysphonetic (*n* = 5); DE = Dyseidetic (*n* = 4); MX = Mixed (*n* = 2).

Table 11

Means and standard errors of performance measures on the verbal search task according to Boder subgroups

	Group		
	DP	DE	MX
Measure	M(SE)	M(SE)	M(SE)
Total time (sec)	198.2(26.9)	254.4(57.0)	213.7(16.3)
Inter-target distance (pixel)	150.0(14.2)	153.6(15.0)	141.0(2.50)
No. Omissions	1.25(1.12)	1.25(0.447)	2.00(1.41)
No. Commissions	4.60(2.93)	0.500(0.289)	8.50(8.50)
Inter-target time (sec)	4.00(0.617)	4.92(1.01)	3.58(0.570)
log (ITT)	0.578(0.071)	0.664(0.089)	0.549(0.070)
Search score	8.26(1.96)	10.0(2.26)	6.60(0.550)
Uncertainty (H2)	80.6(1.72)	80.8(4.94)	83.0(1.00)
Ratings	2.0(0.866)	2.5(0.316)	1.0(0)

Note. DP = Dysphonetic (*n* = 5); DE = Dyseidetic (*n* = 4); MX = Mixed (*n* = 2).

standard errors. This sample contained two fewer subjects per group (DP $\underline{n}$ = 5, DE $\underline{n}$ = 4, MX $\underline{n}$ = 2) and was therefore not subjected to formal statistical analysis.

The mixed group does show interesting differences from the other two groups on P1 and N1 mean amplitudes (see Table 10). In particular it appears that the mixed group exhibits a near baseline P1 amplitude and a larger N1 amplitude than either dysphonetic or dyseidetic groups. There is, however, considerable overlap between the groups. It appears that a larger sample is needed to clearly establish if the mixed subgroup does indeed have smaller amplitude P1 and larger amplitude N1 than the dysphonetic and dyseidetic groups. Latencies of these components did not appear to differ between subgroups; these values are not presented.

Statistical Assessment of the Cognitive Performance of the Boder Subgroups

Tables 12 - 14 give the descriptive measures of the cognitive performance of the three Boder subgroups. These tables are divided according to type of processing strategy thought to be utilized during the specific task (Das et al., 1982).

Table 12

Means and standard errors of performance of the three subgroups of dyslexic children identified by the Boder: Planning Tasks

			Group		
			DP	DE	MX
Task	Subtest	Measure	*M*(*SE*)	*M*(*SE*)	*M*(*SE*)
Visual Search					
	Letters	time (sec)	10.1(1.46)^{a}	8.33(1.03)^{a}	15.6(3.65)^{b}
	Digits	time (sec)	7.66(0.855)^{a}	6.50(0.225)^{b}	9.83(1.44)^{b}
	Pictures	time (sec)	10.6(0.961)^{a}	10.2(1.91)^{a}	15.9(2.45)^{b}
Matching Numbers					
	Test 1	No. correct	7.71(1.84)	7.20(0.167)	7.50(0.289)
		time (sec)	63.1(5.11)	63.7(7.75)	73.0(8.50)
	Test 2	No. correct	4.29(8.92)	3.70(0.955)	3.00(0.577)
		time (sec)	121(0.184)	120(0.833)	121(0)
	Test 3	No. correct	3.86(0.340)	3.30(0.615)	3.50(0.289)
		time (sec)	121(0)	121(0)	121(0)

Note. DP = dysphonetic (*n* = 7); DE = dyseidetic (*n* = 6); MX = mixed (*n* = 4). Times of 121 sec denote exceeding of 2-min time limit. Superscripts identify group membership such that groups with ^{a} significantly differ from groups with ^{b} e.g. mixed < dysphonetic = dyseidetic groups on the letters visual search task.

Table 13

Means and standard errors of performance of the three subgroups of dyslexic children identified by the Boder: Attentional Tasks

			Group		
			DP	DE	MX
Task	Subtest	Measure	M(SE)	M(SE)	M(SE)
Posner Selective Attention					
	Test 1	No. correct	44.4(1.95)	42.7(4.77)	44.25(2.56)
		time (sec)	124(12.1)	130(18.6)	140(8.22)
	Test 2	No. correct	34.0(1.46)[a]	26.7(2.19)[b]	30.8(1.38)[a]
		time (sec)	180(0.986)	181(0)	181(0)
Stroop					
	Words	time (sec)	27.9(2.98)	25.2(1.78)	29.3(1.25)
	Colours	time (sec)	41.6(3.79)	36.0(2.05)	44.3(3.30)
	Interference	time (sec)	74.6(6.23)	76.5(4.11)	90.3(11.7)

Note. DP = Dysphonetic (n = 7); DE = Dyseidetic (n = 6); MX = Mixed (n = 4). Times of 181 sec denote exceeding of 2.5-min time limit. Superscripts identify group membership such that groups with [a] significantly differ from groups with [b], e.g. dyseidetic < dysphonetic = mixed groups on the no. correct on the Posner, Test 2.

Table 14

Means and standard errors of performance of the three subgroups of dyslexic children identified by the Boder: Successive and Simultaneous tasks

			Group		
			DP	DE	MX
Task	Subtest	Measure	*M*(*SE*)	*M*(*SE*)	*M*(*SE*)
Successive					
	Word recall	No. recall	34.1(4.04)	47.3(4.64)	41.0(8.53)
	Sentence repetition	No. recall	6.00(0.535)	6.67(0.955)	5.00(1.41)
	Sentence question	No. correct	4.10(0.553)	4.80(0.477)	5.20(1.65)
Simultaneous					
	Verbal	No. correct	15.1(0.670)	16.2(0.703)	16.3(1.31)
		time (sec)	6.68(0.570)	8.22(0.374)	7.99(1.11)
	Figure Memory	No. recall	10.0(0.756)	10.8(0.792)	11.0(1.78)
	Matrices	No. correct	13.5(1.73)[b]	16.5(1.18)[a]	18.5(1.56)[a]

Note. DP = Dysphonetic (*n* = 7); DE = Dyseidetic (*n* = 6); MX = Mixed (*n* = 4). Superscripts identify group membership such that groups with [a] significantly differ from groups with [b], e.g. dysphonetic < dyseidetic = mixed groups on the matrices task.

One-way ANOVA between groups established a significant effect on planning tasks only on the controlled visual search tests ($F = 5.23$, $p < .05$). Post-hoc comparisons demonstrated that the mixed subgroup took significantly longer to locate each of the three stimulus types than the other two groups. Due to the similarity of these tasks with the computer visual search task, means and standard errors of the time to identify a target on the paper-and-pencil search task was plotted with the inter-target time observed on the computer verbal search task. Figure 7 illustrates these values according to sub-group. A significant group difference emerged on the Posner attentional task for number of correct responses on identification of matching letter names, e.g. Nn vs. Nt (see Table 13, Test 2). Post-hoc analysis revealed the dyseidetic group identified significantly fewer correct matches than the other two groups ($F = 4.7$, $p < .05$) on this attentional task. Groups did not differ on the measures of number of correct responses and time on the Stroop task. Analysis between groups of the successive and simultaneous processing tasks

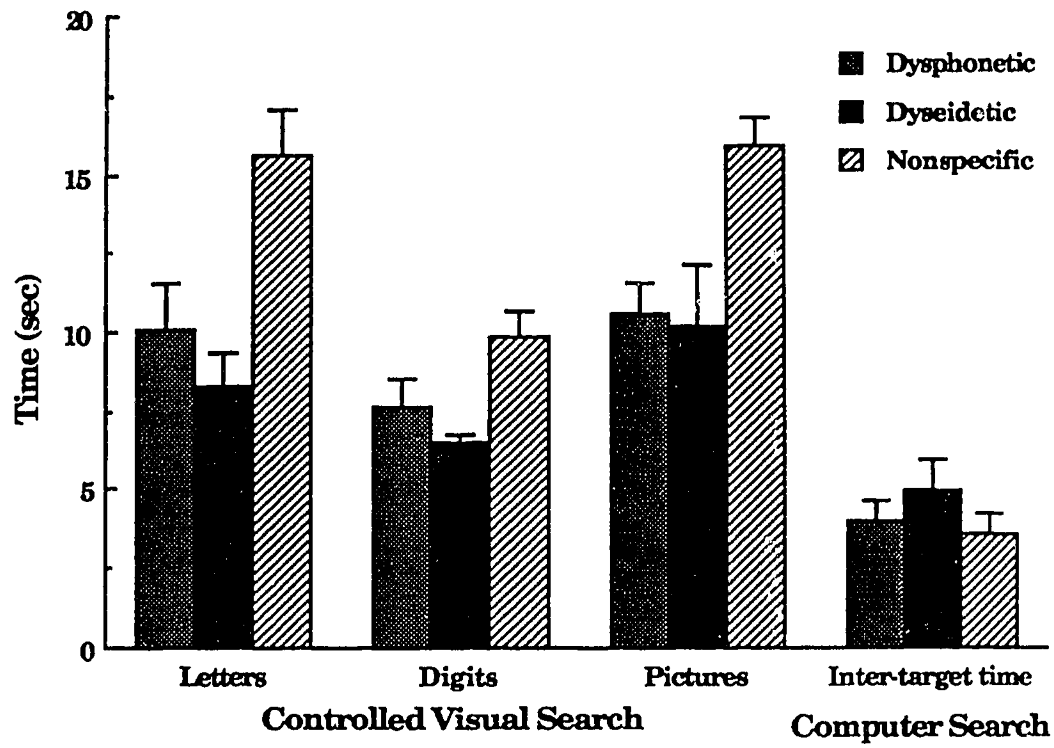

Figure 7. Means and standard errors of the mean time to search arrays of letters, digits, or picture stimuli contained on the Controlled Visual Search Task concurrent with inter-target time observed on the computerized visual search task. Bars represent the subgroups of reading disabled children identified by the Boder Diagnostic Screening Procedure (Boder, 1973); bars illustrate dysphonetics (stippled), dyseidetics (filled), and mixed (striped) subgroups.

revealed few differences (see Table 14). Only the dysphonetic group recalled significantly fewer figures than the dyseidetic or mixed group on the matrices task ($F = 4.89$, $p < .05$). Performance on this task, however, may be more related to intelligence than to group differences. A significant correlation was found between Full Scale intelligence scores and number of matrices recalled (R-squared = .35; $F = 9.15$, $p < .01$).

In summary mixed type dyslexics were significantly poorer at finding a stimulus within an array than either dysphonetic or dyseidetic dyslexics. The dyseidetic group, however, was poorest at letter name discriminations, whereas the dysphonetic group recalled significantly fewer complex figures than the other two subgroups. The groups, however, were not found to significantly differ on the majority of tests.

Discussion

There appeared to be consistent differences between dyslexic and control children in the ERP/Search part of this study at specific sites according to task. Specifically, it was revealed that the dyslexic group had a significantly smaller [illegible] amplitude at the left central site elicited during the verbal search task. Dyslexics were also observed to have longer measures of inter-target distance and inter-target time on this particular task. These results are consistent with the literature and were predicted by the probe theory. Furthermore, the lack of significant differences between groups at right hemisphere sites is consonant with the literature suggesting that dyslexia is characterised by a left hemisphere dysfunction.

Few significant differences in cognitive functioning were found between the three Boder subgroups of dyslexics.

<u>ERPs between Dyslexics and Normal Controls</u>

It was expected that the dyslexic group would exhibit significantly smaller amplitude and increased latency on the ERP attention-related components. Dyslexics did exhibit a smaller amplitude P1 component only at the left central site during the verbal search task. The groups were not significantly different on measures of latency.

Amplitudes of the N1, P2 and P3 components elicited by simple target discriminations have generally been found to decrease significantly in dyslexics compared with normal controls (Harter, Anllo-Vento, Wood, & Schroeder, 1988; Harter, Diering, & Wood, 1988; Harter et al., 1989). It has been suggested that ERPs recorded in this manner are bound to the stimulus parameters and thus, do not adequately assess differences between groups in the cognitive aspects of these components (Papanicoulau & Johnstone, 1984). The probe paradigm, by employing task-irrelevant, repetitive stimuli concurrent to cognitive assessment provides a more accurate description of the neural components underlying the cognitive task since the recording of electrical activity is of irrelevant sensory information. Processing of this information, therefore is limited by the amount of resources available and not on the relevance of the stimuli.

Johnstone et al. (1984) used a visual probe during various reading related tasks and measured differences among ten identifiable components of the ERPs between dyslexic and normal controls. They found that dyslexics had significantly smaller amplitudes of the factors associated with N1, P1 and N2. Precisely these results were expected in the present study. The advantage of the irrelevant probe paradigm used in this study is its dissociation of the sensory aspects of the probe stimulus from the cognitive demands of the task (Papanicoulau & Johnstone, 1984). Therefore, the difference in sensory modality between the probe and task stimuli can not account for the failure to replicate the effects obtained by Johnstone et al. (1984) using same modality stimuli. The only significant effect observed between group means was a smaller amplitude P1 component at the left central electrode site. It is interesting that this significant effect corresponded to the group by electrode and group by side interaction effects observed by Johnstone et al. (1984). That is, Johnstone and his colleagues found that dyslexics compared with controls had reduced N1 and P1 components on the left side particularly at the central site. This provides support for the hypothesis that the left hemisphere may be dysfunctional in dyslexia (Hynd et al., 1990). Hynd et al. reported evidence suggesting that dyslexics differ from both children with attention deficit disorder and normal children in brain morphology observed on magnetic resonance images. Specifically, these authors observed that dyslexics have a smaller left planum temporale than children with attention deficit disorder or normal children. The planum temporale is a cortical area located within the lateral fissure immediately posterior to the auditory cortex and serves as an anatomical measure of hemispheric asymmetry (Kolb & Whishaw, 1985). It is easily identifiable on brain scans and can be measured, yielding an approximate index of cortical development (Hynd et al., 1990). The observation by Hynd et al. that dyslexics have a smaller left planum, therefore, suggests that dyslexics have an underdeveloped left hemisphere. Furthermore, these authors have observed that significantly more dyslexics exhibit a reversed asymmetry of the plana than in attention deficit and normal controls. That is, more dyslexics have a right greater than left planum than the normal left greater than right pattern. The authors concluded that this reversed asymmetry may be related to an abnormal pattern of cortical development.

It is unclear why all ERP components of this study did not show similar decreases in amplitude as in the Johnstone et al. (1984) study. One possible explanation is that the Johnstone study employed a different statistical assessment than that used here. In this study the variability associated with almost all the ERP measures was substantially large compared with the mean. Thus, it may be that differentiation of factors corresponding to ERP components is a more sensitive way to assess group differences. That is, it is likely that some significant results were not identified on the tests of means due to large error terms. This may have been avoided by employing a technique that first characterizes variance into meaningful factors and subsequently analyzes the factors between groups, as did the Johnstone study. Principal Components Analysis may be a suitable statistical procedure to employ in future studies, provided a sufficient number of subjects participate in the study.

Measures of latency in this study did not significantly differ between groups at any site as has been observed in ERP target identification studies (e.g. Taylor & Keenan, 1990). Possibly the recording of ERPs to irrelevant stimuli accounted for the lack of positive findings. In the Johnstone study, qualitative observations between dyslexics and controls did not reveal differences in latencies at midtemporal sites but the groups did appear to exhibit marked changes in latency at central and parietal sites. Unfortunately, the authors did not specify the direction of this change although it is likely that the dyslexic ERPs were of longer latency.

Search Performance of Dyslexics and Normal Controls

Results of performance on the search task provided some support for the hypothesis that dyslexic children would have more problems with the verbal than the nonverbal task. Although total time and number of errors did not significantly differ between groups, the significant increase in the inter-target distance and inter-target time observed in the dyslexic group suggested that the processing of individual stimuli did differ between the groups.

It has been observed that dyslexics have problems in the processing of individual word components (Posner, Sandson, Dhawan, & Shulman, 1989). Given that the number of detected targets was similar for the two groups, it is curious that there was an increase in inter-target time but not total time. One would anticipate that the two would increase together. It is likely that the larger error terms associated with the total time measure obscured the difference between the groups.

Evaluation of the Boder Subgroups on the ERP/Search Study

The sub-division of the ERP and search measures into Boder type categories provided data with interesting implications. It is unfortunate that the small sample size did not permit any statistical analysis of group differences. The mixed group does appear to be different from the dysphonetic and dyseidetic groups in that the mixed group exhibits smaller amplitude P1 and N1 components. The two children comprising the mixed type group exhibited a smaller amplitude P1 component and larger N1 component than the other two groups. Error estimates, however, were large, suggesting considerable overlap between the subgroups. It is puzzling why the mixed subgroup was observed to have a larger N1 component although inferences cannot be drawn from such a small sample size and with large error estimates. No apparent differences emerged between subgroups in comparing search performance measures. It would be imperative for future research to include a normal control group for comparing differences according to reading ability and to have sufficiently large numbers of participants in each subgroup.

Assessment of the Boder subgroups on the paper-and-pencil visual search tasks revealed interesting patterns of performance between the three groups. Whereas the mixed type dyslexic was consistently poorer than dysphonetics and dyseidetics at locating the target on the pencil-and-paper search task (see Figure 7), this pattern was not observed on the computer search task. It is impossible, however, to draw inferences based on two subjects identified as being of the mixed type in the ERP/Search study.

Cognitive Evaluation of the Boder Subgroups

It was expected that the Boder classification would reveal significant differences among groups on several different cognitive tasks and that the mixed group would perform poorly overall. This hypothesis was not well supported. There were few significant differences between groups on any particular task.

Planning tasks. Only on the visual search task was the mixed subgroup significantly differentiated from the other two groups. Since the visual search task requires identification of letters, digits and objects it was expected that the mixed group would have more difficulty than either the other two groups. This hypothesis was supported.

Selective attention tasks. The dyseidetic group was only differentiated from the other two subgroups by the Posner selective attention task providing support for earlier evidence that dyseidetic dyslexics are poorer at these types of tasks (Obrzut, 19[illegible]). All groups performed equally well on the Stroop task suggesting that dyseidetics perform normally on some tests of selective attention but not on others.

Successive processing tasks. It was hypothesized that the dysphonetic subgroup would perform poorly on tests requiring successive processing. There were no significant differences between dyslexic subgroups on word recall, or sentence repetition/question tests suggesting that dysphonetic dyslexics were not dysfunctional on these tests of successive processing. This result is similar to that found by Van-den-Bos (1984) who tested Boder type subgroups of dyslexics on an auditory letter processing task. The dysphonetic group performed as well as the dyseidetic and mixed group on this task contrary to the author's prediction. Similarly, neither of the three subgroups were differentiated from each other on a phonetic representation task but all three groups made significantly more errors than controls. The author concluded that dyslexics are more similar in their disability to process phonemes than the Boder classification system assumes.

Simultaneous processing tasks. Dyseidetics were also expected to perform significantly worse on tasks involving simultaneous processing (figure memory, matrix identification and letter discrimination); the dysphonetic group, however, was observed to identify fewer correct matrix items. Performance on the matrix identification test was also correlated with performance and full scale IQ suggesting that intelligenc   .er than reading disability, is associated with   .ity on thi' task. Clearly, tests requiring simultaneous processing strategies did not differentiate the dyseidetic group from dysphonetic and mixed subgroups. It is possible that the concurrent validity of the Boder classification of subgroups is not as strong as initially postulated (Hooper, 1988).

The lack of a normal control group makes it impossible to relate differences on any of these tests to general reading impairment. It may be the case that reading disability itself is the differentiating factor on these tests (Das et al., 1990).

Implications for Future Research

In general, the hypotheses of the present study were not supported. It is likely several factors can account for the lack of significant results, which if corrected might yield differences between dyslexics and normal controls on the ERP/Search study. Firstly, the estimates of error of the means were large relative to the respective means for the ERP amplitudes and latencies in this study. Johnstone et al. (1984) successfully identified ten factors using Principal Components Analysis of the ERP waveform and performed ANOVA techniques subsequent to this initial identification of pertinent factors. This statistical technique requires a substantially higher number of subjects than the eleven participants per group in this study. Future research should incorporate this technique before performing statistical procedures to identify group differences.

Another potentially useful suggestion to incorporate into future research is multiple tests of cognitive assessment concurrent with presentation of the probe. Although no group differences were found on the search parameters here, it is likely that these groups could differ on other tests. Perhaps tests of reading could be given, as in the Johnstone et al. (1984) study in addition to other cognitive tests previously identified as being suitable indicators of reading disability. Multiple measures of cognitive assessment in conjunction with the auditory probe should be incorporated in future research.

The use of alternative probes is another potentially useful suggestion. Although auditory probes were used in the present study, visual probes could also have been used. It could be possible to incorporate both types of probes crossed with type of task. For example, dyslexics and normal controls could be tested on an auditory task given concurrently to visual and auditory probes. It may also be useful to assess performance on some similar cognitive tasks prior to the employment of the sensory probe. This would provide a suitable baseline to ensure that the groups do differ in cognitive processing before studying differences in sensory processing with the probe. Furthermore, this would support the theory of the probe paradigm that a limited amount of cognitive resources are available to perform both the cognitive and sensory processing of the stimuli.

Although the division of the dyslexics into the Boder subgroups did not allow statistical testing of ERP effects, it was observed that the two mixed type children had ERPs elicited by the probe that were smaller in P1 and larger in N1 amplitude than the other two groups. This observation could serve as the stepping stone for future research which could focus on the differences between the mixed, and dysphonetic/dyseidetic subgroups. It would also be imperative to examine the differences between the mixed type dyslexic and the normal control.

Although the Boder subgroups were not differentiated among themselves on the cognitive assessment of planning, attention, simultaneous and successive processing tests, no control group was available for comparison. It may be that the reading disabled group's performance is different from normal controls. It would be imperative for future research to incorporate a control group in which to compare the performance of reading disabled children. A sufficient number of subjects in each of the subgroups would also have to be obtained in order to increase the statistical power of finding group differences between the Boder subgroups.

Collectively, it would be necessary for future research to incorporate multiple measures of both cognitive and sensory assessments in studies assessing suitable numbers of normal control, dysphonetic, dyseidetic and mixed type dyslexic participants.

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