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Orthographic Specific Visual Processes During Word Recognition in Developmental Dyslexia: An Event-Related Potential Study

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Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

The University of Texas at Austin
August 2006

Acknowledgements

The data utilized in this dissertation were collected as part of a larger study conducted by Steven Pliszka, M.D., and co-investigator, Margaret Semrud-Clikeman, Ph.D, supported by NIH grant K-K-85 024117

Orthographic Specific Visual Processes During Word Recognition in Developmental Dyslexia: An Event-Related Potential Study

Publication No._____________

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The University of Texas at Austin, 2006

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There is accumulating evidence from Event-Related Potential (ERP) studies with adult populations of a visual system specialization for orthographic information, which is thought to develop during childhood with increased exposure to text. However, few ERP studies of word reading in children have focused on orthographic specific visual processes involved single word reading. The current examination of electrophysiological activity during word recognition in children was an investigational one to further the current understanding of normal development of brain systems involved in reading. A comparison of brain activity between normally developing readers and children with dyslexia provided opportunity to look for impairment at a basic level of visual processing. The relationship between ERP activity and reading and language skills was also examined. ERP data were obtained from children aged 9-15 in a group of children with dyslexic (n = 12) and a group of normally developing readers (n = 11) to examine activity during an implicit word recognition task. ERPs elicited by orthographic (words, pseudowords, consonant strings) and visual (false fonts, symbol strings) word-type stimuli were recorded at sites over the posterior scalp. In order to examine the relationship between ERP activity and language processes, these children completed measures of phonological, orthographic, and naming processes. Grand averaged ERP waveform for both groups showed a negative going component between 170-270ms with a peak around 230 for all word-type stimuli. ANOVA results found the N230 amplitude elicited by orthographic stimuli significantly larger than the ERPs elicited by visual stimuli in the control but not dyslexic group. The robust orthographic effect in the control group is consistent with the developmental hypothesis that visual word expertise increases with age and reading exposure and supports the understanding of the N1 as an index of reading related visual specialization. Regression analyses found measures of phonological, not orthographic, processes to significantly predict variance in ERP amplitude

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Chapter 1: Introduction

Reading and language processes have been an ongoing area of research among a number of disciplines with the goal of understanding normal and impaired reading development. Developmental dyslexia is a prevalent disability in children that has been attributed to a deficit in the central nervous system (National Joint Committee for Learning Disabilities, 1991). It is widely accepted that dyslexia is characterized by a core deficit in phonological processes (Pennington, 1991, Stanovich & Seigel, 1994; Wagner & Torgesen, 1987). Neurobiological investigation of dyslexia has found abnormalities in structure or function associated with phonological processing deficits.

Dyslexia is a heterogeneous disorder. While impairment in phonological processes has long been established as a core feature of reading disability, multiple language processes support reading development and therefore have the potential to differentially influence reading. Indeed, some children with dyslexia show considerable variability in level of skill in phonological, orthographic and naming processes (Berninger, Abbott & Thomson, 2001), and it is this observation that fuels subtyping research. Movement toward the characterization of the dyslexic phenotype in terms of this heterogeneity has been constrained by an incomplete understanding of the cognitive and language component processes in normal reading development.

Reading is a complex process in which linguistic and sensory/perceptual systems are interactively engaged. Thus, neurobiological investigation employs many methodologies toward understanding the functional networks engaged during reading.

Mechanisms of interest to researchers include the low-level auditory and visual sensory systems that underlie word reading to the higher level cognitive and language processes.

Currently, the neurobiological study of word reading aims to understand functional connections among regions of the brain that occur in the process of reading. Toward this end, ERP technique is often used in conjunction with other neuroimaging techniques to examine the timing of cortical activity. The benefit of ERP as a measure of cognitive activity is the high temporal resolution on the order of tens of milliseconds. Given that aspects of single word reading occurs within 200ms, ERPs are a good tool to capture the time-course of word reading and language processes as they occur in the brain. ERPs are also particularly suited for use with children.

The current study uses ERP to examine the *early* basic visual system processes of word recognition in children with dyslexia and normal readers. Only one of the few developmental ERP studies (Breznitz, 2002, Coch, Maron, Wolf & Holocomb, 2002; Grossi, Coch, Coffee-Corina, Holcomb & Neville, 2001) have focused on this particular aspect of word recognition in children (Maurer, Brem, Bucher & Brandeis, 2005). In this regard, the current examination of early visual system activity in normally developing readers was an investigational one with the general aim to contribute to the extant research concerned with the normal development of brain systems involved in reading.

Another goal was to explore how the ERPs of early visual word recognition processes differ in children with dyslexia to look for neurocognitive impairment at a basic level of processing. Furthermore this study assessed language and reading skills with a comprehensive battery to address questions regarding heterogeneity of language and reading skills. Recently, there has been accumulating evidence that the construct of orthographic processing is a unique language component of reading (Barker, Torgesen & Wagner, 1992; Cunningham, Perry & Stanovich, 2001; Lennox & Siegel, 1994), independent of its association with phonological processes. Therefore, measures of phonological, orthographic and naming processes were selected to be sensitive to differing skill level across and within language components (Berninger & Abbott, 1994, Cunningham et al., 2001; Olsen, Forsberg & Wise, 1994).

Of specific interest to the current investigation is the specialization of the visual system for written language (Cohen, Lehericy, Chochon, Lemer, Rivaud, & Dehaene, 2002). In the act of reading a single word, prior to being recognized as a word, the visual word form automatically engages visual perceptual processes common to all visual objects. Word recognition occurs at the point when the physical features of the visual word form are recognized as orthographic, or word specific. The capacity to automatically and quickly recognize word specific visual features reflects a form of visual expertise, an orthographic specialization of the visual system (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Cohen et al., 2002; Maurer et al., 2005). Conceptually, such a specialization of the visual system is necessary for rapid coding of orthographic to phonological information during fluent reading.

Evidence for word specific visual specialization has been demonstrated in normally reading adults in neuroimaging and ERP studies. Theory predicts word-specific specialization develops during reading acquisition, however, to date there has been only one study conducted with children. Therefore an aim of the current study is to investigate this form of visual expertise in typically developing readers. Furthermore, if the visual system specialization for words is important for normal reading acquisition, it is a candidate for neurobiological impairment in children with dyslexia.

The following chapter provides a review of the literature relevant to these topics. After a brief description of criteria used to define dyslexia, the language component processes of reading will be discussed. Phonological, orthographic, and automaticity processes will be defined in preparation for a review of the research on the interconnected relationship of these reading component processes. The focus then shifts to a review of the neurobiological investigation of reading and dyslexia. Investigation word-specific visual specialization is informed by research on low-level visual mechanisms underlying reading related language processes and on the higher-level meaning making cognitive processes engaged in reading. Both areas will be reviewed. This chapter concludes with research pertaining to the concepts of visual specialization for written language.

Chapter 2: Review of the Literature

Reading Development and Dyslexia

The term learning disability refers to a condition in which a person has difficulty acquiring an academic skill despite having adequate intelligence and learning experiences; a condition assumed to be due to central nervous system dysfunction (National Joint Committee on Learning Disabilities, 1991). The most common learning disability is specific to reading processes, a condition also referred to as developmental dyslexia. The diagnosis of dyslexia involves examining the level of reading achievement relative to some estimate of ability. While specific diagnostic criteria varies across states and institutions, ability is frequently defined as intellectual functioning (IQ). Reading difficulties are attributed to a learning disability when reading achievement falls below what is expected given intellectual functioning. What constitutes an unexpected, or severe, 'discrepancy' between level of reading achievement and IQ varies, though, in terms of standardized scores, it generally ranges from 1 to 2 standard deviations. Other methods of diagnosing dyslexia focus on the discrepancy between actual level of reading achievement and level expected given grade or age. These methods include children with severe reading difficulties without consideration of IQ.

An outcome when using the IQ-achievement discrepancy criterion to determine learning disability is to exclude struggling readers whose intellectual abilities are commensurate with level of reading achievement. The dichotomy inherent to the IQ-achievement discrepancy criterion has significant educational consequences for these children and is an ongoing area of controversy (Fletcher, 1992; Kamphaus, 2001). A point of debate concerns the assumption of the IQ-achievement discrepancy that children who fall within this category are etiologically different from children without such discrepancy. This issue is particularly relevant to research seeking to better understand the neurobiological contributions to the development of dyslexia. While it's not clear if the same mechanisms contribute to all reading difficulties independent of IQ, biological underpinnings are more likely to be isolated with neuroimaging techniques in individuals with severe dyslexia (Semrud-Clikeman, 1997).

Reading is a complex process in which linguistic and sensory/perceptual systems are interactively engaged. Of the multiple language and cognitive processes that support reading development, impairment in phonological processes has long been established as a core feature of reading disability (Pennington, 1991; Stanovich, 1988; Stanovich & Siegel, 1994; Wagner & Torgesen, 1987). However, consistent with the fact that many mechanisms have the potential to disrupt reading acquisition, developmental dyslexia is a heterogeneous disorder. Research spanning several decades has aimed to define distinct subtypes based on selective deficits in other reading processes in addition to, or in the absence of, impaired phonological processes. Movement toward the characterization of the dyslexic phenotype in terms of this heterogeneity is constrained by an incomplete understanding of the cognitive and language component processes in reading (Newby & Lyon, 1991). Some of these processes are defined in the following section.

Language Component Processes of Reading

The process of reading involves getting information from text. A single word in print contains multiple types of information including semantic, phonological, and orthographic. Of interest to the current study are phonological and orthographic information processing, two major language processes involved in learning to read.

Phonological information refers to the sounds of language, both written and oral, and includes the word's acoustic and phonemic structure (Wagner & Torgesen, 1987). Awareness of a word's sound structure increases throughout speech acquisition. Knowledge of phonological information is initially specific to word-length units then over the course of normal language development this awareness becomes attuned to smaller phonological units such as syllables and phonemes (Wagner, Torgesen & Rashotte, 1999). Phonological awareness is knowledge and use of this sound information in comprehension of speech and when reading unfamiliar words. In studies of reading and language phonological processing is operationalized by measures that tap different aspects of the construct, typically phonological awareness, decoding, and memory. Measures of phonological awareness assess the capacity to manipulate sounds in spoken word; measures of phonological decoding assess applied knowledge of sound information specific to written words in order to sound out unfamiliar words or pseudowords.

In addition to phonological information, each printed word has an orthographic form. Orthographic information includes, but is not limited to, the physical features of text—the visual representation of lexical information. "Orthographic knowledge involves memory for specific visual/spelling patterns that identify individual words, or word parts, on the printed page" (Barker, Torgesen, & Wagner, 1992, p. 335). Just as language contains phonological information in units of various sizes, the written word contains orthographic information at the level of the whole word, letter clusters, and individual letters (Berninger, 1996). The visual word form is a symbol for phonological information; the name of a word in print is (or is contained in) its phonological representation. The smaller units of sound have corresponding sublexical orthographic representations; each syllable has a letter cluster, each phoneme a letter (or grapheme).

In the process of learning to read, phonological information becomes associated with its corresponding orthographic representation. With repeated pairing the association between the orthographic form and sound information is strengthened (a similar association is established with semantic information). The sound-symbol transformation of decoding an unknown word is based upon grapheme to phoneme correspondences (Ehri, 1980). Orthographic knowledge speeds up the process of grapheme to phoneme conversion (GPC). Instead of decoding a word letter by letter, the visual word form quickly elicits the phonological representation (instead of c=/c/, a = /a/, t = /t/, cat = cat). The capacity to store word-length orthographic representations in visual memory enables learning words for which the grapheme to phoneme correspondence is irregular.

The connections among orthographic and phonological units of information increase in strength throughout the course of reading acquisition. It is this process that allows a fluent reader to quickly and automatically retrieve the phonological representation of a word-length orthographic unit from what is referred to as the mental lexicon. The efficiency of coordination between orthographic and phonological processes, or automaticity, is another language component process that has the potential to impair reading. Automaticity is demonstrated by the speed by which a reader can retrieve from their mental lexicon the names of letters and other familiar visual symbols of language, such as numbers, colors, and simple objects (Denckla & Rudel, 1976; Wagner, Torgesen, & Rashotte, 1999; Wolf, Bally, & Morris, 1986).

Developmental Dyslexia

While each model of reading has a way to explain developmental dyslexia, there is an uncontested relationship between learning to talk and learning to read. Many children with dyslexia were slow to develop language, most often due to difficulty in distinguishing phonemes in speech. Impaired discrimination of sound information in speech corresponds to the difficulty learning the sound-symbol relationships of reading. Thus, the Phonological Core deficit—Phonological impairments are the most outstanding deficit (Wagner & Torgensen, 1987). Yet, for some individuals other language component processes are also impaired (Berninger et al., 2001; Castles & Coltheart, 1993; Cunningham et al., 2001). Relative to the well developed understanding of how phonological processing deficits contribute to reading development, the independent role of other processes in the normal acquisition of reading as well as in the reading abilities of children remains unclear despite decades of research that has sought to address the heterogeneity in developmental dyslexia.

The development of orthographic processing skill is somewhat independent on phonological processing skill such that in mature readers these processes are highly interconnected. The interconnectivity occurs very early in the course of normal reading acquisition such that differentiation among them has been difficult to assess because lacking the measures to isolate these processes.

Recent research has investigated measures of orthographic processing skills to learn if it contributes to acquisition of reading and spelling abilities beyond its relationship with phonological skills. To date, findings have been inconsistent. An obstacle to assessing the independent contribution of language components to reading difficulty has to do with measurement of these processes, primarily because the construct of orthographic processing has not been operationalized to the extent as phonological info. Another related confound to this research is grouping methodology.

Subtyping Methods in Reading Research

Past research has divided dyslexics into subgroups along the visual-verbal dichotomy.

The dual route model depicts information processing in reading as consisting of two distinct processes (Coltheart, 1985). The orthographic image of the text can be processed by (1) the direct lexical route, where the semantic and phonological information associated with the visual word form are directly accessed, or (2) the indirect route or phonological system where the orthographic image is first translated into it's phonological representation using GPC rules (Chase & Tallal, 1991; Berninger et al., 1994). The direct lexical system is required to learn irregular words that become part of sight word vocabulary.

Based on the Dual Route model, the breakdown of reading should result in two types of reading deficits: a deficit in the direct lexical route (commonly defined by poor sight word reading) Surface dyslexia, causes deficit in storing the visual form of words, while phonological decoding is not impaired. Or phonological deficits from an impaired indirect route, unable to decode (commonly defined by poor pseudoword reading) must rely on sight word reading/lexical access.

Consistent with the core deficit in phonological processes, people with dyslexia frequently use lexical access when reading; using visual memory with large sight vocabularies. While much fewer in number, there are dyslexics who do have lexical impairment, who instead use GPC strategies. However, often even these orthographically impaired individuals also have some degree of impairment in phonological processing (Chase & Tallal, 1991). The dichotomous characterization of developmental dyslexia doesn't account for varying degrees of deficits in orthographic and phonological processes. These confounds are described below:

Measures of nonword or pseudoword and exception word reading are frequently used to define individuals with dyslexia in research. As previously mentioned, exception words/irregular words violate the grapheme to phoneme conversion (GPG) rules that operate in the phonological decoding route (Olson, Forsberg, & Wise, 1994). They are often used as a measure of orthographic processing because they are thought to be read via direct lexical route in which the word's phonological representation of meaning "based on participant's memory for their specific orthographic patterns" (Coltheart, in Olson, Forsberg, Wise & Rack, 1994). However, sublexical units within the exception words follow the common GPC rules. Similarity of the pseudowords to real words make reading by analogy (orthographic coding of a sublexical unit) a confound to the sensitivity of this measure of phonological processing. For example, /kaid/ is a pseudoword, but the letter cluster /aid/ maps directly onto the name code for this rime /aid/ when the reader is familiar with this word family.

While dual route models depict information moving from in a sequential, serial fashion, connectionist models describe simultaneous connections between multiple language component processes. Connectionist models account for the sublexical interactions between the phonological and orthographic processes yielding a more realistic (and complicated) model for reading development (Berninger, 1994).

Assessment of Language Processes

Recent improvement in the definition and measurement of these processes allow for assessment of differing skill levels across and within language components. When component language processes are measured with a greater degree of specificity (particularly, when measure of sublexical orthographic processing are added) it is possible to determine the unique contribution to level of reading skills made by each (Berninger, 2001).

In an effort to characterize the heterogeneity within the dyslexic phenotype, as well as to understand the normal process of reading acquisition, more studies are including measurement of the component language processes in reading. In addition to pseudowords and exception word reading, other measures of Orthographic and

Phonological processing have provided external validity to the subgroups created based on a specific deficit or combination of deficits (Manis, Seidenberg, Doi, McBride-Chang, & Peterson, 1996).

Validity for the construct of orthographic processes has been established in several studies in which orthographic processes were demonstrated to contribute to reading beyond its association with phonological processes (Cunningham, Perry & Stanovich, 2001; Berninger, 1990).Genetic studies of the heritability of language processes contributing to reading initially found phonological coding (speed & accuracy of nonwords reading) to be heritable while orthographic coding (speed & accuracy of Orthographic Choice task) was not. However, later analyses on a larger sample size concluded orthographic processes were heritable as well. By using methods such as hierarchical regression analysis, several studies have established orthographic processes to make a unique contribution to reading skills (Cunningham et al 2001; Berninger, 1990)

The past decade has focused on orthographic processing and in isolating individual differences. In fact, several researchers have been able to attribute unique variance to orthographic processes. Cunningham et al (2001) found that orthographic processing accounted for 10.2% of the variance for a group of 8-10 year olds on a measure of word recognition. Hierarchical regression analyses were used to partial out both phonological processing abilities, but also exposure to print. A later study (Barker, et al., 1992) extended these results by examining the relationship between orthographic processing and measures of reading. Unique variance in reading skill was accounted for by orthographic processing for each of these variables with the variances ranging from 5% to 20% percent.

Olson, Forsberg, & Wise (1994) studied the relationship between orthographic and phonological processes by using data from a long term study of learning disabilities using identical and fraternal twin pairs in which at least one twin had a diagnosed learning disability in reading. The results of the factor analysis and hierarchical regression analysis made clear that orthographic and phonological factors are distinct, although greatly correlated. Specifically, using word recognition as the dependent variable, there were independent contributions.

Finally, in a comprehensive study of orthographic and phonological processes, Berninger, Abbott, and Thomson (2001) used learning-disabled children and their affected parents in attempt to elucidate the across-age phenotype in reading and writing disabilities. A major finding was that orthographic and phonological factors had significant covariance in adults, but not in the children. Phonological factors were found to have the largest direct and unique contribution to reading disabilities in children as measured by reading accuracy, rate and comprehension, and spelling and composition. Question remains as to what point in typical reading development these language processes become interconnected to the degree that their individual contribution to reading is no longer identifiable.

To date, few psychophysiological or neuroimaging studies of reading have measured the language component processes with much specificity. Since the construct of orthographic processing as a unique predictor of reading skill (Castle & Coltheart, 1993; Barker et al 1992; Manis et al 1996; Berninger 2001; Cunningham et al 2001). There has been renewed interest in the contribution of basic visual system function to development of dyslexia (Sperling, 2003; Milen et al 2003; Tallcott; Witton; Stein & Walsh), and the relationship between orthographic processing and low-level visual processes. One of several questions of interest is the relationship between language abilities and the neurobiological mechanisms of word reading.

Neurocognitive Study of Reading and Language

The study of reading and dyslexia has been investigated with a range of neurobiological methodologies. The body of research has succeeded in mapping certain reading component processes to specific brain structures. Neuroanatomical differences in these structures have been demonstrated in individuals with dyslexia (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Hynd & Semrud-Clikeman, 1989) which correspond to behavioral deficits (Larsen, Hoien, Lundberg & Odegaard, 1990; Semrud-Clikeman, Hynd, Novey & Eliopulos, 1991). There is general agreement that dyslexia is related to a disruption in neurocognitive language processes (Shaywitz et al., 1998). However, beyond localization, the normal functioning of these processes during reading is not understood. Current investigations aim to elucidate the interactions among the regions that comprise the neurobiological reading system.

Accumulating evidence from functional imaging studies have converged on several distinct regions engaged in reading and language component processes that make up the network of functionally connected cortical systems (Fiez,& Petersen, 1998; McCandliss & Noble, 2003). The activity of these regions show abnormal or disrupted activation during reading tasks in individuals with dyslexia (McCandliss & Noble, 2003; Shaywitz et al, 2002).

Another approach in the neurobiological study of reading and dyslexia is to examine the lower-level perceptual processes engaged in reading. There exists a large body of research on basic visual and auditory functions normal and impaired readers. While gross perceptual deficits are not characteristic of dyslexia, there is evidence of a reduced sensitivity in lower level sensory processes, both visual and auditory (Stein, 2001; Talcott et al., 2002). Many studies have found children with learning disabilities have impairment in low-level auditory processes (Orzbut, 1991; Tallal, 1980), including temporal processing of sound information, reduced sensitivity to tones (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999) and the sounds of speech. Importantly, these low-level auditory deficits have consistently been linked with phonological processes involved in reading (Breznitz & Meyler, 2003; Naatanen, 1999; Tallal, Miller, Jenkins & Merzenich, 1997; Witton, Stein, Stoodley, Rosner & Talcott, 2002).

Though the relationship between auditory functioning and reading component processes is well established the mechanisms by which low-level visual processes affect reading are not well understood. In early dyslexia research, visual perceptual impairment was thought to underlie reading problems due to some of the more salient/easily observable manifestations of dyslexia in reading errors (such as those that result from the superimposition of parts of words or adjacent words) and spelling errors (reversals in a single letter or a whole word was=saw or dog=bog). However, with further research gross visual deficits were not found (Vellutino, 1980). As the linguistic basis of dyslexia was increasingly understood, these ‘visual’ errors were explained as a manifestation of an underlying phonological impairment (Stein & Walsh, 1997).

Visual perceptual processes refer to the automatic activity elicited by visual stimuli. A word in print is differentiated from other visual objects when its physical features are recognized as specific to words, or orthographic. Cognitive processes of single word reading are engaged after the brain has recognized the stimulus is a visual word form and is treated as written language. Here begins the interactive engagement of phonological and orthographic processes of grapheme to phoneme conversion and other linguistic cognitive operations.

There is converging evidence that the time-course of word recognition occurs within 200 ms in adults. The capacity to automatically and quickly recognize word specific visual features reflects a specialization of the visual system for written language (Cohen et al., 2002). Conceptually, a reading related visual expertise is necessary for rapid coding of orthographic to phonological information during fluent reading. Evidence for word specific visual specialization has been demonstrated in normally reading adults in neuroimaging and ERP studies (reviewed in later section) and though theory predicts visual expertise for words would increase over time and experience with text (during reading acquisition). To date there has been only one study conducted with children designed specifically to examine automatic orthographic specific visual processes (Mauer et al., 2005).

Of specific interest to the present study is the point in time when words (or orthographic forms are recognized as a visual word form. Therefore, an aim of this study is to investigate the time-course of word reading for evidence of a visual expertise in typically developing readers and if the visual system specialization for words is important for normal reading acquisition, it is a candidate for neurobiological impairment in children with dyslexia. This timing aspect of word recognition is a part of the functional network of reading, at the intersection of basic visual functioning and the higher-level cognitive processes of reading. Investigation word-specific visual specialization is informed by research on low-level visual mechanisms and research on the higher-level meaning making processes engaged in reading. Both areas will be reviewed in following sections before turning to the concepts of visual specialization for written language.

Visual Processes in Reading and Dyslexia

Visual System Anatomy. Visual information travels from the retina to the lateral geniculate nucleus (LGN) of the thalamus, then to the primary visual cortices of the occipital lobe where the visual percept is first formed. The LGN contains two distinct cell types that attend to very specific physical features of the image in the visual field; these cells, parvocellular and magnocellular, are differentially responsive to dimensions of spatial frequency, color and movement. Perception of fine details of high spatial frequency and sensitivity to color are functions of parvocellular system. Magnocellular system responds preferentially to low spatial frequencies and light/dark contrasts occurring at the boundaries within an image, such as the dark of a letter against the white of the paper (Stein & Walsh, 1997). Motion detection, including sensitivity to direction of movement and gaze are also magnocellular functions.

Magnocellular and parvocellular cells remain segregated in distinct projections from the LGN to the visual cortices where the information begins to integrate as it travels from the primary visual cortex to other cortical areas in ventral and dorsal projections. While magnocellular projections are part of the dorsal information stream and parvocellular projections are part of the ventral visual stream these two pathways exchange information they travel through the visual association cortices. Both dorsal and ventral pathways project to areas known to be involved in reading and language. Projections from visual cortices to the posterior parietal cortex have been suggested given posterior parietal functions include eye movement control and visuospatial attention.

The specific mechanisms by which basic visual processing effects reading skills have not been established however these processes have been associated with reading and the language component processes (Stein, 2001, for review). Furthermore, there is evidence of decreased contrast and motion sensitivity in dyslexia. The following section reviews these findings from psychophysical studies of visual sensory processes and reading.

Visual Perceptual Processes in Reading. The relationship between basic visual functions and reading has been investigated in children and adult populations, with a focus on both normal and impaired reading. Many of such studies are interested in the association between phonological and orthographic language component processes and visual perceptual processes. Though the specific mechanism has not been identified, a slight reduction in control in one of these processes could constrain orthographic specific visual processes. As described by Stein (2001), visual sensory deficits could by reduce the capacity to "lay down reliable memories of the common spelling patterns that govern their orthography" (p. 517).

One visual deficit implicated in dyslexia is sensitivity to light/dark contrasts (Sperling et al., 2003). Psychophysical tasks of contrast detection manipulate the luminance and spatial frequency of meaningless visual forms, such as sine wave gratings, checkerboards, or patterns of dots. The threshold at which the form can be detected provides an index of sensitivity to light/dark contrasts. Some studies of contrast sensitivity deficits in dyslexia have examined sub-typing and the relationship between low level visual processes and orthographic and phonological abilities. Several studies found contrast sensitivity to be impaired only in the group with phonological processing deficits (Borsting et al., 1996; Slaghuis & Ryan, 1999; Spinelli et al., 1997). While these findings do not support the theory of a relationship orthographic and visual perceptual processes, the language processes were not measured with much sensitivity in these studies.

A limitation in many contrast sensitivity studies has been in the method of grouping the dyslexic sample using the Surface/Phonetic dichotomy of Castles and Coltheart (1993). As discussed previously, the surface/phonetic determination is made by ability to read irregular words, which has been critiqued because the task engages both phonological and orthographic processes. A recent study that assessed the language processes with additional measures found contrast sensitivity to have a higher correlation with orthographic than phonological processing (Sperling, Lu, Manis, & Seidenberg, 2003). Yet another study found dyslexics did not differ on contrast thresholds from the controls (Williams, Stuart, Castles, & McAnally, 2003). In general the findings across studies of contrast sensitivity deficits in developmental dyslexia are equivocal (see Skottun, 2001 for review).

Motion detection tasks have also been used as an index of visual perceptual sensitivity and examined in relation to reading and language component processes. Motion detection tasks are similar to those of contrast sensitivity in the use of meaningless visual stimuli. In one typical task an array of dots is manipulated to appear as if moving across the screen—when the spatial frequency of the dots increases in density the movement is easier to detect. Several studies found decreased sensitivity to motion in individuals with dyslexia when compared to controls (Demb, Boynton, Best & Heeger, 1998; Slaghuis & Ryan, 1999; Talcott, Hansen, Assoku, & Stein, 2000). Additionally, sensitivity to visual motion was found to have a strong relationship with orthographic processing skill in other studies (Cornelissen, Hansen, Hutton, Evangelinou & Stein,1998; Talcott et al, 2000; Talcott et al, 2002).

While these findings suggest decreased sensitivity of basic visual system functions in developmental dyslexia, it is difficult to draw clear conclusions from this body of research due to inconsistencies in the psychophysical tasks of visual functions and characterization of the dyslexic sample. The relationship between reading deficits and visual processes will be better understood when studies define the sample of individuals with dyslexia in regard to the heterogeneity in language component deficits.

If basic visual processes have a stronger association with orthographic than phonological processes it suggest a singular neurobiological mechanism underlying the impairments in the visual system, as well as the higher-level language processes. Another possibility is that the neurobiological impairment in higher-level language processes creates lower-level impairments over the course of development. The following section will provide a review of the research that has sought to understand the functional neuroanatomy of word recognition, the development of these interconnected brain systems over the normal course of reading acquisition, and possible impairment of word recognition processes in dyslexia.

Neurobiological Investigation of Word Recognition

Cognitive processes engaged in the reading of a single word have been localized to specific regions of the brain, though how these regions interact during the process of single word reading is not fully understood. The focus of the present study is on word recognition, specifically the point early in the time-course of visual processing that the brain recognizes orthographic specific information as distinct from non-orthographic visual stimuli. The point of word recognition is significant to the comprehensive understanding the functional neural network of reading because it marks the onset of higher-level processes and the interactive engagement of orthography, phonology and semantic processes.

Reading related systems of the posterior cortical network include the occipital and occipito-temporal regions (extrastriate cortices; fusiform & lingual gyrus; Broadman Areas: 18; 37/19). Converging evidence suggests the occipito-temporal region is involved in the automatic fast processing of the visual word form (Price, Moore, & Frackowiak, 1996; Cohen et al., 2000; Maurer, Brem, Bucher, & Brandeis, 2005). Superior to the occipito-temporal region lies the parieto-temporal regions that receives input from the primary visual cortex and from language areas of the temporal lobe. This parietal region is hypothesized to function in the cross modal integration of auditory linguistic information with that of the visual word form during grapheme to phoneme conversion.

The posterior cortical network responds preferentially to word specific visual information, and as part of the posterior network, the occipito-temporal region, is involved in word recognition processes and is implicated as a region of neurological impairment in dyslexia (see McCandliss & Noble, 2003 for review; Shaywitz et al., 2002). The posterior region is one of several regions that make up the neurofunctional reading system. The present study is focused upon the earliest point of word recognition. Accumulating evidence indicates word recognition occurs in occipito-temporal regions within the first 200 ms post stimulus (Sereno & Rayner, 2003).

The remainder of this chapter presents findings of neuroimaging studies pertaining to posterior region involvement in word recognition of non impaired and dyslexic readers, with particular focus on development. This section concludes with ERP and MEG studies that reveal the timing of cortical activity during word recognition. Prior to turning to this body of research, an overview of the experimental paradigms used to isolate word reading and word recognition process is presented.

Experiment Manipulations of Words and Word Forms. The tasks used in functional neuroimaging and electrophysiological studies of word reading stimuli are manipulated to create contrasting conditions which will isolate the cognitive process of interest to the region of greatest activity and can also provide information regarding the sequencing of events in the course of single word reading. One approach is to manipulate words to isolate higher-level reading related language processes (e.g., phonological, orthographic, semantic). Another approach compares the activity of reading related language processes with the activity of basic visual functions. Both approaches are relevant to examination of early word recognition and the process of visual specialization.

Studies that are interested in the process of letter to sound transformation during decoding processes contrast words manipulated on dimension of regularity in spelling to sound correspondence. Studies designed from a model of reading where a direct route to access the phonetic representation of irregular words is hypothesized, stimuli are selected based on regularity in spelling only at the level of the whole word. When the manipulation occurs at the whole word level, the contrast is between regular and exception words, or between high and low frequency words. Other manipulations are designed to detect sensitivity to spelling/sound regularity of sublexical information. One method is to contrast pseudo-homophones—letter strings that are identical in pronunciation but orthographically different. For example, the pseudo-homophone pair (gnoome-nume), generated by Simos et al. (2001) engages phonological decoding with minimal influence from sublexical orthographic activation (in addition to eliminating whole word access).

In the study of single word reading orthographic and visual stimuli are manipulated to differentially engage visual, orthographic, phonological and semantic processing. Conditions include orthographic word-type forms (single letters, consonant letter strings, pronounceable pseudowords, and regular words) and strings of non-orthographic visual characters such as, □♦〉□ or ///\ , alphanumeric symbols ("&@$£), and false-fonts (Bentin et al., 1999; Peterson et al., 1988; Shaywitz et al., 1998). The visual word-like forms are intended to be similar to letters and words in physical properties but lacking orthographic content. Thus, studies of word recognition typically compare orthographic word-type forms with non-orthographic, visual stimuli that control for the visual specific activation. Pairwise contrasts reveal sensitivity to sublexical variation in grapheme to phoneme regularity and orthographic specific activation.

Finally, the experimental task is another feature of this body of research important to consider. Two common paradigms used in the examination of reading specific cognitive processes presents words and word-like stimuli in list format, to be responded to by either silently generating the word's name, passive viewing, or detecting size or repetition features (Picton et al., 2000). Though the variation in tasks are very subtle, different levels of processing are induced. Significant differences in activity can be elicited given the same stimuli but different task (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999) and such task effects reduce ability to compare results across studies.

The paradigms used in the neurobiological investigation of word *recognition* aim to capture word-specific activity that can be differentiated from visual control stimuli, in terms of regional activation (fMRI, PET) or temporal activity (ERP) or both (MEG). This body of research has determined the posterior regions of the brain to have an important role in the early process of word reading—the orthographic specific activity occurring in occipito-temporal regions within the first 200 ms post stimulus.

Neuroimaging Studies of Word Recognition. Neuroimaging studies of the posterior reading systems focus on the occipito-temporal region encompassing visual extrastriate areas. Occipital and temporal-occipital regions (viz. extrastriate cortices;

fusiform & lingual gyri; Brodman Areas [BA] 18, 37/19) respond preferentially to word specific visual information in contrasts between orthographic and non-orthographic visual stimuli in typical reading adults, but not in individuals with dyslexia. A specific region of the mid fusiform gyrus has been identified as supporting the visual representation of words; this region was termed by Cohen et al. (2000) the Visual Word Form Area (VWFA). This posterior area showed increased activation elicited by orthographic word-types when contrasted with visual control conditions (Brunswick, et al., 1999; Paulesu et al., 2001; Peterson et al., 1988; Polk and Farah, 2002; Price et al., 1996; Shaywitz et al., 1998; Tagamets et al., 2000). Adults with dyslexia were found to have reduced activity during word reading tasks relative to normal readers (Brunswick et al., 1999; Horowitz, Rumsey, & Donahue, 1998; Rumsey et al., 1997; Shaywitz et al., 1998).

Word Recognition: Visual Expertise for Orthographic Information

Neuroimaging studies of word reading have identified occipito-temporal regions of the posterior system to be responsive to the visual features of words. The temporal aspects of word specific activation are illuminated by contributions of ERP and MEG. In the study of word recognition, timing information is needed to determine when orthographic forms are differentiated from other visual stimuli. Research combining eye movement measures with ERP technology in the study of single word reading has estimated the time frame needed to understand word reading mechanisms to be at 200ms post stimulus onset or sooner (Sereno & Rayner, 2003). Therefore the temporal sensitivity of ERP makes the technique well suited for this research question. MEG allows for simultaneous measurement of timing and location of cortical activation.

ERP Technique. Electrophysiological techniques are used to examine the neurobiological mechanisms that underlie learning disabilities. The brain emits an ongoing electrical signal that can be measured and recorded by electroencephalogram (EEG). Large populations of neurons are measured by electrodes placed on the scalp: event-related potentials (ERPs) are a distinct part of electroencephalogram. An ERP is a change in the ongoing EEG signal (or waveform) that occurs in response to a cognitive event, such as when an object is detected in the visual field. The ERP is obtained by averaging the response that follows the eliciting event over many identical trials, the ERP is extracted from the averaged waveform (Hannay, 1986). ERPs provide information about the stages, sequences and timing of cognitive events on the order of milliseconds making it possible to follow the path of the brain's activity with great precision. ERPs have been used extensively in the study of auditory and visual processes and in study of reading ability (Harter, 1991).

ERPs are demarcated from the ongoing EEG waveforms by positive and negative peaks ordered from stimulus onset (Gevens, 1986). For example, the N4 is a negative wave occurring 400 msec after stimulus onset often used in the study of reading processes. The N400 is accepted as an index of semantic and phonological information in verbal and written language and there is some evidence that it is sensitive to orthographic and phonological qualities within words (Kramer & Donchin, 1987; Rugg & Barrett, 1987). N4 has been successfully used in studies of dyslexia to demonstrate deficit in phonological processing (McPherson, Ackerman, Holcomb, & Dykman, 1998).

N1 & Visual System Specialization for Words. The visual N1 is an ERP component that occurs in occipital-temporal regions of the posterior scalp in response to visual stimuli, responding preferentially to familiar categories of visual objects (Cohen et al., 2002). Bentin et al. (1999) examined ERPs elicited by passively viewing orthographic or non-orthographic character strings in adults. Orthographic stimuli elicited a N170 over posterior-temporal/occipital regions of the scalp, larger in left hemisphere than in the right hemisphere. In other ERP and MEG studies of single word reading, activity in the posterior scalp occurring within the first 200ms differentiates orthographic from visual word-type stimuli in healthy adults (Maurer et al., 2005; Nobre, Allison, & McCarthy, 1994 ; Salmelin, Service, Kiesila, Uutela, & Salonen, 1996).

Only recently have we begun to examine these processes in normally reading adults and normal developmental variations or impairments due to dyslexia have not been adequately studied. Using MEG, Simos et al., (2001) found normally reading children and adults diverged in the timing of activation across the scalp's topography. Early word reading activity shifted from occipital to visual association areas in the same time frame in both age groups. However, adult activity indicated significantly longer cerebral engagement in the basal temporal area pseudowords compared to real words (357ms) while the children showed relatively no difference between conditions (37ms). This finding indicates children process pseudowords as real words that are unfamiliar and require sound symbol transformation to be read. Other significant age related changes suggest increased efficiency of word process with age. For example, children demonstrated a significantly longer duration of peak activation in temporal-parietal regions area (of phonological decoding) than did adults. One developmental ERP study has investigated the N1 (as an index of visual expertise for words) in children (Maurer et al., 2005). This study provided the first evidence that the N1 is sensitive to the effects of visual experience with words during reading acquisition.

When compared to normally reading adults, dyslexic subjects have reduced activity to word stimuli in the left inferior temporal occipital regions; this group difference has been demonstrated by 180 ms post stimulus onset. (Helenius et al., 1999; Salmelin et al., 1996). This finding of abnormal posterior activity is consistent with neuroimaging findings (Horowitz, et al, 1998). The left fusiform region identified in fMRI studies as responding specifically to visual features of words, has been suggested by Cohen et al. (2000) as the cortical generator of activity recorded between 150 to 250ms at the left ventral occipital-temporal sites in ERP word recognition studies. As discussed in Flowers et al. (2004), aberrant activity of early visual processes in individuals with dyslexia could be related to an impairment specific to the region, or to a disturbance in lower level sensory processes from which the posterior-temporal/occipital cortices receive projections. Such a disturbance could interfere with orthographic specific learning (Stein, 2001; Booth et al., 2002).

Therefore, an aim of the current study is to examine the differentiation between visual objects and the visual word-form, in children with and without developmental dyslexia, to work toward an understanding of the normal developmental of visual system in relation to reading acquisition and its contribution to reading difficulties. Specific hypotheses are detailed in the following *Statement of the Problem*.

Statement of the Problem

This study was an investigation of electrophysiological activity of the brain during visual word recognition in typically developing children and children with developmental dyslexia. The experimental Evoked Related Potential (ERP) paradigm was designed to capture early (< 200 ms) automatic activation of visual processes unique to orthographic stimuli (visual words and word-like forms) occurring at the posterior scalp. The use of ERPs permitted investigation of activity occurring within milliseconds from stimulus onset. The relationship between this ERP activity and reading and language skills was also examined.

The first negative going ERP (N1) in inferior occipito-temporal regions, (typically occurring within 200ms) elicited by all visual objects is stronger for familiar categories of stimuli. The increased strength of the N1 for familiar stimuli indicates proficiency that comes from experience with the category of objects (Gauthier, Tarr, Moylan, Skudlarski, Gore & Anderson, 2000), which reflects a domain specific visual specialization. There is accumulating evidence that N1 activity is also sensitive to words as category of visual objects. ERP and MEG studies with adults have found that the brain differentiates between stimuli of orthographic and non-orthographic content at around 170 ms at occipito-temporal locations (Bentin, et al., 1999; Maurer et al 2005, Salmelin et al., 1996; Nobre et al., 1994). Thus in the context of single word reading, the N1 or N170 is thought to reflect visual activity involved in the analysis of the physical features of words. Differentiation of orthographic from non-orthographic visual stimuli at this early stage of processing may be interpreted as evidence for a visual specialization for written information. Despite the recent interest in the N170 in word recognition, its significance has not been studied extensively as the later occurring ERP components that have an established relationship with reading and language.

While accumulating evidence from adult ERP studies points to the N1 as an index of visual expertise for words, little is known about the N1 in child populations. Of the developmental ERP studies that have examined word processing mechanisms in children (Coch, Maron, Wolf, & Holcomb, 2002; Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001) only one has focused on the *early* activity of basic visual system processes to investigate orthographic specificity of the visual system (Maurer et al., 2005). In this regard, the current examination of early visual system activity in normally developing readers was an investigational one with the general aim to contribute to the extant research concerned with the normal development of brain systems involved in reading. This study also explored how these processes differ in children with dyslexia. A comparison of brain activity between normally developing readers and participants with dyslexia provided opportunity to look for neurocognitive impairment at a basic level of processing.

In the first stage of this study a neuropsychological assessment was conducted to define two distinct groups of children with normal or impaired reading abilities. Measures of phonological, orthographic and naming processes were selected to allow for differing skill level across and within language components (Berninger & Abbott, 1994; Cunningham et al., 2001; Olson, et al., 1994). Relative to the well-established relationship of phonological processes and reading abilities, only recently has research provided evidence of validity for measures that converge on the construct of orthographic processing as a unique language component of reading (Barker et al., 1992; Lennox & Siegel, 1994; Cunningham et al., 2001). In the current study, orthographic processing was operationalized based on these recent developments. The second stage of this study was an Evoked Related Potential (ERP) experiment, an implicit word recognition task in which words and word-like forms were passively viewed. Contrasts among the 3 orthographic conditions (words, pseudowords, consonant strings) and 2 non-orthographic conditions (false fonts, symbol strings) permitted measurement of orthographic specific visual activity by controlling for basic visual processes. ERP amplitudes were calculated at posterior regions of the scalp then averaged across conditions. ERPs elicited by orthographic stimuli were contrasted with ERPs of visual stimuli both within and between groups. The relationship between ERP amplitude data and orthographic, phonological and naming processes was examined. Specific study hypotheses are detailed below.

Study Hypotheses

The ERP component of interest is the N1, the first negative going deflection elicited between 150-250 ms post stimulus onset with a distribution across the posterior scalp (inferior occipito-temporal, and temporo-occipito-parietal regions). Predictions regarding the N1 latency window and scalp distribution are based upon findings from similar studies examining the N170 in adult populations (Bentin et al., 1999; Maurer et al., 2005). However, developmental studies of ERP components such as the N400 (Coch et al., 2003; Grossi et al., 2001) found the ERPs to occur later in children than expected based upon the adult literature. Thus, it is possible that the ERP component predicted in the current study will be later occurring than the typical range of the N170.

Hypothesis 1

N1 mean amplitude will be significantly greater for orthographic word-type forms than for visual control stimuli in the control group.

N1 amplitude for orthographic word-types will not be significantly different than for visual control stimuli in the dyslexic group.

N1 to orthographic word-types will be significantly different between control and dyslexic groups; and,

(i) If the N1 reflects *word-specific* visual specialization that is impaired in dyslexia the N1 to visual stimuli will not be differentiated between control and dyslexic groups; or,

(ii) If the reduced N1 in the dyslexic group is a reflection of a diffuse lack occipito-temporal responsiveness, significant group differences in N1 amplitude to visual forms are also predicted.

Rationale: This hypothesis predicts that in the control group the N1 at posterior occipital temporal sites will be modulated by orthography (stronger for orthographic word-type forms than other visual forms). Because there have been very few ERP studies with children examining the word recognition processes reflected in the occipital N1, the development of visual system sensitivity for orthographic forms is not known. If the

N170 modulation by orthography found in adult populations reflects visual specialization for words children are likely to demonstrate some degree of visual expertise for words by the age of 10.

The finding of no differentiation between orthographic and visual word-type stimuli in the dyslexic group will be in line with findings of a disruption of the posterior cortical system demonstrated by functional imaging studies (Shaywitz et al., 2002).

If abnormal ERPs are observed in the dyslexic group, comparison with the control group will aid interpretation. In particular, if the dyslexic group does not differentiate among word-type stimuli, group comparisons across orthographic and visual categories will help determine if such an effect is due to a reduced capacity to develop domain specific visual expertise or due to overall reduction in activity in the posterior regions.

Hypothesis 2

Two competing hypotheses will be tested regarding changes in N1 amplitude related to variation in the *regularity of orthographic structure* in contrasts among the three orthographic word-type conditions (word/pseudoword, words/consonant strings, pseudowords/consonant strings). In the controls but not the dyslexics, there will be significant differences in mean amplitude based on degree of orthographic regularity such that words > pseudowords > consonant strings, or, N1 amplitudes will not differ significantly among words, pseudowords, and consonant strings in either the control or dyslexic group.

Rationale: At what point in the time course of word processing does the brain recognize variation in regularity, or legality of words and letter strings? ERP effects due to orthographic regularity (legal from illegal word strings words v pseudowords v consonant strings; or high frequency from low frequency words) have been consistently found in *later occurring* ERP components (Coch, et al., 2002; Holcomb, Grainger & O'Rourke, 2002). However, adult N1 findings are equivocal regarding earliest point of differentiation of orthographic word types based on regularity.

If words, pseudowords, and consonant strings are not differentiated by N1 amplitude, (as is the more likely outcome) it provides evidence for the N1 as an index of visual expertise for orthographic stimuli. If N1 ERP activity varies based on legality of words or letter combinations, it will occur only in the control group because it is a function of expertise. The differentiation of words from pseudowords implicates word frequency effect at the whole word level prior to engagement of phonological processes.

Hypothesis 3

Behavioral measures of language processes (phonological, orthographic and naming processes) will be related to ERP activity and will predict a significant portion of variance in mean amplitude. The relationship predicted is based on the assumption that the ERP activity reflects the orthographic specificity of basic visual system processes in the posterior language system. ERP variables will be defined to reflect the differentiation of orthographic from other visual stimuli. Tests of Hypothesis 3 will examine the amount of variance in ERP amplitude accounted for by each of the language processes independently and together as one model. Of specific interest is a comparison of the unique variance accounted for by orthographic and by phonological measures.

Rationale: As reading research has reexamined the construct of orthographic processing as a unique predictor of reading skill (Castle & Coltheart, 1993; Barker et al 1992; Manis et al 1996; Berninger, 2001; Cunningham et al 2001), there has been renewed interest in the contribution of basic visual system function to normal and impaired reading development (Sperling et al., 2003; Milne, Hamm, Kirk, & Corballis, 2003; Talcott et al., 2002; Stein & Walsh, 1997), and the relationship between orthographic processing and low-level visual processes. To date, few psychophysiological or neuroimaging studies of reading have defined orthographic processes in a way that minimizes the confound of phonological processing. Assuming that the ERP activity measured in the experimental task is a reflection of orthographic specific processing, the question remains whether such activity will have stronger association with orthographic than with phonological processes.

Chapter 3: Method

Participants

Study participants included 26 right-handed children (20 males, 12 females) aged 9 to 15. In the clinical group were children with developmental dyslexia, while the comparison control group consisted of normally developing readers. This study was part of a larger study on inhibition in ADHD conducted by The University of Texas at Austin and the University of Texas Health Science Center San Antonio (UTHSCSA) Research Imaging Center. Informed consent was obtained from all participants according to the norms of the Institutional Review Board of both institutions.

Study Groups

Clinical Group—Children with Developmental Dyslexia. The goal of this study was to evaluate children with severe and ongoing difficulty with reading acquisition. Thirteen participants (3 females, 10 males) were recruited for the clinical group from a number of sources including a private school for children with dyslexia, a reading recovery/remediation program, and special education programs in public schools. Reading disability (i.e. developmental dyslexia) was defined by an ability-achievement discrepancy of ≥ 20 points.

Control Group—Normally Developing Readers. Participants in the control group (6 males, 7 females) were recruited using study advertisements placed in local newspapers and flyers posted around the campus of UTHSCSA. Participants were included in the control group when reading ability was found to be commensurate with intellectual ability defined by an ability-achievement discrepancy of no greater than 15 points. The comparison group requirement that reading achievement be no greater than one standard deviation below estimated ability reduces overlap between diagnostic groups, creating distinct categories more likely to exhibit differential functioning of neurobiological mechanisms hypothesized to underlying reading impairment (Semrud-Clikeman, 1997).

Participant Selection Procedure

Participants underwent a diagnostic screening conducted to exclude those with psychiatric disorders and to carefully control for ADHD. Intellectual and achievement testing was conducted to confirm the diagnosis of reading disability in the clinical group and exclude participants recruited for the control group who demonstrated learning difficulties (Measures used in the process of eligibility determination are described below). Participants with low intellectual functioning were excluded. Participants had normal or corrected to normal vision, used English as their primary language and had no history of head injury. Participant selection criteria is summarized in Table 1.

Diagnostic Screening Instruments

Emotional & Behavioral. All sections of the Diagnostic Interview Schedule for Children Version-IV-Parent Version (DISC-IV-P; National Institute of Mental Health, 1997) were administered and parent and teacher versions of the Iowa Conners Rating Scales-Revised (CRS-R; Conners, 1994) were completed. The diagnostic screening also used information from the following sources: Parent Behavior Assessment System for

Children rating scales (BASC-PRS, Reynolds & Kamphaus, 1992), and self-report measures of symptoms of depression, [Children's Depression Inventory (CDI; Kovacs, 1992)] and anxiety [Revised Children's Manifest Anxiety Scale (RCMAS; Reynolds & Richmond, 1978)].

The *DISC-IV* was administered to parents in a computerize-assisted format that presents DSM-IV criteria for psychiatric disorders in child populations (Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000). The *CRS-R* (Conners, 1994), parent and teacher versions, is a short, 10 item rating scale that assesses the presence of hyperactive, impulsive and emotionally reactive behaviors characteristic of individuals with attentional difficulties. The *BASC-PRS (*Reynolds & Kamphaus, 1992) is a measure of behavior at home and other social settings for children 4-18 years. Clinical scales assess the presence and severity of externalizing, internalizing and atypical behaviors to aid in differential diagnosis of emotional and behavioral disorders. Subscales are derived from 111 items of the BASC-PRS and take 10-20 minutes to complete. Items contain descriptors of behavior and a four choice response format for rating behavior frequency from Never to Almost Always. The PRS standardization sample of 3,065 is stratified on gender, age, race and geography based on data from the 1990 U.S. Census. The standardization sample includes several groups for comparison; this study used the general sample to derive subscale T scores. Median values for test retest reliability of the BASC PRS range from .70 to .88.

The *Revised Children's Manifest Anxiety Scale* (RCMAS; Reynolds & Richmond, 1978) is a self-report scale for children consisting of 37 items that tap different manifestations of anxiety in children (physiological, social and generalized). Each item is a statement to which the participant responds yes or no based on the degree to which the statement is perceived as true. T-scores derived for the Total Anxiety composite are stratified by gender and age. Standardization data based on ethnicity is not representative of the geographic region; norms are available only for White and Black populations. This study used the normative data from the White sample for Hispanic and Asian participants. The Total Anxiety score is reliable with good internal consistency (low .80s). Concurrent validity indices with other measures of anxiety are moderate.

The *Children's Depression Inventory* (CDI; Kovacs, 1992) is a 27-item scale used to assess depressive symptomology in children ages 7 thru 17. Each item consists of 3 sentences that depict different levels of symptom severity. The participant selects one sentence that best describes the symptom's prevalence during the previous two weeks and is given the corresponding score of 0, 1, or 2 points. T-scores are stratified on gender for two age groups: 7-12 and 12-17. Internal consistency of this scale is good with moderate test-retest reliability. High correlations with other measures of internalizing symptoms have determined the CDI to have good concurrent validity.

Intelligence. The *Differential Ability Scales for Children* (DAS; Elliott, 1990) is an individually administered measure of intellectual ability. The battery of core subtests combine to form several composite scores: the verbal composite measures word knowledge and comprehension of word relationships; nonverbal composite measures ability to integrate visual and auditory information; and the spatial composite measures ability to perceive complex visual information. The General Cognitive Ability (GCA) composite is a measure of overall cognitive functioning determined by performance on all *core* subtests administered. GCA was used in the ability-achievement discrepancy calculations for reading disability determination to establish study eligibility.

The GCA and composite scales yield age-based standard scores (Mean 100; SD 15) and core subtest yield T-scores (Mean 50; SD 10). Correlations between the GCA and the Wechsler Intelligence Scale for Children-III (WISC-III; Wechsler, 1991) have provided indication of convergent validity; correlations range from .84 (8-10 year old children) to .91 (14-15 year old adolescents). Psychometric properties reported in the technical manual include internal consistency estimates of .90-.95 for the GCA and .86-.92 for the composite scales.

Achievement. The *Wechsler Individual Achievement Test, Second Edition* (WIAT-II; Wechsler, 2002) was used to assess reading abilities. The psychometric properties of the WIAT-II are derived from a standardization sample of 3,600, stratified by grade, age, sex, race/ethnicity, geographic region and parent education level, approximating the percentages reported in the 1998 US Bureau of the Census. Subtests of the WIAT-II have good evidence of validity indicating each measure provides an assessment of the specified achievement construct. The three subtests of the Basic Reading composite were administered. Word Reading measures word recognition and phonological decoding skills in reading words of increasing difficulty presented in a list format. Pseudoword Decoding assesses ability to apply knowledge of sound symbol correspondences to decode non-words. The Reading Comprehension subtest measures ability to read for meaning in paragraph length passages. Split-half reliability coefficients for these three subtests were reported as .97, .97, and .95, respectively. Age-based standard scores (Mean 100; SD15) were calculated for use in this study. All three reading subtests were used to determine the presence and absence of reading disability in study participants. Word Reading and Pseudoword Decoding were also used in correlational analyses in tests of Hypothesis 3.

Table 1

Summary of Participant Selection Criteria

Selection Variable	Criteria
Age Range	9.0 – 15 years 11 months
DISC (DSM criteria)	Excluded if met diagnostic criteria for behavioral, anxiety, depressive or psychotic disorders
CRS-R (ADHD)	Excluded if T-score > 65 on Global Index on CRS
IQ	Standard Score ≥ 85 on two of the three DAS Ability composites
Ability-Achievement Discrepancy	Dyslexic Group: ≥ 20 points difference between the GCA (DAS) and two of the three WIAT-II reading subtests
	Control Group: Two of the 3 WIAT-II reading subtests within 15 points of GCA; No history of placement in special education classes.

Measures of Language Processes

Automaticity

Rapid automatic naming (RAN) is a task that measures the speed with which names of familiar visual objects can be retrieved from the mental lexicon (Denckla & Rudel, 1976). The four categories of visual objects measured in separate trials are colors, letters, numbers and objects (40 items per category). All items of a given trial are presented on a single page. Instructions to the participant are to say aloud the name of each item, proceeding in order from left to right until the last item has been named. Time and error data was collected for each of the four trials. RAN tasks have been found to be highly correlated with reading skill (Semrud-Clikeman, Guy, Griffin, & Hynd, 2000; Denckla & Cutting, 1999). To reduce number of variables used in hypothesis testing only the completion time (in seconds) for the letter trial was used. Previous research has demonstrated RAN Letters discriminates between children with reading disabilities and normally developing readers, in both young and older groups, and is predictive of performance on reading recognition and comprehension (Semrud-Clikeman et al, 2000; Wolf & Bowers, 2000).

Phonological Processing

The Nonword Repetition subtest from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, Rashotte, 1999) was used to assess short-term memory for phonological information. The Nonword Repetition task consists of 18 pseudowords; each consecutive item increases in length and difficulty. For example, compare item 1, /meb/, to item 18, /dook-er-sha-te-pi-ta-zom/. To increase the range of variability in this task, rather than awarding one point for each correct item (of 18), each correctly repeated syllable within the items was awarded a point, for a maximum score of 63. In this task items are presented in serial fashion via audiotape. Following standardized administration procedures, participants were instructed to repeat the pseudoword immediately after item presentation. Psychometric properties and standardization data was derived from a sample of 1656 persons, representative of the U.S. population in gender, ethnicity and socioeconomic status (Wagner et al., 1999). For ages 8-15, reliability coefficients for this subtest averaged .78. Content validity of the Nonword Repetition subtest was determined by acceptable discrimination coefficients. Analyses of the criterion predictive validity of the Nonword Repetition test found moderate correlations with measures of single word reading and phonological decoding.

Phonological awareness was assessed in a task wherein the participant manipulated the sounds in words and pseudowords by segmenting and removing a designated phonological unit. The size of the unit ranged from whole syllables to phonemes within syllables. A word or pseudoword is presented with the instructions to repeat the word aloud then say what remains after a designated sound is removed (e.g., ‘say cats,’ ‘now say cats without the sound /t/, or ‘unler’ without the /ler). Task items were selected from the Phoneme, Syllable, and Rime subtests of the Process Assessment of the Learner: Test Battery for Reading and Writing (PAL-RW; Berninger, 2001), collectively referred to in the current study as the Sound Deletion task. The items of the

Sound Deletion task were dichotomously scored and summed to reflect total correct of 36 possible.

Orthographic Processing

The *Word Choice* task from the PAL (Berninger, 2001) was used as a measure of long term memory storage for orthographic representations of whole word, letter cluster and grapheme size units. The task requires the selection of the correctly spelled word of three phonologically identical letter strings, the target and two pseudohomophones (e.g. road, rowd, roed; enjoy, enjoi, injoy; swim, swym, swimm). Since all three letter strings have the same phonetic representation, use of decoding skills does not help identify the correctly spelled word. The task consists of one practice item and 30 test items presented on a single sheet of paper. Standard administration instructions were followed. The task was explained and the participant was given feedback from the examiner on a practice item. The participant was instructed to complete the remainder of the page, work quickly but with accuracy and to guess if necessary. This task has a three-minute time limit. The items of the Word Choice task were dichotomously scored and summed to reflect total correct out of 30. Measures similar to the Word Choice task have been used frequently to operationalize the construct of orthographic processing, because speed and accuracy on such lexical decision tasks rely on orthographic information rather than phonological processes.

The Receptive Coding subtest of the PAL-RW (Berninger, 2001) was used as a measure of short-term memory for orthographic information. A word printed in the center of an 8.5” x 5.5” card is presented for 1 second, then removed and replaced with a card containing a single letter or letter cluster (e.g., /fender/ followed with /de/). The task is to determine if the letter(s) on the second card were present in the first word. The Receptive Coding task requires the orthographic representation of the whole word to be briefly held in memory to accurately recall its sub-lexical features (note the accuracy in sub-lexical detail required for a correct response to the word /rabbit/ followed with /ab/ versus /ba/). Participants responded with a yes or no. If no response was given within 5 seconds, the examiner turned to the next item. The rapid speed of presentation and 5-second response limit is intended to minimize recall of the orthographic representation from long-term memory or use of subvocal phonological decoding to generate the correct response (Berninger et al., 2001). 54 items of increasing difficulty are presented in a three-ring folder. Correct responses receive one point and are summed to reflect total correct.

The Colorado Perceptual Speed Task (CPST) is an unpublished measure of speeded visual discrimination of letters and numbers constructed by DeFries and colleagues for use in assessment of learning disabilities (personal communication, DeFries, October 2003) referenced in DeFries, Plomin, Vandenberg, & Kuse, (1981). Each item consists of a target non-word letter string presented to the left of four similar strings, only one of which is identical to the target. (e.g. target: /jzrv/: choices: rzvj jvzr jrvz jzrv). The task is to quickly scan the four choices and mark the string identical to the target. Participants are given a one-minute time limit. Scores reported are number correct minus number of errors.

Though normative data of the CPST is not available, it has been used as a measure of orthographic processing in studies of normal and impaired reading development (Berninger, et al., 2001). Use of the CPST as a measure of orthographic processes is supported by findings of an unpublished study that found the measure to have discriminative validity with adults with dyslexia (C. Coleman, personal communication, February 2004).

Table 2

Summary of Language & Reading Variables

Variable	Instrument	Scores
Automaticity		
Rapid Automatic Naming-Letter Trial	Letter Naming (RAN)	Completion time in seconds
Orthographic Processing		
Orthographic representation in long term memory of whole word, letter cluster and grapheme size units	Word Choice (PAL)	Total Correct, maximum 30
Orthographic representation of sub lexical units in short-term memory	Receptive Coding (PAL)	Total Correct, Max 56
Speeded visual discrimination of stimuli with orthographic representations at level of grapheme (Trial 1) or grapheme and letter cluster (Trial 2).	Colorado Perceptual Speed Task (CPST)	Number correctly completed in 60" minus errors. Max: 40
Phonological Processing		
Phonological Memory: short term memory for phonemic information:	Nonword Repetition (CTOPP)	Total Correct, Maximum 63
Phonological Awareness: discrimination and manipulation of sounds of various sizes (syllables; phonemes of consonant blends)	Sound Deletion task (PAL)	Total Correct Maximum 36
Reading Ability		
Single word reading: Word recognition and phonological decoding skills	Word Reading (WIAT-II)	Age based standard scores, mean 100, standard deviation 15
Phonological decoding of nonsense words (facilitated by phonological awareness and orthographic representations of sublexical units)	Pseudoword Decoding (WIAT-II)	

Electrophysiological Measure: Visual Word Recognition

Visual system specialization for orthographic stimuli was examined in an ERP experiment. Brain activity was recorded during an implicit word recognition task in which participants passively viewed words and word-like stimuli presented serially in list form on a computer monitor. The ERP effects of interest concerned contrasts between orthographic and non-orthographic stimuli occurring within the first 300 ms from stimulus presentation. Of specific interest was the earliest point in time wherein stimuli with orthographic content were differentiated from other visual information. See Appendix A for examples of stimuli described below.

Word Recognition Stimuli Conditions

Five stimuli types of words and word-like strings included 3 orthographic conditions (Real Words, Pseudowords and Consonant strings) and 2 non-orthographic, or Visual conditions (False Fonts and Symbol Strings). Stimuli were matched on length (3-6 characters). At the level of the whole form all conditions were word-like, that is, the physical attributes of the outer configuration similar to that of real words. A further distinction was made based upon regularity of orthographic representations: Words, Pseudowords and Consonant strings differ in the regularity of orthographic structure (the legality of grapheme to phoneme correspondences).

Words (WRD). Words were at the second grade reading level or below, highly regular in pronunciation and derived from common word families. Because the variable of interest was the automatic processing of implicit word recognition, stimuli were selected to be easily recognized as words.

Pseudowords (PW). Pronounceable non-words—made-up words that follow regular rules of grapheme to phoneme conversion. In children, pseudowords are equivalent to words not yet learned; in adults pseudowords are treated as low frequency real words. Some pseudowords were taken from stimuli used in previous studies (Manis et al., 1996; Olson et al., 1994) and some were generated by the experimenter.

Consonant Strings (CS). Strings of consonants were assembled such that within a given string, no three consecutive letters were identical. Consonant strings have illegal grapheme-phoneme correspondence at sublexical levels that make them non-pronounceable (e.g, NTP or NTPFTM).

False Font (FF). Character strings with visual features similar to orthographic word-types. Though the physical attributes of the outer configuration are similar to that of real words, false fonts have no orthographic representation, thus simulating an alphabet with which the participant has had no exposure. The FF stimuli were created with *New Arabesh* font characters and are comparable to stimuli used in other studies (Petersen, Fox, Posner, Mintun, & Raichle, 1988).

Symbol strings (SS). Strings of non-alphanumeric ASCII characters (#$%)(@) randomly assembled with the requirement that within a given string, no three consecutive symbols were the same. SS are lacking orthographic and phonological information but engage basic visual processes, thus were used as a visual control condition.

Word Recognition Task

The word recognition experiment used a simple detection task consisting of two trial types: non-targets, consisting of the stimuli describe above, and targets. Targets were words, pseudowords, consonant strings, false fonts and symbol strings that differed from non-targets only in that they were larger in size. The task was similar to the paradigm used in Bentin et al (1999). Examples of targets and non-targets of each word-type were shown to the participant prior to beginning the practice block. Participants were instructed to respond to targets by pressing a button on a hand-held game pad. Non-targets trials required no response as the activity of interest was that associated with passive viewing, and only the non-target trials were included in data analysis. Task directions make the non-targets irrelevant to correct performance. The requirement of an overt behavioral response to the targets was intended to maintain participant attention to the stimuli. Instructions were worded so as not to encourage active processing (word reading) or other attempts to differentiate among stimulus types. Participants were instructed to keep their eyes fixated on a crosshair, slightly offset from the monitor's center, which remained on the screen throughout the experiment.

The experiment included 80 trials of each word-type condition (240 total), delivered over 4 blocks. Each block presented 20 non-target trials and 2-3 target trials from each word-type category. Targets occurred with a 12% probability and were easily detected as different from non-targets. Stimuli within each block were randomly delivered. The stimulus of each trial remained on the monitor for 300 ms; intertrial interval varied from 700 – 1000 ms (mean=1 ms), trials varied from 1000-1600 ms (mean=1.3 s). Time for each block was 2.5 minutes.

ERP Participant Set-up Procedures

EEG activity was recorded with a 64-channel electrode array housed in an elastic cap (Elastocap, Eaton, OH). Proper fitting of the electrocap took approximately one hour. To be fitted with the electrocap, at each of the 64 sites the skin of the scalp was gently scraped with a wooden dowel and an electrolyte (saline) gel applied. To minimize discomfort during this process, participants watched a movie on a television set in the lab.

Once fitted with the cap, the participant was moved into an electrically and acoustically shielded room and seated in a comfortable upholstered chair facing the computer monitor used for stimulus delivery. A camera and intercom device secured on top of the monitor was used to observe and communicate with the participant from the equipment station located just outside the shielded room. A technician remained in the room during a practice block given to familiarize the participant with the gamepad and insure understanding of the task. Prior to the start of each block the participant was reminded to limit blinking and fixate their eyes on the cross mark on the screen. During the experiment, the participant was monitored for attention to task and excessive eye blinking or other movements. At the end of each block, the participant was instructed to rest their eyes for a few minutes while the next block is being prepared. The entire experiment was 15 minutes in duration.

EEG/ERP Recording

Electrodes were positioned according to the International 10-20 system: To control for ocular artifacts, electrodes were placed below right and left eyes to monitor blinks and vertical eye movements, and electrodes placed on the outer edge of each eye in-line with the pupil monitored horizontal eye movements. Electrical impedance at each electrode-scalp juncture was kept below 5 k throughout recording. During the experiment, the ongoing EEG signal is passed through an amplifier, converted from analog to digital (digitized) and saved on computer hard drive for off-line processing. Acquisition of EEG data used the following parameters: bandpass of .01 – 100 Hz, analog filtering, gain of 10(4), sampled at a continuous rate of 400 Hz. During recording, electrodes were referenced to the right mastoid.

Feature Extraction

Initial processing of raw EEG recording serves to reduce the large amount of data and isolate meaningful information (Picton et al., 2000). For each participant the data was sorted, filtered and averaged to isolate the electrical activity generated by passive viewing of word and word-like forms. The averaged data were digitally filtered at 20 Hz lowpass to remove residual high-frequency noise and baseline corrected over the 100 ms prestimulus period.

The EEG recordings were examined and portions of the signal that were contaminated with non-neuroelectric artifacts (eye movements, body movement, disrupted electrode contact) were removed through manual editing using rejection thresholds calibrated for individual participants. The EEG activity is time-locked to the stimulus onset of each trial. Data remaining after artifact rejection were sorted according to word-type condition then averaged for a 600 ms epoch beginning 100ms pre stimulus presentation (See Figure 1). The outcome of this first stage of data processing is an ERP waveform for each word-type condition at the 64 electrode sites for individual participants.

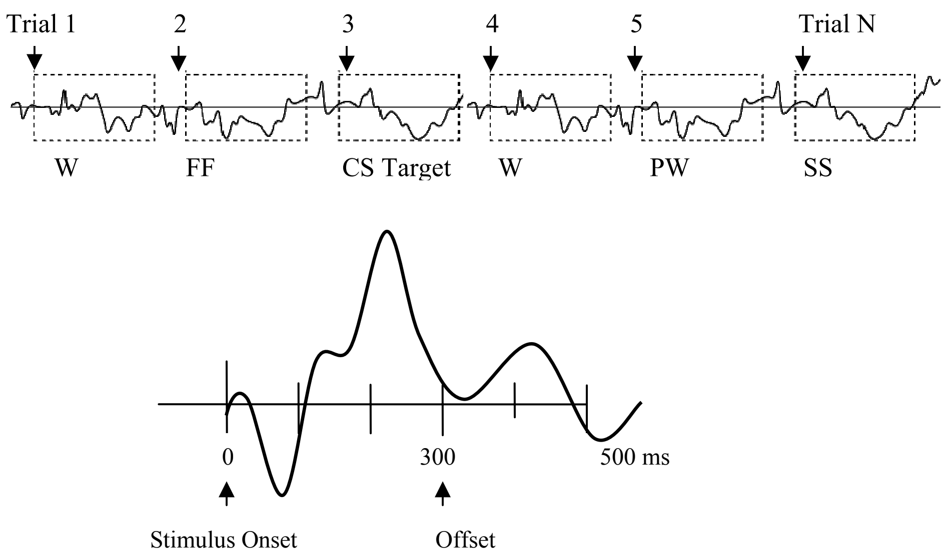


Figure 1. Example of Averaged ERP Waveform Generated from EEG Signal

Fig. 1. The sum of Trial 1 + Trial 4 + … Trial 80 results in the averaged waveform for the Word (W) condition (in this example).

Next, ERP data from each participant were grand averaged according to group membership. Grand averaged waveforms for each of the 5 word-type conditions were plotted according to scalp distribution and examined for the presence of observable ERP effects. Visual inspection revealed a negative deflection in the posterior region of the scalp distribution occurring during the first 300 ms, as predicted in Hypothesis 1. Thus, this ERP component served as the primary dependent variable used in hypothesis testing. The ERP was present in occipital and temporal-parietal regions during 175-275ms window. The N1 ERP peaked between 225-230ms, so to best capture the activity, the mean voltage amplitude was calculated in the window of 195-255 ms (see Figure 2). Calculations were made for 10 electrode sites TO1/2, T5/6i, T5/6s, O1/2i, O1/2s. See Appendix A for electrode positions. Sites were selected when the ERP was present (observable by visual observation) in the posterior regions predicted from other ERP studies of the N170 in word recognition (Bentin et al 1999; Mauer et al., 2005).

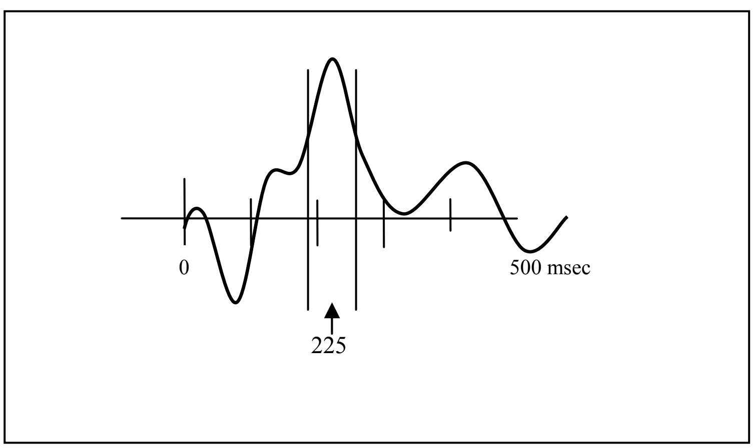


Figure 2. Latency Window for 195-255ms

Fig. 2. The waveform depicted is plotted with negative voltages up

Data Analysis

Tests of Hypotheses 1&2. A combination of methods was used in analysis of the ERP data: inspection of ERP grand-averaged waveforms, repeated measures and univariate ANOVAs, and examination of topographical maps of ERP difference waves across the posterior scalp.

The N230 amplitude measured between 195-255 at each of the 10 sites was entered into an omnibus repeated-measures ANOVA, with three within group factors, Word-Type (word, pseudoword, consonant strings, false fonts, symbol strings) x Site (5) x Laterality (Left and Right hemispheres), and Group (CON, DYS) as the between-subjects factor. Use of repeated-measures, or within subjects ANOVA is the conventional analysis for ERP data because, for a single trial, the dependent variable (mean voltage amplitude) is measured at multiple locations (in this study at 64 electrode channels). In ERP experiments the assumption of sphericity is more frequently violated than other designs due to the higher correlation between adjacent than distant electrodes; to address this issue the Greenhouse and Geisser (1959) epsilon was applied to adjust downward the degrees of freedom. Subsequent to significant interaction effect involving group (Word-type x Group), separate 3-way ANOVAs were conducted for each group. Finally, to examine the Word-Type x Group interaction more specifically, a series of univariate ANOVAs were conducted to contrast groups for each word-type condition at a channel at the occipito-temporal region (T5/6 inferior, collapsed across hemispheres). Planned pairwise comparisons were conducted using the Bonferoni statistic to decrease the probability of a Type I error for multiple comparisons.

Tests of Hypothesis 3. Correlational analyses were conducted to examine the relationships among scores of reading ability and language component processes and the brain activity in the posterior occipito-temporal regions. For each participant, the mean amplitude elicited by words was subtracted from mean amplitude elicited by symbol strings at 4 electrode sites. The difference in amplitude was used to quantify the degree of differentiation of orthographic from non-orthographic stimuli as an index orthographic specificity of the posterior language system. These difference scores were entered into the correlation and regression analyses along with scores for behavioral measures of reading ability and language component processes.

Chapter 4: Results

Results of the analyses described in Chapter 4 are presented in the sections that follow. Descriptive data including the IQ and reading measures used to define the Control and Dyslexic groups are reported below followed by results of ERP analyses. Correlation and regression analyses conducted to examine the relationship between language component processes and ERP activity are presented in the last section of this chapter.

Three of the 26 participants who completed the Neuropsychological assessment did not complete the ERP portion of the study (2 declined, 1 moved) and are not included in the following analyses. Of the 23 participants who completed the ERP experiment, one did not complete the measures of language processes and was not included in the regression analyses.

Descriptive Analysis

A t-test was conducted to examine the significance of group differences in age, IQ, and reading measures. No significant differences were found for participant average age ($t=.21$, $p = .83$) or average IQ ($t= .37$, $p = .714$) and, as expected, significant group differences were found on the three reading measures used to determine group membership with the dyslexic group scoring significantly more poorly (about 20 points less) than the control group. (See Table 3).

Table 3

Demographic, IQ and Reading Achievement Variables: Analyses by Group

	Control (n=11)	Dyslexic (n=12)	**t-test**	
	Mean (Stdv)	Mean (Stdv)	**t**	**p**
Age	11 y 8 m (1.72)	11 y 7 m (1.71)	.213	.834
GCA	118 (8.9)	117 (9.4)	.372	.714
Word Identification	109 (6.5)	87 (13.8)	4.81	.000
Pseudoword Decoding	108 (6.1)	89 (7.9)	6.383	.000
Comprehension	118 (6.0)	96 (13.7)	4.90	.000

Chi square analyses were conducted to determine the significance of group differences in ethnicity and gender (See Table 4). Of the 23 participants, 18 were White and 5 Hispanic, similar in proportion for both groups, $X^2(1, N=23) = 3.486$, $p > 0.05$). The distribution for gender was significantly different between groups, $X^2(1, N=23) = 0.157$, $p > 0.05$) with the dyslexic group having more males than the control group. Analyses were conducted to determine the effects of gender on the ERP and language variables, and are discussed in following sections.

Table 4

Chi-Square Analysis for Gender and Ethnicity by Group

	Control		Dyslexic		**χ^2**	**p**
Gender	Males	Females	Males	Females		
	4	7	9	3	3.486	.062
Ethnicity	White	Hispanic	White	Hispanic		
	9	2	9	3	.157	.692

ERP Data Analysis: Test of Hypotheses 1 & 2

Hypothesis 1 predicted significant differences in ERP amplitude between orthographic (words =W, pseudowords=PW, consonant strings=CS) and visual (false fonts=FF, symbol strings=SS) word-type conditions, in the control group (a), but not the dyslexic group (b), and group differences for the orthographic word-types (c). Competing predictions were made regarding group differences for visual word-like forms (d). Hypothesis 2 examined the three orthographic word-type conditions for differences in ERP amplitude related to the regularity of orthographic structure. Regularity refers to the legality of grapheme to phoneme correspondences, thus consonant strings (CS) are irregular, pseudowords (PW) regular at the sublexical level, irregular at word level, and words (W) highly regular. Evidence that regularity of grapheme to phoneme correspondences modulated ERPs would be found in significant differences in mean amplitude such that W> PW> CS. If regularity was found to significantly influence ERP amplitude, this effect was predicted to occur in the control and not the dyslexic group.

Main ERP effects of interest concerned the contrast between orthographic and visual word-type stimuli (Hypothesis 1), and contrasts among the three orthographic word-type conditions (Hypothesis 2) both within and between dyslexic and control groups. Inspection of ERP grand-averaged waveforms through repeated measures and univariate ANOVAs and examination of topographical maps of ERP difference waves across the posterior scalp indicated major effects involving word type and group occurring in the first 300 ms post-stimulus.

Visual inspection of Grand-Averaged ERPs

Inspection of the grand averaged waveforms for contrasts among the five word-type conditions indicated several major ERP effects in the 150-250 ms window. Dyslexic group ERPs were markedly attenuated in contrast to those of the control group for all word-types at posterior (but not anterior or central regions). A prominent negative-going ERP component (N1) elicited by all word-type stimuli, maximal in lateral sites in occipital, occipito-temporal and posterior temporo-parietal regions. The N1 mean amplitude was markedly larger for orthographic than visual word-types in controls, but not in dyslexics, as expected in part (a) of Hypothesis 1.

Posterior N1. Grand averaged ERP waveforms across the posterior scalp for both dyslexic and control groups showed a positive going component (P1) with a peak around 150ms for all word-type conditions. The P1 was followed by a negative going deflection from 170-270ms with a peak around 225 (N1) maximal at occipital and occipito-temporal sites. ERP amplitudes for the dyslexic group were markedly attenuated with a more restricted distribution across the posterior scalp relative to the control ERPs.

In the control group, N1 ERPs to orthographic word-types were markedly larger than visual word-types, the difference first observable in the early aspect of the N230 component (approximately 150ms), and broadly distributed across the posterior scalp. In contrast, the N1 ERPs of the dyslexic group showed very little differentiation between orthographic and visual word-type, the first point of divergence being around 250ms (at what may be either the later aspect of the N230 or the onset of the P300).

Control group ERP peak amplitudes were similar for the three orthographic word-type conditions though ERPs for words appeared slightly greater than for pseudowords and consonant strings. Orthographic ERPs also appeared slighted right sided across the occipito-temporal and posterior parietal scalp. Symbol strings and false fonts elicited similar ERPs; larger false font than symbol string ERPs were observed at TO1/2 and T6i.

The N1 peaked around 225ms, so to best capture the activity the mean voltage amplitude was calculated in the window of 195-255 ms at 10 electrode sites TO1/2, T5/6i, T5/6s, O1/2, O1/2s.

Latency Window 195-255 ms

Global Analysis. The ERP data were initially analyzed using an omnibus repeated-measures ANOVA, with three within group factors, Word-Type (word, pseudoword, consonant strings, false fonts, symbol strings) X Site (TO1/TO2, T5/T6 inferior, O1/2 inferior, O1/2 superior, T5/6 superior) X Laterality (Left and Right hemispheres) and group (control, dyslexic) as the between-subjects factor. P-value was set at 0.05 using the Greenhouse-Geisser adjustment for violations of sphericity. There were main effects for Word-Type, $F(4, 84) = 7.49$, $p < .000$, and for Site, $F(4, 84) = 7.20$, $p = .001$, GG = .55, but not for Laterality, $F(1,21) = 4.10$, $p = .056$.

There was a Word-Type by Site interaction, $F(16, 336) = 2.65$, $p = .022$, GG epsilon = .35) due to larger ERPs at (TO, T5/6i) inferior and lateral occipito-temporal sites for orthographic stimuli. A significant Word-Type x Site x Laterality interaction, $F(16, 336) = 2.55$, $p = .029$, GG epsilon = .34, reflected that pseudowords elicited larger ERPs at T6 (inferior, Right Hemisphere) than at the left hemisphere homologue (as revealed by a significant Site x Laterality interaction). The finding most pertinent to this study was the significant Word-type x Group interaction, $F(4, 84) = 4.34$, $p = .004$, which indicated follow-up ANOVAs for each group to test a priori hypotheses of within group word-type effects (reported in the following sections).

Control. Results of the 5 (word-type) X 5 (site) X 2 (laterality) repeated measures ANOVA with the control group showed significant main effects for Word-Type, $F(4, 40) = 9.21$, $p<.000$) and for Site, $F(4, 40) = 6.03$, $p = .008$, GG = .53). No significant interactions were present. N230 amplitudes for Word-Types revealed the largest amplitude to words (-2.614uv), pseudowords (-2.065uv), and consonant strings (-2.030uv), followed by reduced N1 ERPs to false fonts (.607uv) and symbol strings (1.670uv). These waveforms are plotted together at occipito-temporal sites (T5/6, inferior) in Figure 3. With an alpha level of .05, pairwise comparisons (using the Bonferroni adjustment) revealed that the Word-Type main effect was due to significantly smaller amplitude for symbol strings compared to words ($p = .003$), pseudowords ($p = .016$) and consonant strings ($p = .045$), thus, provided confirmation of the hypothesis of ERP effects between orthographic and visual word-types in the control group (Hypothesis 1). ERP amplitude did not differ significantly among the orthographic word-types providing evidence to address Hypothesis 2. ERPs to false fonts did not significantly differ from any orthographic word-type or from symbol strings although the difference between words and false fonts approached significance (p= .083).

Summary/Discussion: These results indicate that ERPs to orthographic stimuli are differentiated from visual stimuli during the N1 latency window as predicted for the control group in Hypothesis 1. This ERP effect can be seen in Fig 4 of the topographical map of the voltage amplitudes for the orthographic minus visual difference wave in the 195-255 ms window. The orthographic minus visual effect has a bilateral distribution across the posterior occipito-temporal scalp with focal activity over the right hemisphere however the Word-type x Site x Laterality interaction was not significant, $F(16, 160) = 2.225$, $p = .108$, $GG = .18$. The ERPs to the orthographic word-types decreased in amplitude as regularity of orthographic structure decreased (W>PW>CS). Although this pattern is consistent with predictions made in Hypothesis 2, the differences did not reach statistical significance.

Dyslexic Group. Results of the 5 (word-type) X 5 (site) X 2 (laterality) repeated measures ANOVA confirmed visual examination of ERPs that found the N1 waveform reduced in amplitude for all 5 word-type conditions, in fact none in the negative range, and did not differentiate between orthographic and visual conditions. As listed in Table 5, pseudoword ERPs were most negative (1.688uv) followed by consonant strings (3.065uv), symbol strings (2.708uv), words (3.041uv) and false fonts (3.235uv). See the average waveforms plotted together at occipito-temporal sites (T5/6, inferior) in Figure 3. The only significant effect was one for site; not a meaningful effect.

Dyslexic Group Summary: The finding of no significant difference in mean amplitudes among word-type stimuli was consistent with predictions of hypotheses 1 and 2. The ERP amplitudes for orthographic word-types were averaged together and contrasted with the average of ERPs to false fonts and symbol strings in a topographical map of the posterior scalp (Figure 4). The lack of differentiation between orthographic and visual stimuli is in sharp contrast to that observed in the topographical map of the control group.

Table 5

Mean Voltage Amplitude for Word-Type Conditions for Participants in Control and Dyslexic Groups

Word-Type	Words	Pseudowords	Consonant String	False Fonts	Symbol Strings
Control	-2.614	-2.065	-2.030	.607	1.670
Dyslexic	3.041	1.688	3.065	3.235	2.708

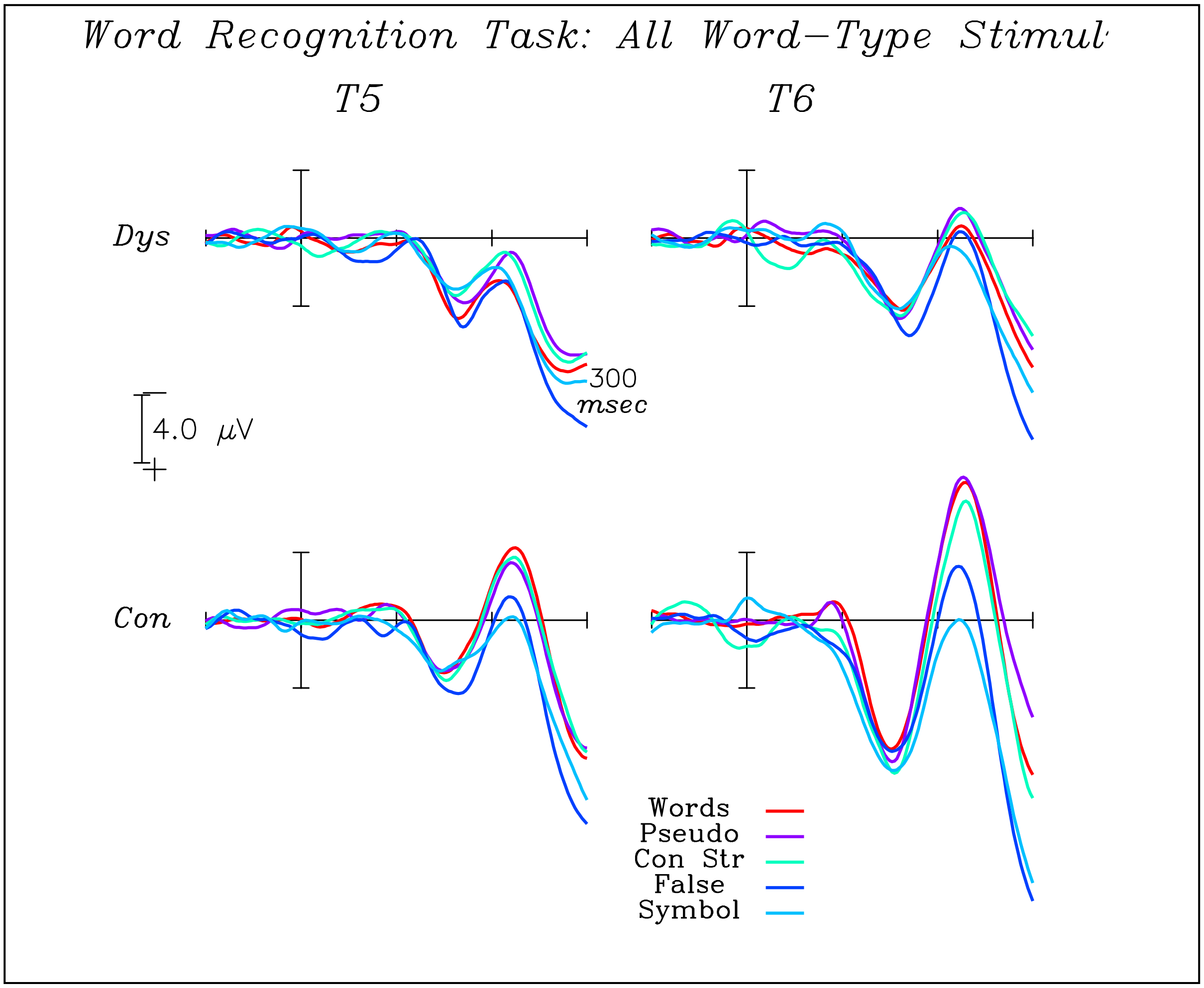


Figure 3. Average Waveforms for Words, Pseudowords, Consonant Strings, False Fonts, Symbol Strings at Site T5/6i

Botttom: Control Group: Note that the waveforms elicited by orthographic word-types are very similar from 0 to about 250 ms, beginning to diverge during the later aspect of the N230. Symbol strings are clearly differentiated from the three orthographic word-types, with the ERP for false fonts more negative than symbol strings but reduced compared to orthographic word-types.

Top: Note in the dyslexic group the ERP amplitudes for all 5 word-types are considerably reduced when compared to the Controls; also note the lack of differentiation between orthographic and visual categories.

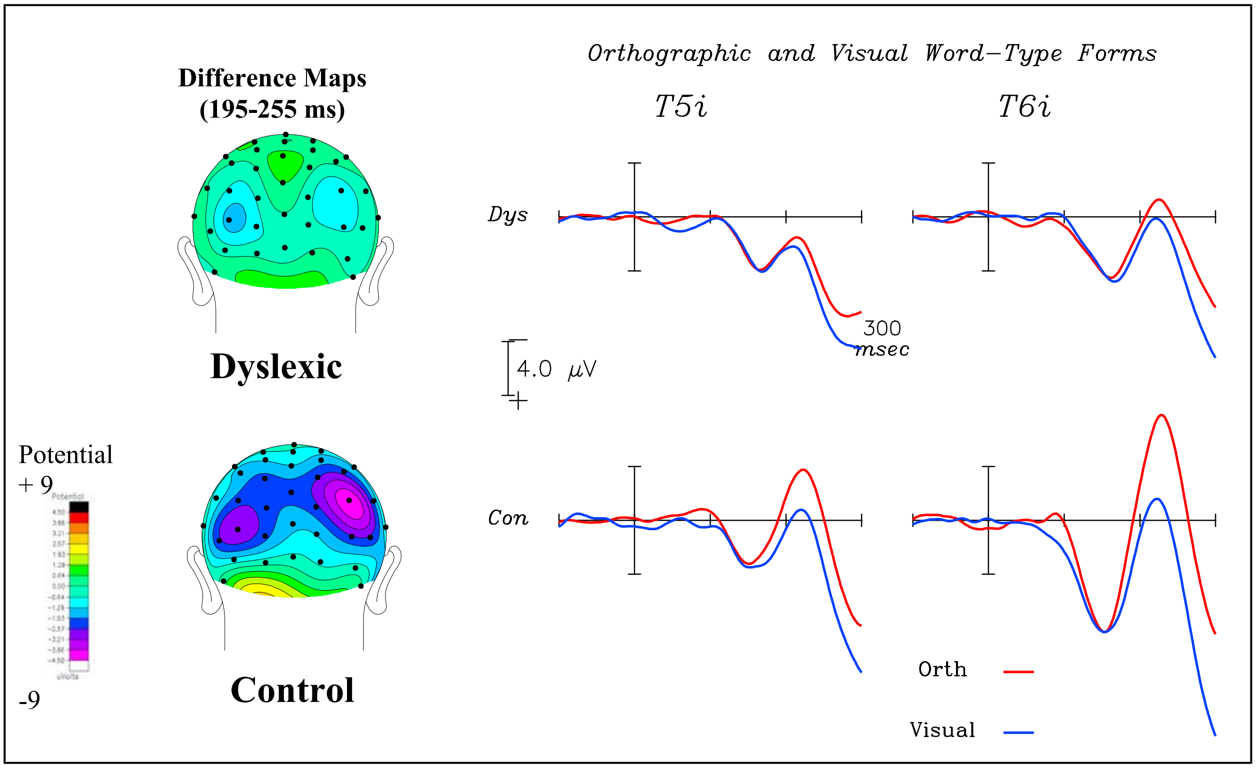


Figure 4. Orthographic minus Visual Word-Types: Topographical Maps and Average Waveforms During the 195-255ms window

Figure 4 illustrates confirmation of Hypothesis 1 that predicted N1 mean amplitude would be significantly greater for orthographic stimuli than for non-orthographic stimuli in the control group, but not the dyslexic group.

Left: Scalp Topographical maps of the N230 (195-255 ms) Orthographic minus Visual Word-Types for Controls (N=11, bottom) and Dyslexic (N=12, top). ERP amplitudes for visual stimuli (FF, SS) were averaged together and contrasted with the averaged ERPs for orthographic stimuli (W, PW, CS). Voltage amplitudes in uV. Purple and pink hues indicate negative voltages. Note that the Orthographic minus Visual effect is greater in the Control than Dyslexic group across the posterior scalp and that this ERP effect in the Control group has a peak intensity value over right occipito-temporal scalp (though not statistically significant).

Right: Grand-average ERPs at T5i and T6i for the orthographic conditions (red line) and visual conditions (blue line) illustrate the main effect for word-type in the Control group (top panel) and lack of word-type effect in the Dyslexic group (bottom panel).

Group Analyses

Group differences in ERP amplitudes to word-type stimuli predicted in Hypothesis 1 were confirmed in the previously reported significant Word-type X Group interaction of the global repeated measures ANOVA. To examine group differences, topographical maps were generated by subtracting ERP amplitudes of the dyslexic from the control group for the orthographic and visual conditions. The difference in scalp potentials are distributed across the posterior scalp. See the topographies in Figure 5. An obvious and important distinction between the topographical maps is that group differences are observably greater for orthographic stimuli than for visual stimuli, the difference in voltage amplitude for orthographic stimuli is more broadly distributed across the posterior scalp than for visual stimuli.

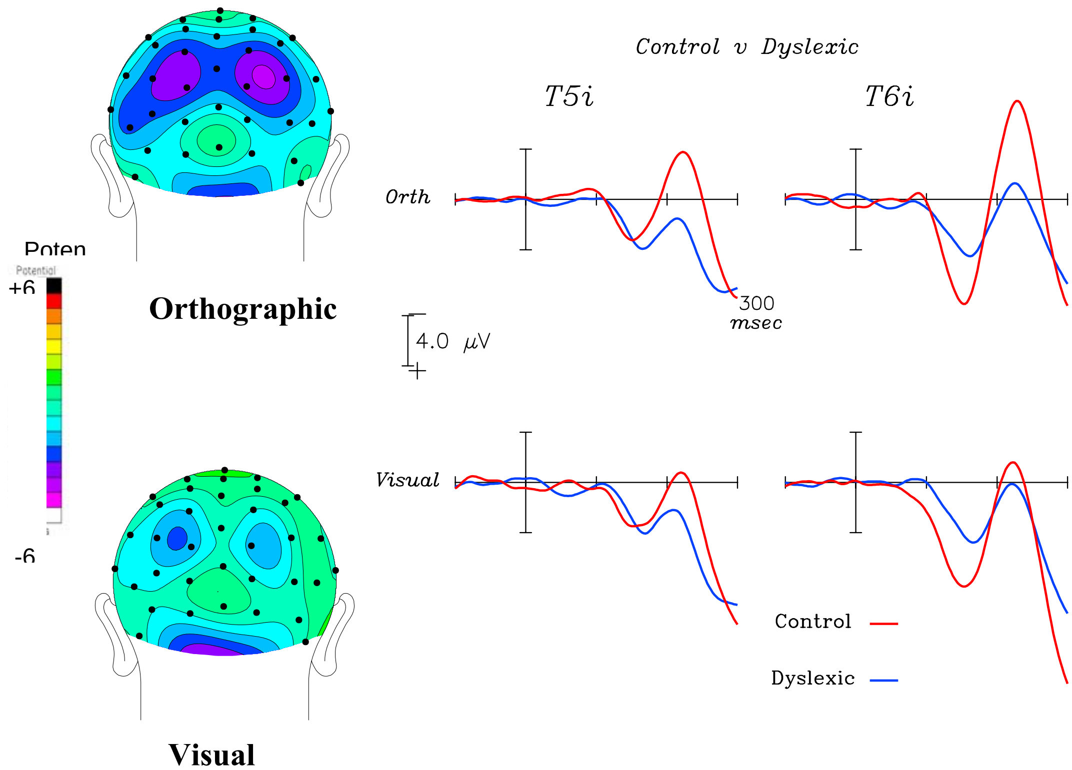


Figure 5. Control minus Dyslexic Topographical Maps and Average Waveforms for Orthographic and Visual Conditions

Fig. 5. Topographical maps depicting difference in mean amplitude between control and dyslexic groups calculated with waveforms from195-255 ms. The group differences are clearly greater for orthographic stimuli than for visual stimuli, the difference in voltage amplitude for orthographic stimuli is more broadly distributed across the posterior scalp than for visual stimuli.

To further investigate the statistical significance of word-type effects between groups, separate univariate ANOVAs were conducted to compare ERPs of control and dyslexic groups for each five word-type conditions at the lateral occipito-temporal scalp (T5/6, inferior collapsed across hemispheres). This site was selected for the ANOVAs because in the control group, the word-type effect was very strong at this location. Results of the ANOVAs found significant group differences for ERPs elicited by words, pseudowords and consonant strings but not to false fonts or symbol strings. A summary of ANOVA results is presented in Table 6. To examine these group differences across the posterior scalp, topographical maps were generated for each word-type condition using difference in mean amplitude between control and dyslexics waveforms from 195-255 ms (see Figure 6)

Table 6

Summary of Univariate ANOVAs for Word-Type at T5/6i by Group

	Mean Amplitude: Control minus Dyslexic	F (1,21)	P
Words	-6.489	18.996	.000
Pseudowords	-4.863	21.002	.000
Consonant Strings	-4.332	10.348	.004
False Fonts	-2.992	3.912	.061
Symbol Strings	-1.270	.780	.387

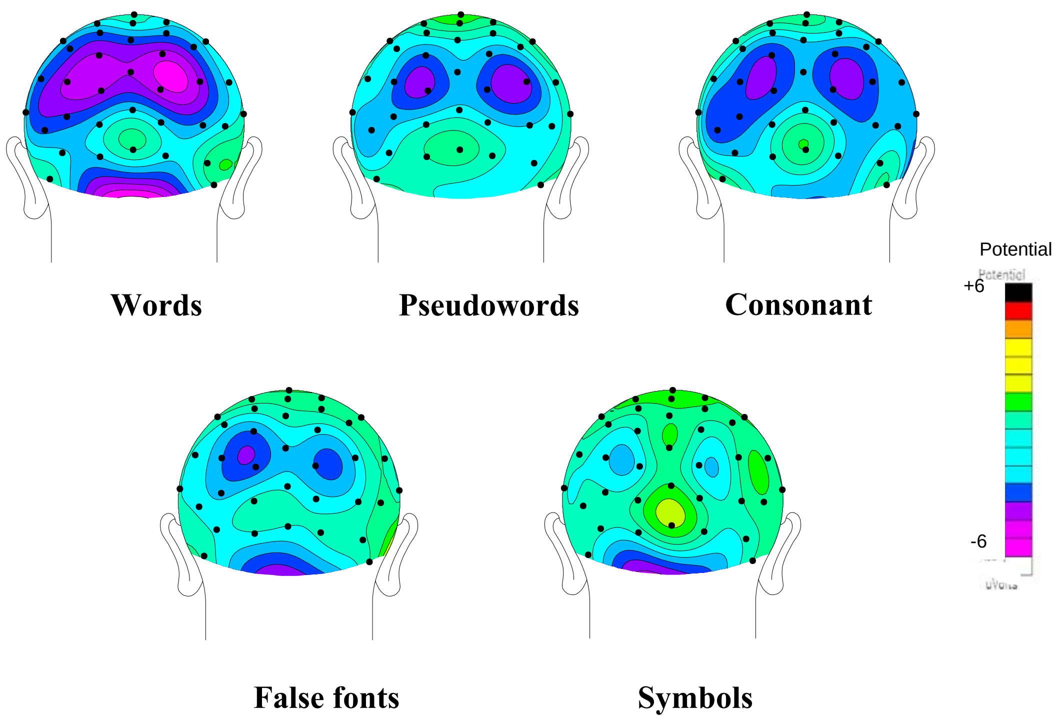


Figure 6. Control Minus Dyslexic Topographical Maps During 195-255ms by Word-Type Condition

Fig. 6. Topographical maps depicting difference in mean amplitude between control and dyslexics groups calculated with waveforms from195-255 ms. ERP effects were found with a bilateral distribution across the occipito-temporal scalp for all orthographic word-types. The strongest effect was for words with a larger and more inferior distribution on left than right and more widespread compared to pseudowords and consonant strings. At a more focal/restricted region the group difference to false fonts was as strong as seen for consonant strings and pseudowords. The topography of false fonts resembles that of pseudowords and consonant strings to a greater degree than it resembles symbols.

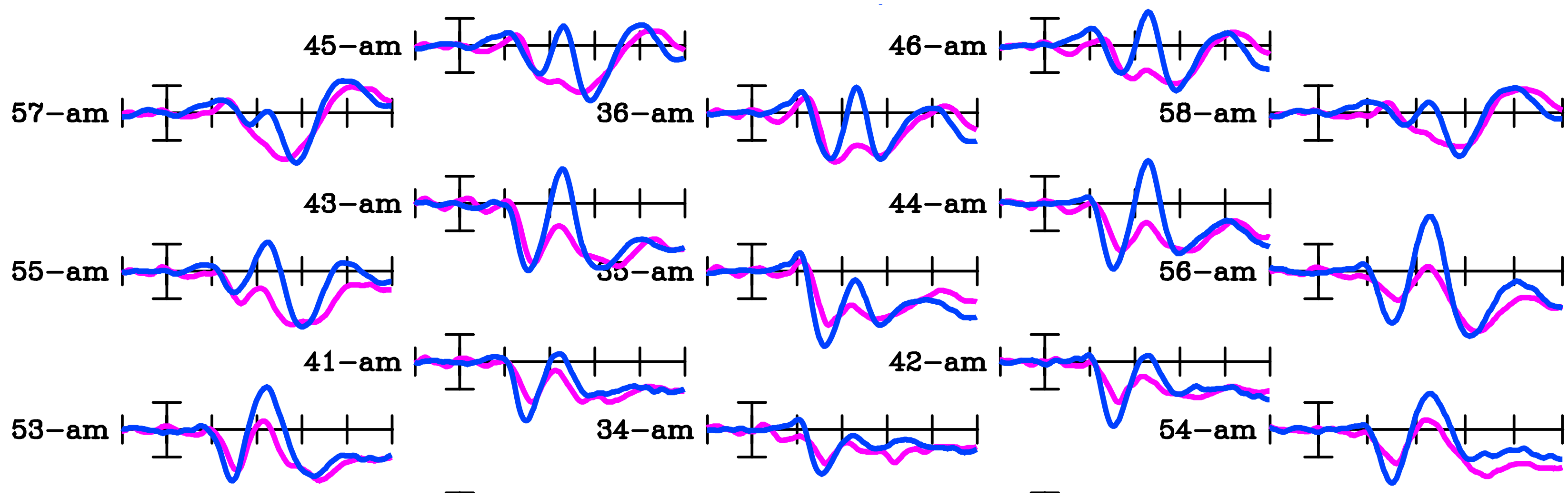


Figure 7. Control and Dyslexic Grand-average ERPs for Words Plotted at Posterior Sites

ERP waveforms for Dyslexic group (pink line) and Control group (blue line) at 15 posterior sites. The dyslexic group N230 is significantly attenuated relative to the control N230.

Language & ERP Data: Tests of Hypothesis 3

Hypothesis 3 examined the relationship between language component processes and ERP activity and predicted that the language measures would account for a significant portion of variance in ERP amplitude. The ERP activity was defined by subtracting the amplitude for Symbol Strings from the amplitude for Words (W-SS) at site T5/6 collapsed across hemispheres (see Figure 8). Descriptive statistics for W-SS ERP and measures of phonological, orthographic and naming processes (in raw score form) are presented in Table 7 along with results of a t-test conducted to determine the significance of observed group differences (Note: Means and t-tests for Word Reading and Decoding were reported earlier in Table 2).

Table 7

Means and Standard Deviations for Language Measures and Word-Symbol N230

	Control (n=10)	Dyslexic (n=12)	**t-test**	
	Mean (Stdv)	Mean (Stdv)	**t**	**p**
Phon Nonword Rep	50.90 (6.66)	42.33 (5.98)	3.180	.005
Phon Sound Deletion	28.50 (3.54)	20.58 (5.838)	3.753	.001
Orth Word Choice	28.60 (2.28)	23.08 (6.529)	2.735	.016
Ortho Code	48.50 (2.991)	41.00 (5.377)	3.924	.001
Ortho CPST	10.10 (3.178)	8.00 (3.742)	1.402	.176
RANL	23.60 (4.648)	27.67 (5.499)	1.85	.079
Word-Sym ERP	-5.54 (3.107)	-.389 (3.64)	-3.530	.002

Note: Naming values represent time in seconds; lower values indicate better performance.

Results of t-tests found that scores for the dyslexic group were significantly below the scores for the control group on both measures of phonological processes (Repetition and Sound Deletion) and two orthographic measures (Word Choice and Coding), but not on the Colorado Perceptual Speed Task (CPST, the third orthographic measure) or Rapid Automatic Naming-Letters (RANL).

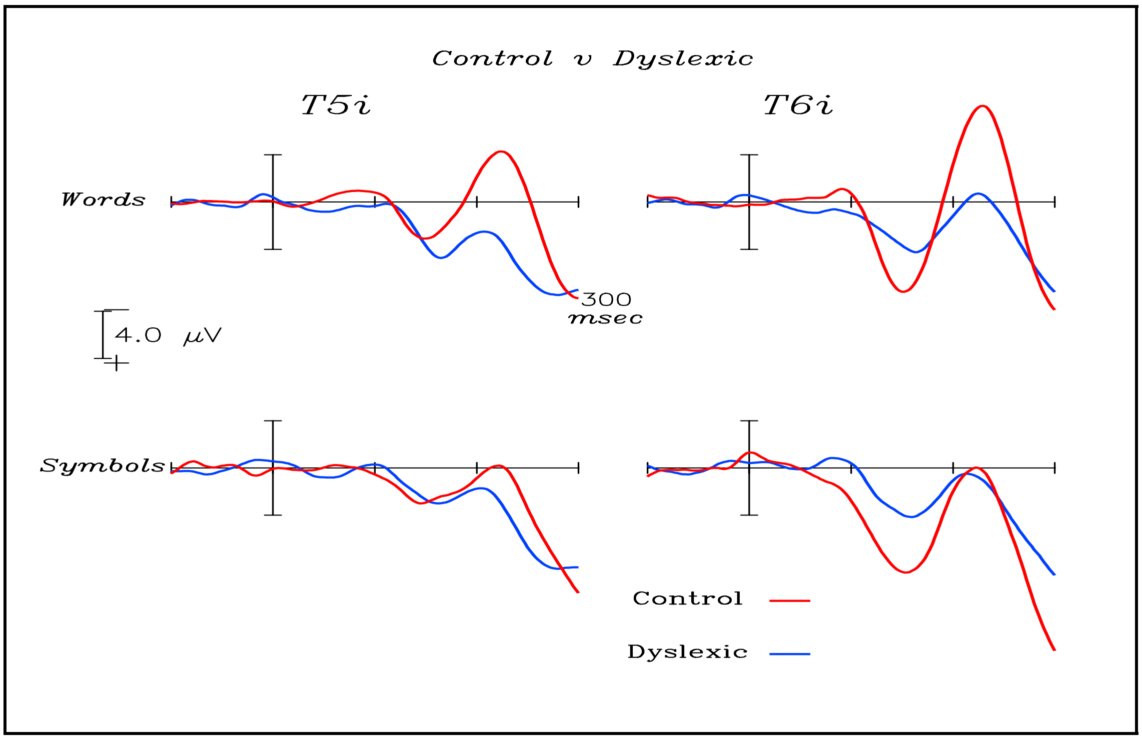


Figure 8. ERPs to Words and Symbols Contrasted at T5/6i

Fig 8. The ERP variable used in correlation and regression analyses was defined by subtracting the amplitude for Symbol Strings (bottom ERPs) from the amplitude for Words (top ERPs) at site T5/6 (collapsed across hemispheres). A Word-Symbol String (W-SS) variable was calculated for the control and dyslexic groups.

A correlational analysis was conducted to test the hypothesis that the language component processes (phonological, orthographic, automaticity) would be related to ERP activity (orthographic minus non-orthographic mean amplitude). Because hypothesis 3 presupposes that the language processes are related to basic reading skill, correlations were calculated for measures of word reading and decoding and are presented below in Table 8.

Table 8

Intercorrelations Between Reading, Language Processes & Word-Symbol Amplitude

	1	2	3	4	5	6	7	8	9
Reading Achievement (N=23)									
1. Word Reading	1	.779**	.239	.460*	.706**	.462*	.539**	.345	-.521*
2. Decoding		1	.320	.479*	.622**	.532*	.640**	.270	-.512*
Automaticity (N=23)									
3. Naming (Letters)			1	.315	.368	.394	.610**	.427*	-.297
Phonological (N=22)									
4. Phon Nonword Rep N=22				1	.403	.224	.514*	.318	-.538**
5. Phon Sound Deletion N=22					1	.592**	.539**	.486*	-.303
Orthographic (N=22)									
6. Word Choice						1	.649**	.529*	-.033
7. Coding							1	.467*	-.264
8. CPST								1	.092
ERP Variable (N=23)									
9. Words-Symbols Amplitude									1

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

ERP activity was significantly correlated with both reading measures while only one of the language measures was significantly related, Nonword Repetition, r(22) = -.54, p=.010). The other correlations with the ERP variable ranged from moderate to very small with the weakest found with Word Choice, r(22) = -.03, p=.884). Correlations between reading and language measures were all statistically significant with the exception of RANL and CPST. Word Reading and Pseudoword Reading were strongly correlated with Sound Deletion, r(23) = .71, p<.000 and r(23)= .62, p=.002, respectively) and Coding, r(23) = .54, p=.010 and r(23) = .64, p=.001). Examination of the relationships among the language measures found orthographic measures significantly intercorrelated at the level of .05 or .01, with the largest correlation between Word Choice and Coding, r(22) = . 65, p=.001). In contrast, the two phonological measures were only moderately correlated, r(22)= . 40, p=.063). RANL was significantly correlated with two orthographic measures, Coding, r(23) = .61, p=.003) and CPST r(23) = . 43, p=.047).

A series of multiple regression analyses were conducted to examine the prediction of hypothesis 3 that measures of phonological, orthographic and naming processes would predict ERP activity. ERP activity included in the regression was the Word minus Symbol String difference in mean amplitude during the 195-155 window (N230 Word-Symbol ERP). Change statistics and b and β coefficients for the regressions are reported in Table 9 below. Regressions were first conducted to determine the variance in Word-Symbol ERP accounted for by orthographic predictors alone, then the phonological predictors alone. Orthographic predictors (Word Choice, Coding, CPST) did not significantly predict variance of ERP amplitude, $R^2 = .14$, $F (3,18, N=22) = .980$, $p = .42$). Further, the regression coefficients reveal that of the three measures, only Coding had a relationship with the ERP amplitude in the expected direction. Phonological measures (Repetition, Sound Deletion) were found to predict a significant portion of variance in ERP amplitude, $R^2= .30$, $F(2,19, N=22) = 4.033$, $p =.03$). The regression coefficients reveal a strong relationship between ERP and Repetition with $\beta = -.50$ ($p < .05$).

To determine ERP variance explained by combinations of the language component processes, the two phonological variables, three orthographic variables, and naming were regressed onto the ERP criterion as separate blocks (see Models 3 and 4 in Table 9 below). In Model 3 orthographic measures (Word Choice, Coding, CPST) were entered in a simultaneous block after the phonological block (Sound Deletion and Nonword Repetition). In Model 4, Naming was entered in a third block to create the full equation with measures of phonological, orthographic and naming processes.

When Orthographic variables were included in the regression (Model 3) an additional 13% variance in amplitude was predicted, however, this increase did not significantly add to the prediction of variance beyond that accounted for by Phonological variables alone ($p = .35$). The inclusion of Naming accounted for an additional 7% of the variance ($p = .17$), thus the full model predicts 50% of variance in ERP amplitude. The standardized coefficients of Model 4 reveal that Repetition, Sound Deletion, and Naming have a relationship with ERP amplitude in the expected direction. Comparison across models showed no significant change in R2 after adding the orthographic block of variables to the Phonological model, or when adding RANL.

Examination of the regression coefficients across the models shows that when phonological and naming measures are in the model, the association between ERP amplitude and orthographic measures decreases in strength. The instability in orthographic beta weights (for coding and CPST) observed across models is not unexpected given the moderate level of collinearity indicated by intercorrelations among the language variables. The amount of ERP variance accounted for by Sound Deletion increased when the orthographic measures were added to the model. Finally, Nonword Repetition was found to be a strong and significant predictor of ERP amplitude, largely uninfluenced by the addition of other predictors in the model.

Table 9

Change Statistics and b and β Coefficients of the Regression of N230 Word-Symbol ERP on Measures of Orthographic, Phonological, and Naming Processes

Predictor Variables	Model 1 Orthographic[a]			Model 2 Phonological[b]			Model 3 Phonological Orthographic			Model 4 Phonological Orthographic Naming[c]		
Statistics												
R	.37			.546			.652			.705		
R^2	.14			.298			.425			.497		
Adj R	-.00			.244			.246			.296		
R Change	na			na			.127			.072		
F Signif.	.42			.035			.348			.165		
Coefficients	*B*	*SE*	*β*	*B*	*SE*	*β*	*B*	*SE*	*β*	*B*	*SE*	*β*
Repetition				-.28	.12	-.50*	-.29	.13	-.52*	-.30	.13	-.53*
Sound Deletion				.00	.14	-.10	-.20	.17	-.30	-.20	.17	-.29
Word Choice	.11	.23	.15				.00	.22	.12	.00	.21	.08
Coding	-.34	.21	-.47				.00	.21	-.09	.00	.23	.11
CPST	.28	.31	.23				.46	.28	.38	.54	.28	.46
Naming										-.27	.19	-.35
Group												

[a]Orthographic Variables: Word Choice (PAL), Code (Orthographic Coding, PAL), CPST (Colorado Perceptual Speed Task)
[b]Phonological: Repetition (Non-word Repetition, CTOPP), Sound Deletion (PAL)
[c]Naming: Rapid Automatic Naming-Letters
*p < .05

Summary

The control and dyslexic group were found to be similar in age, ethnicity, and IQ, but not similar by gender. The control sample consisted of significantly more females than males, and the opposite was true for the dyslexic group. Therefore, additional repeated measures ANOVAs were conducted using gender as a covariate. This is to control for the demographic differences in the two groups.

The strong orthographic effect in the control group was found in the first negative deflection in occipito-temporal regions peaking at 230ms post stimulus. This finding is interpreted in line with the word specific N170 reported in studies with adults (Bentin et al., 1999; Maurer et al., 2005). Very few ERP studies with children have examined the occipital N1 during word recognition processes; therefore, the robust orthographic N230 provides new information on the development of reading related visual processes. Additionally, the N230 orthographic effect was not present in the dyslexic group and the ERPs of the dyslexic group were significantly smaller than the ERPs of the controls for Orthographic, but not Visual forms.

A related question also investigated by this study was regarding the sensitivity of the N170 to variation in regularity within the orthographic stimuli. In other words, would there be amplitude differences elicited because words, pseudowords and consonant strings differ in degree of sublexical regularity (the legality of grapheme to phoneme correspondences). In the present study, the N230 was not modulated by sublexical regularity across words, pseudowords, or consonant strings.

Regression analyses were conducted to examine the association between orthographic measures and the N230 when the effects of phonological processing were held constant. Orthographic measures were not found to be significant predictors of variance in ERP amplitude, while phonological processing, specifically nonword repetition, remained a strong predictor of the N230.

Chapter 5: Discussion

The current investigation of electrophysiological activity of word recognition examined the occipito-temporal region for an orthographic specific sensitivity in normally developing readers and children with dyslexia. Event-Related Potential (ERP) and other neurophysiological methodologies have demonstrated in healthy adults that activity over the posterior scalp occurring within the first 200ms post-stimulus reflects visual specialization for orthographic forms (Bentin et al, 1999; Nombre et al., 1998; Tarkiainen et al., 1999). Thus the N170 elicited during word recognition has been proposed as an index of expertise for visual words that develops as a function of reading experience (Bentin et al., 1999; Cohen et al., 2002; Mauer et al., 2005). To date, only one study has investigated this reading-related visual expertise of the N1 in children (Mauer et al., 2005).

The goal of the current study was to examine ERP data recorded during an implicit word recognition task in a group of typically developing readers for evidence of orthographic specific activity. Furthermore, in the comparison between normally developing readers and children with dyslexia, a neurobiological deficit at the level of orthographic analyses was investigated. Finally, behavioral measures of reading and language were examined in relation to ERP activity.

ERP data revealed several robust orthographic effects. In the control group, the N1 (or N230) was significantly stronger for orthographic than visual forms. This finding provided confirmation of Hypothesis 1 and replicated (partially) the N170 effect consistently found in adult studies. Moreover, as this is only the second of such studies in children, these data contribute to current understanding of the development of automatic word specific visual processes. A strong group effect was found between the control and dyslexic group: significant group differences were found for ERPs elicited by orthographic word forms but not by visual forms. This group effect is an important finding regarding disruption of automatic word specific visual processes in children with dyslexia. Together these findings suggest that in normal readers a word specific specialization of the visual system develops gradually as a function of reading experience, and that the normal development of this specialization is impaired in hildren with dyslexia.

Tests of Hypothesis 2 found that the N230 was not modulated by variation in sublexical regularity (legality of letters combination) across the word, pseudoword, and consonant string conditions. Finally, tests of Hypothesis 3 revealed significant correlations between N230 amplitude and performance on measures of reading and phonological processing. Regression analyses found measures of phonological, not orthographic, processes to significantly predict variance in ERP amplitude. These findings are detailed in the sections that follow. A discussion of this study's limitations and directions for future research conclude the chapter.

N230 Orthographic Effect

The N1 or N170 ERP component in adults is considered an index of visual expertise for words that has been hypothesized as an outcome of reading experience. While the visual N1 is thought to develop in childhood, only one study has specifically examined this process in children (Maurer, et al., 2005). Furthermore, no studies have examined the N1 in children with dyslexia. The findings of the current study will be discussed first for the control group, then for the dyslexic group.

Control Group

Hypothesis One (a) was confirmed by significantly larger N230 amplitudes for orthographic word-types (words, pseudowords, consonant strings) than for symbol strings in the control group. The strong orthographic N230 replicated the central finding across the adult ERP and MEG studies (Bentin et al., 1999; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999) of a word specific visual expertise and extends the findings of the N1 examined in kindergarten-aged children by Maurer et al (2005). Compared to the visual N1 in adults (>200ms), the longer latency of this study's ERP (230 ms) is a reflection of developmental changes. The earlier onset of the N1 in adults reflects the faster, automatic word recognition that is theorized to parallel the age/experience related increase in reading fluency.

The orthographic N230 also extends findings of the N1 in children. The study conducted by Maurer et al (2005) with typically developing kindergarten aged children provided the first evidence that the N1 is sensitive to the effects of visual learning. This conclusion was based upon small N1 amplitudes that were present only in the children who had some knowledge of letters. In these children, the orthographic N1 was bilaterally distributed with the strongest effect occurring at channels T5/6 in the contrast between words and symbols, with a peak amplitude at 223ms. These data are remarkably similar to the N230 of the current study. Thus, the small orthographic N1 (223ms) was interpreted as evidence for the N1 as an index of experience with letters. However, because the effects were small and different than the N170 in topographic distribution, questions remained regarding the development of the orthographic specific N1. The present study was the second to examine the N1 during implicit word recognition in children, but the first for children with experience with reading. Thus, the strong orthographic N230 in the control group is consistent with the developmental hypothesis that visual word expertise increases with age and reading exposure and supports the understanding of the N1 as an index of reading related visual specialization.

In comparison to the adult N170, the child N1 is not lateralized to the left hemisphere. Maurer et al (2005) attributed the lack of left lateralization in kindergarten children to inexperience with reading and predicted the N1 to increase in strength and lateralization with age and experience with grapheme-phoneme conversion processes. The present findings are not entirely consistent with this prediction. The orthographic N230 was a very strong effect, yet was bilaterally distributed. Since the mean age of our control group was approximately 5 years older than Maurer's kindergartners, it is reasonable to suggest that the strength of the N230 developed over time and with reading experience. Therefore, the bilateral orthographic effect in these two studies is likely an indication of immature orthographic specialization that may become left lateralized over time as word recognition processes become increasingly automatic and reading becomes more fluent.

Dyslexic Group

The present study was the first to investigate the N1 during implicit word reading in dyslexia. The lack of orthographic specific activity of the N230 recorded in the dyslexic group provided confirmation of Hypothesis One and is in line with the findings of disrupted posterior reading system (Shaywitz et al., 2002). Moreover, the implications regarding visual specialization are strengthened by comparisons with the control group. Specifically, group difference in ERPs elicited by orthographic but not visual stimuli demonstrates that the attenuated activity in the dyslexic group is specific to words. Because the strength of the N230 to visual stimuli was approximately equal to that of the controls yet the orthographic ERPs significantly attenuated, the possibility of a diffuse reduction in responsiveness to visual stimuli can be ruled out in favor of a word-specific impairment. This finding is consistent with the fact that automatic word recognition is a crucial skill that is generally not found in children with dyslexia

The finding of atypical activity in the occipito-temporal ERPs is consistent with neuroimaging findings of posterior cortical activity disrupted during reading in adults with dyslexic adults (Brunswick et al., 1999; Helenius et al., 1999; Horowitz et al., 1998) and children with dyslexia (Shaywitz et al., 1998; Shaywitz et al., 2002). There are several mechanisms that could potentially contribute to impairment in visual word specialization and the associated abnormal activity in posterior regions in children with dyslexia. For instance, an impairment in the region, or in the projections feeding this region. Given that the occipito-temporal regions receive projections from the visual stream it would be reasonable to suggest that a reduced capacity for word specific visual feature analysis has a basis in low-level visual deficits in psychophysiological research (Lovegrove, Martic, & Slaghvis, 1986; Stein & Walsh, 1997; Demb, Boynton, Best, & Heeger, 1998) and ERP studies (Brandeis, Vitacco, & Steinhausen, 1994).

The specialization for orthographic stimuli found at the left inferior occipito-temporal channels consistently observed in adult studies has been discussed as a function of the Visual Word Form Area. Neuroimaging studies of the VWFA find that this region of the left hemisphere responds specifically to visual features of words and, as suggested by Cohen et al. (2000), is likely to be a the cortical generator of visual N1 activity at occipital-temporal sites during word recognition. Basic visual processes are implicated as mechanisms that could constrain orthographic processes during reading acquisition.

Sublexical N230 Sensitivity

Hypothesis 2 addressed the sensitivity of the N170 to variations in orthographic regularity. The N230 was not modulated by sublexical regularity across words, pseudowords, or consonant strings in either control or dyslexic groups. The lack of sensitivity to the legality of grapheme/phoneme correspondences lends further support for the N1 representing a reflection of orthographic specific activity occurring prior to the phonological analysis.

Previous studies of word reading and word recognition find contrasts among orthographic word types consistently elicit sublexical effects in later occurring ERPs, however, the modulation of early visual ERPs are not clear. Inconsistent findings may be due to task variation (for review see Maurer, 2005). For example, different levels of processing are induced when silently reading compared to passive viewing. Such task effects reduce ability to compare results across studies.

Relationship between the N230 and Language Processes

Tests of Hypothesis three found N230 activity was correlated with individual differences in reading and language abilities. Words minus symbol difference in mean amplitude was used in these analyses to quantify the degree of differentiation of orthographic from visual stimuli. Analyses found reading and language abilities significantly correlated with N230, yet none of the behavioral measures of orthographic processing were correlated with N230 amplitude. Regression analyses were conducted to further investigate the phonological, orthographic, and automaticity processes in relation to the N230. Orthographic measures did not significantly predict variance in N230 amplitude, in isolation, or when the contribution of phonological processes was held constant. This finding was somewhat unexpected. Given that the ERP activity is assumed to be a reflection of orthographic specialization of the visual system, some relationship with behavioral measures of orthographic processing was anticipated.

The finding that Nonword Repetition predicted variance in amplitude of the N230 is in line with psychophysiological and neuroimaging studies that have correlated phonological processing with activity in the posterior occipito-temporal regions. Recent investigations of posterior cortical networks in a developmental study of normal and impaired readers (Shaywitz et al., 2002) found individual's scores on word and pseudoword reading measures significantly correlated with posterior activation.

Summary

The N230 of the control group is consistent with the understanding of N170 in adults as a reflection of visual specificity for words. The N230 was similar to the N1 in preliterate children in its bilateral distribution and later latency, but similar to the N170 in adults in strength of amplitude**.** It is possible to speculate that the strong bilateral orthographic N230 indicates an intermediate stage in the developing visual word specialization. (Future studies with older children will address the question). Despite the lack of left lateralization, the automatic processing of visual words increases in speed and efficiency in normally developing children.

The lack of orthographic N230 in the dyslexic group suggests that visual specialization for orthographic word-types is developmental in nature and does not follow the same trajectory in children with dyslexia. Additionally, the absence of an orthographic N230 demonstrates impairment at a low level visual process that occurs prior to engagement of higher-level cognitive processes in reading.

Behavioral measures of reading and language abilities were significantly related to ERP activity associated with word-specific visual processes.

Limitations

This study's limitations pertain to demographics and size of the sample. Relative to comparable ERP studies the sample size was adequate, however, the numbers are low for behavioral studies of reading and language processes in children. There were significantly more boys in the dyslexic group. The unequal gender ratios were taken into consideration in the ERP data analysis. When included as a covariate in both between and within groups ANOVAs, gender did not significantly change the findings.

Developmental dyslexia was defined using a 20 point discrepancy between reading and IQ and those with comorbid psychiatric diagnoses were excluded. Therefore these results only generalize to children with a severe and specific impairment in reading processes.

Clinical Implications and Future Directions

Neurocognitive investigations of developmental dyslexia have established phonological processes as a core deficit underlying reading impairments (Shaywitz et al., 1998); basic visual processes and other low level sensory deficits have been implicated as well (Stein, 2001). Yet the frequent association between language processes and low level visual deficits is not understood. The comorbidity of such deficits can be conceptualized as independent manifestations of the same developmental deviation in phonological processes. This view concludes that low level visual deficits are an outcome of higher level language deficits (top-down), thus observed deficits in orthographic processes are secondary to the phonological impairments rather than a distinct function of reading with its own neurophysiological underpinning. An alternative explanation is that visual and phonological impairments are independent manifestations of the same developmental deviation. A final possibility is that deficits in phonological and orthographic language processes arise from low-level sensory deficit.

However, causality is not easily established, particularly when the functional neural networks in normal reading development are not understood. Therefore the study of dyslexia requires the investigation of typical reading development, both behaviorally and neurobiological. Temporal information is needed to inform the time course of activity in reading systems (Bentin et al., 1999; Coch et al., 2002). The visual N1 is significant to understanding the functional neural networks of reading because the point of word recognition is a marker for lexical access that occurs immediately prior to engagement of phonological processes. Understanding the time course of word recognition provides a reference from which to examine the properties of the visual cortex including the capacity to become specialized. The N230 is an electrophysiological measure of a distinct aspect of word reading. The maturational changes observed in the N1 reflect a reading related visual specialization that is necessary for fast automatic word recognition. Furthermore, the N230 as an electrophysiological marker of lexical access has clinical relevance for developmental dyslexia and is a good candidate for interventions targeting reading fluency.

Several recent reading interventions have used neuroimaging techniques to assess the changes in the brain pre and post intervention. Particularly relevant to the current study was a phonologically based reading intervention for children with dyslexia that used fMRI to investigate effects of the intervention targeting reading fluency (Shaywitz et al., 2004). This study found significant changes in occipito-temporal regions that were associated with increased reading fluency. The combination of neurobiological and educational approaches in reading intervention will contribute toward an understanding of the brain-behavioral relationships in reading, language and dyslexia (McCandliss & Noble, 2003).

The visual N1 as an electrophysiological measure of reading development is sensitive to plasticity of reorganization during reading acquisition. Future ERP studies are needed to replicate the current orthographic N230 in normal readers and children with dyslexia.

APPENDIX A

Word Recognition Task Stimuli and Electrode Positioning

Word Recognition Task Stimuli

Word type stimuli for one of four blocks. The bolded items were converted into “target” items by the experiment generator software used to design this task.

Words	Pseudo words	Cononant Strings	Symbol Strings	False Fonts*
BIKE	BAIM	BCCL	(#(>#{	
BRUNCH	BLOOCH	CNHFD	)=#	
CHESS	CHEED	FPGFWK	%#{#	
CLINCH	CREACH	TCMNS	**{)@)**	
DAY	FLEAR	LTNH	}%#{$	
FIR	FUG	TVJ	$>#	
GOLD	GOACH	MMT	=#/>	
GRAPE	GUD	MPKCN	**)#(**	
HITCH	JUCK	NMPS	((}#(	
MILE	KON	STTDM	)(%#	
NUT	**LEF**	NWK	//#=$	
PEA	LEIZE	PHVW	#%//	
PLANT	MIP	PJSR	#@#/$	
ROOM	PAB	**PTPTHP**	$#/	
SCHOOL	RAICH	**RLCZ**	=(#$(	
SPOT	**SLIRE**	CJPSM	#)(@	
STREET	SPROAT	FSCB	%#$#@#	
TAG	TAW	SRLRH	{)(#(	
TRAIN	**THRAIK**	TDJ	%#$#>	
TRUCK	VEED	**WCF**	<)#	
WORN	VOAM	WPVRCT	(#(>#{	
WOUND	WISS	ZFRQQ	)=#	
	YOSH	QZSCBG	%#{#	

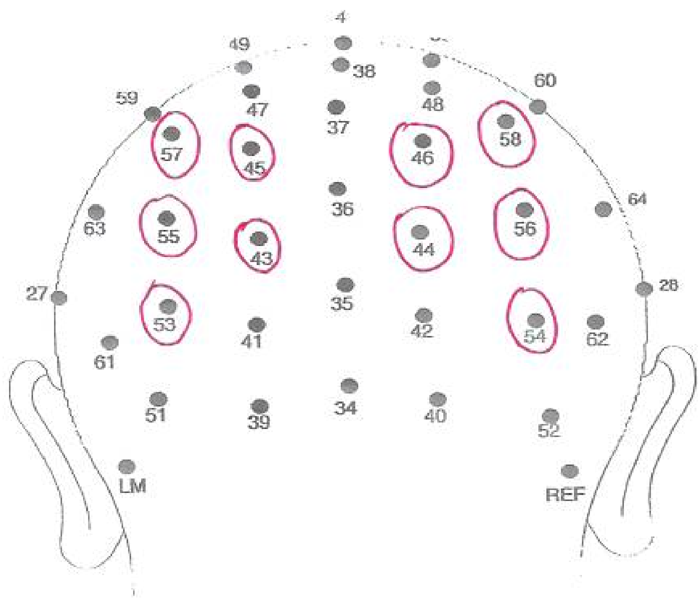
*False fonts not listed due to technical problem with platform compatibility; two false font stimuli are presented on following page.

Word Recognition Task: Target Items

List presented to participants prior to the practice trial along with task instructions
Left column contains non-target items, Right column contains targets.

BEAN	BEAN
SHORT	SHORT
FOB	FOB
PLON	PLON
#$##	#$##
{{@((	{{@((
RJK	RJK
HXQKF	HXQKF

Electrode Positions



Channels used in statistical analysis are circled.

TO 1 & 2 = 53/54
T5/6 inferior = 55/56
T5/6 superior = 57/58
O 1/2 inferior = 43/44
O 1/2 superior = 45/46

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