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Assessing Phonology, Syntax & Working Memory using ERP: Towards an Understanding of the Underlying Cause of Developmental Dyslexia

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Running head: UNDERSTANDING THE UNDERLYING CAUSE OF DYSLEXIA

Assessing Phonology, Syntax, & Working Memory using ERP: Towards an Understanding of the Underlying Cause of Developmental Dyslexia

by

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Abstract

Event-related brain potentials (ERPs) were recorded from 20 children with dyslexia and controls matched on age, sex, nonverbal reasoning, and handedness (ages 8-12 years) as they listened to and read sentences that varied in syntactic complexity and the working memory load they induced [subject-subject (SS) and subject-object (SO) relative clause sentences]. In each modality, control children demonstrated amplitude differences between the brainwave potentials elicited to each sentence type. When listening, controls and children with dyslexia did not differ in the N400 effect elicited in response to the relative verb of SO sentences, thus indicating auditory sentential processing occurred in a similar manner for both groups of children early in the sentences. However, by the later main verb region of SO sentences, thematic role assignment, as indexed by the left anterior negativity (LAN), was absent in children with dyslexia, indicating difficulty. Lack of an occurrence of a P600, an index of syntactic difficulty, suggested that rather than syntactic complexity, overtaxed working memory inhibited dyslexics' ability to assign thematic roles. When reading, the N400 effect was again demonstrated by each group at the relative clause of SO sentences; however children with dyslexia exhibited a latency delay in comparison to control children. Similar to auditory processing at the main verb, while reading only the control group demonstrated LAN effects in response to SO sentences structures. In order to investigate working memory capacity in more temporal detail, slow cortical potentials were measured over the full duration of the sentence. Results demonstrated that while both groups were able to utilize phonological working memory to store sentential information when listening to sentences, only controls could reliably do so when reading. The data indicates that the syntactic deficits inherent in dyslexia are mediated by phonological working memory. These results support the phonological limitation hypothesis posited by Shankweiler et al. (1992), which contends that all impediments related to dyslexia are mediated by a primary deficit in phonological processing.

Keywords: Developmental dyslexia, event-related brain potentials, phonological sensitivity, syntactic sensitivity, working memory, reading, sentence processing

Table of Contents

ASSESSING PHONOLOGY, SYNTAX, & WORKING MEMORY USING ERP: TOWARDS AN UNDERSTANDING OF THE UNDERLYING CAUSE OF DEVELOPMENTAL DYSLEXIA

The foundations of literacy are based on a variety of linguistic factors. Failure to adequately develop even one of these skills can lead to reading difficulty (Bowman & Treiman, 2004). The current study aimed to examine the role that phonological sensitivity, syntactic ability, and working memory play in developmental dyslexia. Currently, researchers debate the underlying cause of the disorder. It has been posited that difficulties stem from a low-level phonological deficit (Shankweiler, Crain, Brady, & Macaruso, 1992). Research has already shown deficits inherent to the disorder, such as working memory, are mediated by this skill (Gottardo, Stanovich, & Siegel, 1996). Alternatively, it has been suggested that reading difficulties are caused by a more general linguistic deficit (Tunmer & Hoover, 1992). In order to address this debate, the current study assessed the function of working memory in children's processing of complex syntactic structures. Two forms of relative clause sentences were utilized: subject-object relative clause (SO; e.g., *The girl who the boy chased caught the fish*) and subject-subject relative clause sentences (SS; e.g., *The boy who chased the girl caught the fish*). Linguistic processing was examined while children listened to and read these sentences. These modalities were compared as a means of dissociating deficits caused by phonological ability and those caused by syntactic ability. The current study utilized event-related brain potentials (ERPs) in order to elucidate the specific timing and sequencing of atypical and typical language processing in children.

Theoretical Approaches to Dyslexia Research

Dyslexia is currently defined as a specific language handling disorder, characterized by reading and spelling deficiencies in the absence of visual and auditory sensory deficits [American Psychiatric Association (APA), 1994; Canadian Learning Disabilities Association (CLDA), 2002]. However, impediments extend to a multitude of other linguistic skills including; vocabulary, automaticity, grammatical and syntactic awareness, working memory, reading fluency, and in particular, decoding and other phonological awareness proficiencies (Gottardo et al., 1996). These deficits occur despite average intelligence, instruction, and socio-cultural opportunities (APA, 1994; CLDA, 2002; Frith, 1985).

Due to the results of countless studies, it is now widely agreed that dyslexia involves a substantial phonological deficit (Bowey, 1986; 2005; Chiappe, Chiappe, & Gottardo, 2004; Gottardo et al., 1996; Stanovich, 1992). A more contentious issue however, has been the underlying cause of the disorder. The phonological limitation inherent in reading difficulties has led to the suggestion that all deficits synonymous with dyslexia can be reduced to this one overarching limitation, a theory known as the Phonological Sensitivity Approach (PSA). A prominent example of this sentiment is the phonological processing limitation hypothesis proposed by Shankweiler et al. (1992). They suggest that knowledge gained through phonological processing is passed on through working memory in order to substantiate other areas of linguistic processing, such as syntactic, semantic, and pragmatic understanding. Shankweiler et al. (1992) compare this flow of information, for those with a low-level phonological impediment, to a bottleneck, where transfer of information is gradually reduced all the way through to the highest levels of the linguistic system. The amount of delay caused by the bottleneck in other processing systems depends on the severity of the phonological impediment. The phonological limitation hypothesis even accounts for a pervasive, seemingly non-linguistic characteristic of dyslexia, low working memory capacity; less defined phonological traces can lead to the inefficient storage of phonological information, and therefore, working memory limitations [Chiappe et al., 2004; Scientific Language Corporation (SLC), 2001].

In contention with the PSA however, a number of studies have found other language abilities to be independent predictors of reading achievement, once phonologically based measures (such as decoding and working memory) have been taken into account (Siegel & Ryan, 1988; Tunmer & Hoover, 1992). For example, Catts, Fey, Zhang, and Tomblin (1999) found that in good and poor grade 2 readers, both phonological and oral language abilities account for independent variance in reading ability, suggesting that other language skills, aside from phonological processing, are important in reading acquisition (Catts et al., 1999). Findings that other language related skills predict reading achievement, when phonological ability is partialled, are problematic for the PSA. It has been reasoned that if the underlying cause of dyslexia is phonological in nature (i.e., PSA), measures of phonological sensitivity should explain all unique variance in reading skill when other measures, such as grammatical sensitivity or working memory, are partialled (Bowey, 2005). In the same vein, findings that other language measures predict independent variance in reading ability suggests an alternative underlying cause of dyslexia.

Studies implicating the importance of other language skills in reading acquisition have challenged the PSA, leading to approaches that attempt to account for the unique variance explained by other linguistic skills. In contrast to the PSA, researchers who prescribe to the Comprehensive Language Approach (CLA), such as Tunmer and Hoover (1992), hypothesize that dyslexia is not a purely phonological disorder, but that it involves difficulty in a metalinguistic capacity (Dickinson, McCabe, Anastasopoulos, Peisner-Feinberg, & Poe, 2003;

Tunmer & Hoover, 1992). They contend that the variety of impediments seen in dyslexia, including phonological sensitivity, can all be attributed to this more global linguistic deficit. Behavioural research that indicates language skills, aside from phonological sensitivity, explain unique variance in reading ability can be seen as evidence of general language impairments. More specifically, a branch of CLA research has focused on a specific set of skills that in past studies have explained some unique variance in reading ability, grammatical or syntactic awareness (Leikin, 2002; Siegel & Ryan, 1988; Tunmer & Hoover, 1992).

To date, studies that suggest syntactic awareness accounts for unique variance in word reading ability remain outnumbered by studies demonstrating the sole predictive strength of phonological awareness (Gottardo et al., 1996). Furthermore, in these past studies that demonstrate an independent role for grammatical ability, there is evidence that working memory (and therefore, phonological awareness) may be the underlying cause. For example, Siegel and Ryan (1988) tested phonological, syntactic, and working memory abilities in children aged 7-14 years, with and without reading impairment. Along with phonological deficits, reading impaired children performed below other children on grammatical tests. Siegel and Ryan (1988) concluded that grammatical deficits were not dependent on working memory limitations because children did not differ on a sentence repetition task, except in the youngest age group, 7-8-year-olds. However, working memory limitations are a common finding in dyslexia research, even affecting adult populations (Brown, Gottardo, & Ferretti, unpublished data). Particularly since younger children differed on the working memory measure, there is the potential that the task used was simply not sensitive enough to capture working memory differences in older children.

Several studies have suggested the role of syntax is mediated by phonological processing ability. Even so, behavioural studies have had difficulty pinpointing the precise mechanisms underlying low-level phonological awareness deficits. For example, Bowey (1986) found that in good and poor fourth-fifth grade decoders, syntactic ability was more highly correlated with decoding skill than reading comprehension, even when differences in vocabulary were statistically controlled. This finding led Bowey to suggest that both abilities are measures of a higher order linguistic factor, such as phonological awareness. However, the nature of the study did not specifically suggest that this primary factor is linguistic in nature. In fact, an equally likely interpretation is that the higher order factor is instead, metacognitive in nature.

More recently, studies have attempted to make causal predictions regarding the contributions of phonological and syntactic awareness in specific reading skills. For example, Gottardo et al. (1996) found that in third graders, grammatical sensitivity did not predict significant unique variance in pseudoword reading once phonological sensitivity and verbal working memory were controlled. In contrast, phonological sensitivity remained a strong predictor once these other variables were considered. This study represents a step forward in pinpointing the root deficit in dyslexia; however, researchers have further argued that these types of studies make artificial predictions in that they are predicting reading development in a sample of children who have already begun developing reading skills. Researchers maintain that predictive studies should begin in preliterate age groups and subsequently chart progress longitudinally, as reading skill develops (Bowey, 2005). Otherwise, certain aspects of the reciprocal nature of grammatical sensitivity and reading ability may be overlooked or all together ignored.

In response to this criticism, Bowey (2005) longitudinally measured phonological and grammatical ability in 4-6-year-olds. Grammatical sensitivity was predicted by earlier language ability, as opposed to cognitive ability, similarly suggesting phonological ability is the underlying factor in reading acquisition. A logical next step would be to define those processes imperative to early language ability. However, in this respect behavioural studies encounter limitations. Generally, in order to effectively test children, they must have reached an age where they can be expected to reliably focus and respond to linguistic tasks. However, this does not necessarily mean that children cannot make linguistic judgments prior to preschool age. Researchers have suggested that precursors to reading acquisition emerge much earlier than previously thought and that the neurological origins are speech perception based (Scarborough, 1990; Friederici, 2002). Furthermore, these abilities appear to be so subtle that behavioural studies are unable to detect future reading difficulties based on early language development. For these reasons, researchers have begun to employ ERP methodology in order to more closely examine the underlying deficits in disorders such as dyslexia.

Electroencephalography (EEG) is the recording of electrical activity generated by the brain reflecting the sum of simultaneous postsynaptic firing in a large population of neurons. Event-related brain potentials (ERP) are the recordings of these voltage fluctuations at the scalp, via an electroencephalogram, when they are time-locked to the occurrence of a particular stimulus (Lewine & Orrison, 1995). ERPs represent a more precise, real-time method of studying language processing as it develops in children. Behavioural responses (and sometimes active attention) are not necessary, making it an ideal method when dealing with very young populations or those unable to articulate a response. In the case of reading populations, children are free to silently process the information for comprehension, thereby limiting the confounds caused by oral reading anxiety or embarrassment. Importantly, ERPs also have well established components associated with specific perceptual, attentive, mnemonic, syntactic, and semantic levels of processing. Furthermore, qualitative differences in processing specific stimuli can be demonstrated in terms of latency and amplitude variation in each distinct ERP component. From a developmental perspective, this can be helpful in elucidating not only processing differences between specific groups (such as those with and without reading impairments), but also natural age differences in processing (and ERP components) related to the developmental maturation of specific processes. Lastly, ERPs have excellent temporal resolution which can help in pinpointing the exact time-course of reading processes, aiding in the dissociation between those deficits primary to dyslexia, versus those that are more secondary.

Recently, researchers have begun to utilize ERP in order to focus on the specific contribution of phonological processing in later reading success. Specifically, studies have focused on the possible predictive relationship between exact ERP components that emerge early in life and later language and reading ability (Espy, Molfese, Molfese, & Modglin, 2004; Friederici, 2005). For example, for children that later experience reading delays, relationships have been noted between ERP components that emerge in the first weeks of life and linguistic and reading ability at the age of 8 (Espy et al., 2004). These findings suggest that from very early in life, infants who will later become less proficient readers must utilize more resources in order to perceive auditory stimuli than those who become average readers (Espy et al., 2004).

Studies utilizing early occurring ERP components, such as that presented by Espy et al. (2004), have given insight into the auditory system's attunement and attention toward phonological discrepancies. Such studies are informative in that they demonstrate the phonological processing differences between later good and less proficient readers at an extremely early point in life. However, they do not clearly identify phonological difficulties as the primary deficit in dyslexia. This has lead to studies that attempt to pinpoint the specific level of processing where difficulties arise (Bonte & Blomert, 2004; Georgiewa et al., 2002;

Lachmann, Berti, Kujala, & Schröger, 2005). For example, it has been shown that difficulties for children with dyslexia arise at the word, as opposed to nonword, level of an alliteration priming task, indicating differences are occurring at the lexical or phonological level of auditory processing (Bonte & Blomert, 2004). Additionally, further ERP and fMRI research suggests that during phonological processing tasks, such as pseudoword reading, increased effort, on the part of children with dyslexia, is due to attempts to access phonological codes in working memory (Bonte & Blomert, 2004; D'Arcy, Connolly, Service, Hawco, & Houlihan, 2004; Georgiewa et al., 2002; Lachmann et al., 2005). In other words, the difficulty arises specifically during grapheme to phoneme conversion tasks (Lachmann et al., 2005).

The previously mentioned studies represent a major advance in the linkage between early speech perception ability and later reading acquisition. However, to date, research in the field remains focused on perceptual and word-level linguistic judgment tasks (Bonte & Blomert, 2004), even in literate age groups. Few studies directly examine on-line sentential reading ability in language impaired children. In order to fully utilize the strengths of ERP, it would be beneficial to conduct studies focusing on complex language processing. Potentially such studies could elucidate the sequence and timing of linguistic skills, such as phonological processing, working memory, and syntactic awareness. Studies focused on complex reading could also shed light on the independent and connecting roles of these skills, thereby clarifying underlying abilities important to reading development. Particular consideration of the later occurring cognitive waveforms could provide insight in deciphering the underlying deficit in dyslexia. Many of these waveforms are specifically implicated in linguistic processing and also associated with a particular skill of interest to reading researchers. The temporal precision of ERP could allow for the sequential dissociation of measures such as semantics, working memory, and syntactic processing. Therefore, several of these waveforms were investigated in the present study. For the purposes of the current research project, generally more negative amplitudes of a component elicited in response to one condition relative to another suggest more effortful processing.

One of the most thoroughly researched components in the linguistic literature is the N400.This central-parietal negativity, occurring at approximately 400 msec post-stimulus onset, has been shown to index semantic integration. The component was first demonstrated in response to analogous terminal words (in contrast with appropriate terminal words) in visually presented sentences (e.g. *The pizza was too hot to table*; Kutas & Hilyard, 1980). Since then, the N400 has been utilized in response to speech, as well as other meaningful stimuli, such as pictures. Research has shown that semantic manipulations modulate the amplitude of the N400 in such a way that the easier a stimulus is to integrate with its preceding context, the more reduced the amplitude of the N400. In children, the same effect has been observed, however, in comparison with adults, children demonstrate both longer latencies and larger amplitudes, which decrease with age (Holcomb, Coffey, & Neville, 1992). For example, Atchley et al. (2006) demonstrated that in comparison to adults, the N400s elicited by typical 8-13-year-olds in response to semantic anomalies are delayed by 75 msec on average. It has been suggested that reductions in amplitude specifically relate to children`s decreased reliance on semantic context over time, as their language skills improve (Holcomb et al., 1992). Interestingly, several studies indicate a more anterior scalp distribution in children, as opposed to adults (Atchley, Rice, Betz, Kwasny, Sereno, & Jongman, 2006; Holcomb et al., 1992). It has been suggested that this difference may reflect the presence of a second and overlapping negative waveform only seen in children, indexing focused attention or arduous processing (Holcomb et al., 1992). In studies where maximally frontal distributions have not been demonstrated, waveforms are still more highly distributed throughout various regions of the scalp in comparison to the adult N400 topography (Friederici & Hahne, 2001).

Research on the processing of semantic anomalies in children with and without dyslexia has demonstrated that results are affected by the modality of presentation (Neville, Coffey, Holcomb, & Tallal, 1993; Sabisch, Hahne, Glass, von Suchodoletz, & Friederici, 2006). Studies testing linguistic processing in the aural modality have shown that 9-13-year-olds in both groups demonstrate similar N400s, both in amplitude and scalp distribution (Sabisch et al., 2006). In contrast, Neville et al. (1993) have shown that language impaired children exhibit more negative N400s to anomalous sentences endings compared to typical readers of the same age, signifying a greater effort to contextually integrate semantic information. By comparing these two studies, it may be suggested that the added demand of the phoneme to grapheme conversion specifically was more taxing for the children with language impairments. Interestingly, a subset of the language impaired children in the Neville et al. (1993) study who demonstrated difficulty with grammar, also exhibited atypical (right) hemisphere specialization in response to target words. It remains unclear what effects grammatical difficulty has on reading, particularly because the language impaired children in this study were a heterogeneous group and the study did not have a clear syntactic manipulation.

Syntactic Processing and Language Ability

Syntax Development in Children

Surprisingly few studies have examined syntactic development in children, and even fewer have used on-line methods. Recent studies have shown that children, like adults, process language incrementally (Nation, Marshall, & Altmann, 2003; Neville et al., 1993; Oberecker, Friedrich, & Friederici, 2005; Trueswell, Sekerina, Hill, & Logrip, 1999). As well, children as young as 3 years demonstrate awareness of word order constraints, particularly verb position (Höhle, Schmitz & Ischebeck, 2000; Höhle & Weissenborn, 1999). However, differences in the ways adults and children process grammar have been noted. Until the second or third grade, children are incapable of processing syntax without relevant semantic contextual information (Friederici, 1983). Until this point, children rely on a fixed word order to assign thematic roles, allowing them to focus on semantic interpretation instead of grammatical structure (Friederici, 1983; SLC, 2001). A thematic role denotes the role or actions (denoted by verbs) performed by the subject (denoted by nouns) of a particular sentence (McRae, Spivey-Knowlton, & Tannenhaus, 1998). The specific subject may be either an agent or patient of a given action in a sentence. Agents typically initiate actions, while patients instead are the recipients of the action. For example, in the sentence, *The girl hit the boy*, the girl is filling the agent role while the boy is filling the role of patient. The voice of a sentence denotes which thematic role a subject in a given sentence is assuming, either agent or patient. In the case of active sentences, the subject in a sentence assumes an agent role, while a subject in a passive sentence assumes the role of patient. Thematic role assignment is necessary for sentential comprehension because it enables the reader to decipher who is doing what to whom (McRae, Ferretti, & Amyote, 1997). These relationships cannot be assessed until a verb is reached in a sentence. For children, sentences that deviate from the expected subject-verb-object (S-V-O) order can sometimes lead to mistaken interpretations. For example, *He was called by her* may be instead interpreted as a S-V-O sentence, and therefore as: *He called her* (SLC, 2001).

It has also been shown, that children, like adults, extract thematic role information from verbs quickly in order to assign agents in a sentence (Nation et al., 2003). Nation et al. (2003)

used an eye-tracking device in order to monitor children's eye movements as they listened to spoken sentences with visual aids. Sentences contained either neutral (in relation to the visual aids) (e.g., *Jane watched her mother choose the cake*; all objects displayed were choosable) or supportive verbs (e.g., *Jane watched her mother eat the cake*; cake was the only displayed object that was edible). During supportive verb sentences, children anticipated the target object by quickly shifting their gaze significantly earlier than in the neutral condition (and well before the target noun was uttered). Unlike adults however, children under the age of 7 or 8 years frequently make thematic role assignment errors, by tending to associate a word's thematic role with the verb in closest proximity (Minimum Distance Principle) (SLC, 2001). For example, in sentences such as, *She brushed the hair of the short girl all by herself*, children may become confused as to whom *all by herself* modifies. In the current study, thematic role assignment will be further investigated using an ERP component known as the left anterior negativity component.

In the ERP literature thematic role assignment has been reflected in a left anterior negativity (LAN) occurring 300-500 ms post-stimulus. This component was first described by Kluender and Kutas (1993) in a study that looked at sentences containing long distance dependencies. In addition to the presence of a LAN effect in response to thematic role assignment, more generally, LANs have also been elicited at sentential areas where there is substantial working memory load. This has led researchers to suggest that all sentences that initiate expectations of a later occurring thematic role assignment generally impose a burden on working memory (Kaan, Haris, Gibson, & Holcomb, 2000; Kluender & Kutas, 1993). Furthermore, the LAN is an index of that working memory load, with stimuli involving more difficult integration eliciting larger amplitudes than those that involve less integration (King & Kutas, 1995; Müller, King & Kutas, 1997).

In children, LAN effects in response to thematic role assignment have been demonstrated as early as 2.8 years (Oberecker et al., 2005). Oberecker et al. (2005) had children listen to active simple sentences with either syntactically appropriate (e.g., The lion roars /is roaring) or analogous endings (e.g., The lion in the roars/is roaring). The LAN occurred within its respective time window in response to those sentences that required more integration, analogous sentence endings. However, as would be expected in childhood waves, particularly at this early stage, the component was delayed approximately 100 ms in latency, indicating neuronal development of syntax comprehension is still actively taking place (Oberecker et al., 2005). Interestingly, passive sentence structure processing has been shown to develop much later (Hahne, Eckstein, & Friederici, 2004). When faced with passive syntactically appropriate and anomalous endings, Hahne et al. (2004) found that adult-like early LANs were not elicited to anomalous sentence endings until 13 years and not elicited at all in 6-year-olds. However, 6-year-olds performed above chance on the task, indicating that the early LAN may only index automatic levels of processing. Evidently, in this early age range, automaticity has not been obtained (Hahne, 2004). Interestingly, children between 7-10 years elicited a sustained anterior negativity. It was speculated that this wave was a developmental precursor to the adult early LAN (Hahne et al., 2004).

Syntactic Sensitivity Deficits in Readers with Dyslexia

Syntactic processing has seldom been studied in dyslexic readers, particularly in children. Recently, using ERP methods, Leikin (2002) found evidence supporting a syntactic deficit in Hebrew speaking adult dyslexics. During an oddball paradigm, adults with dyslexia elicited a significantly delayed early ERP component indexing short term memory when compared with controls. Participants were also given a reading task in which the sentential roles of subject, predicate, and object were interchanged with the same noun. Dyslexics demonstrated significantly enhanced early ERP component amplitudes in response to the predicate. In comparison to controls, dyslexics also displayed a delay in syntactic processing for all three grammatical roles, delays in attentional shift processing in response to subjects, and delays in short term memory processing in response to objects (Leikin, 2002). Leikin (2002) suggests these differences support a syntactic deficit in dyslexia.

Due to the highly inflective nature of the Hebrew language, word order can be extremely malleable (Leikin, 2002). Therefore paradigms, such as the one employed by Leikin (2002), are possible in Hebrew while maintaining the integrity of the sentence. However, in a language such as English, where word order is generally fixed, this paradigm is not possible (Leikin, 2002). The differences between the two languages may manifest in different syntactic difficulties in dyslexics. Furthermore, a methodological element of this study is worth noting. Behavioural measures of reading time and comprehension were first taken and later used to assess each individual's ERP presentation rate (Leikin, 2002), an unusual occurrence in the ERP literature. While allowing each participant to read at their own pace may have its advantages, it allows for considerable variability within the experiment. In fact, particularly in the case of dyslexic and other poor readers, it has been suggested that attempts at fluent reading speed are more important than accuracy for both comprehension and motivation (Lyytinen, Guttorm, Huttunen, Hämäläinen, Leppänen, & Vesterinen, 2005). This is particularly relevant when considering several of Leikin's findings. For example, generally differences between participants with and without dyslexia were confined to latency effects in each component (Leikin, 2002). Latency delays are often a sign of delayed, yet qualitatively similar processing as that demonstrated in controls (Neville et al., 1993). It is possible that increases in sentence duration for the slowest readers (presumably dyslexics) caused extraneous working memory load, thereby increasing the difficulty of the task and leading to latency delays. Furthermore, an earlier component of interest in this study was actually a specific index of short-term memory. The confound of working memory and grammatical processing, caused by discrepancies in sentence presentation rate, makes it difficult to determine which is causing significant differences between young adults with and without dyslexia.

Further research is necessary in order to elucidate the role of syntax in language learning. Regardless of the role of syntactic processing in dyslexia, generally, more information is needed on how grammatical processes are developed and executed. However, findings that syntactic sensitivity independently contributes to reading ability are problematic for theories that emphasize a phonological deficit in reading impairments. In an attempt to research syntactic processing, past studies have inadvertently confounded syntax and working memory abilities. Further study of the relationship between syntax and working memory is warranted, in particular, a focus should be placed on their individual roles and the interaction between the two variables, if any.

The Relationship Between Syntax and Working Memory

The sentence types used in the current experiment are those that have been used in the past to study both syntactic ability and working memory in adults (Brown et al., unpublished data; King & Just, 1991; King & Kutas, 1995; Müller et al., 1997; Traxler, Williams, Blozis, & Morris, 2005). They contain embedded subject and object relative clauses. For example:

1a) *The girl who chased the boy caught the fish.*

1b) *The girl who the boy chased caught the fish.*

The first (1a) is known as a subject-subject relative clause sentence (SS), because the subject of the main clause (*the girl*) is also the subject of the embedded relative clause (i.e., The girl is both the agent chasing the boy and catching the fish). In contrast, the second sentence (1b) is known as a subject-object relative clause sentence (SO) because the subject of the main clause (*the girl*) is the object of the relative clause (i.e., *The girl* is the patient of the relative clause because she is the person *who the boy chased*, and at the same time, she is also the agent of the main clause, *who caught the fish*). From reading these two sentence types, one instinctually feels that SO (1b) sentences are more difficult than SS (1a) sentences. This difference in difficulty between the two sentences has been attributed to two sources, variation in syntax difficulty and in working memory load (King & Kutas, 1995; Müller, et al., 1997; Traxler et al., 2005).

SO sentences have been shown to be syntactically more difficult for a variety of reasons (King & Kutas, 1995; Traxler et al., 2005). As was previously discussed, word order in the English language is generally fixed, so that sentences usually occur in an S-V-O pattern. Furthermore, 95% of these cases occur in the active voice (ie., where an agent 'verbed' or 'verbs' a patient). When a noun phrase (NP) is encountered in a sentence, readers generally expect a verb to follow, due to the frequency of this pattern in the English language. SS sentences deliver this expected order pattern. Upon encountering the verb *chased*, the previously encountered NP is immediately assigned its already assumed thematic role of agent, both of the main and relative clause. On the other hand, instead of following the predicted agent pattern, SO sentences continue with the article *the*. This article serves as a signal to the reader that a main verb interpretation of the sentence is no longer valid with the information read. Readers must then pursue the alternative relative clause reading. As well, two different thematic role assignments must be made in this case; upon encountering the verb *chased*, the initial NP is assigned the role of relative clause patient. However, once the reader reaches the main clause verb, *caught*, the initial NP is assigned a second different thematic role, that of main clause agent.

These syntactic differences noted between the relative clause sentence structures also cause added working memory load in SO sentences relative to SS sentences (King & Kutas, 1995; Müller et al., 1997). According to Baddeley's (1986) model of working memory, the memory system is broken down into specialized subsystems, all controlled by the Central Executive. These subsystems are responsible for holding information in an active state until further use. When related back to the linguistic task at hand, both SS and SO sentences involve holding a NP (*the girl*) in working memory until its thematic role can be assigned. However, in SO sentences, like 1b, this does not occur until the main clause verb of the sentence, *caught*, has been reached. All the while the head NP is being held active in working memory, readers are multi-tasking, assigning a separate thematic role to the relative clause NP (*the boy*). In contrast, SS sentences, such as 1a, involve relatively incremental processing, where the head NP is assigned its thematic role almost immediately (*chased*).

Just and Carpenter (1992) further Baddeley's (1986) theory by suggesting the same pool of working memory resources is shared across cognitive tasks, such as the activation of relevant information and the execution of specific processes. Therefore, when the working memory system becomes overtaxed, one of these specific operations must take priority. When related to language processing, certain complex linguistic tasks (i.e., SO sentences) involve the use of further resources than simpler sentences (i.e., SS sentences). If this overtaxes the pool available, either efficiency or accuracy will suffer (Just & Carpenter, 1992). Pertinent to this theory, many studies have found that differences seen in adults linguistic processing are actually mediated by working memory capacity (Just & Carpenter, 1992; King & Just, 1991; King & Kutas, 1995; Müller et al., 1997).

These theories of working memory were originally tested using behavioural reading time (RT) studies that found differences in the speed with which participants, with either high or low working memory capacity, read SO sentences (King & Just, 1991). However, the RT measure was not sensitive enough to demonstrate the subtle differences between sentence type processing hypothesized at the relative clause verb. The paradigm was later tested utilizing ERP (King & Kutas, 1995). Indicative of increased working memory load, adults demonstrated increased LAN effects in response to SO rather than SS sentences at the two areas of interest, the relative and main verb clause. When divided by group, poor comprehenders elicited a significantly more pronounced LAN in response to relative clause verbs than did good comprehenders (King & Kutas, 1995). In addition, poor comprehenders elicited a significant N400 at the beginning of the relative clause, indicating they were less likely than good comprehenders to generate a SO reading of the sentence, as opposed to the predicted main clause verb reading. Both findings indicate that poor comprehenders were more impacted by increased working memory demands because of their more limited working memory capacity (King & Kutas, 1995).

Furthermore, King and Kutas (1995) described a waveform, the slow cortical potential (SCP), that will also be further investigated in the present study. They demonstrated that by taking longer epochs, a frontally developing wave was elicited over the full duration of a sentence that was an indication of working memory load. The wave was found to be relatively more negative in response to SO sentences that are more taxing to working memory, as opposed to SS sentences.

Since King and Kutas' (1995) initial findings, further studies have substantiated the view that SCPs are sensitive to the ease of sentence integration and should be considered a measure of working memory (Ferretti, Schwint, & Katz, 2007; Müller et al., 1997; Schwint, Ferretti, & Katz, 2006). For example, an auditory modality comparison of low and high comprehenders on SO and SS sentence processing has yielded similar results (Müller et al., 1997). However, visual and auditory SCPs sometimes vary in scalp distribution. While visual SCPs tend to occur bilaterally, auditory SCPs generally have a right to bilateral topography (King & Kutas, 1995; Müller et al., 1997). To the extent of the researcher's knowledge, the current study represents the first work on SCPs elicited in children.

Relative Clause Processing in Children

Little is known about the ways children process complex linguistic structures, such as relative clause sentences. It has been found that children are not able to understand these sentence types, particularly SO sentences, until the second or third grade (SLC, 2001). This may be because these sentence types violate a number of linguistic expectations children rely on, particularly when working memory becomes overtaxed (SLC, 2001). SO sentences not only contain the complexity of multiple clauses and an instance of passive voice, they also violate both expected word order and the minimum distance principle (SLC, 2001).

Previous work has demonstrated that children's more limited working memory capacity does affect their ability to resolve syntactic ambiguity (Hurewitz, Brown-Schmidt, Thorpe, Gleitman, & Trueswell, 2000; Trueswell et al., 1999). Trueswell and colleagues gave children visual referential contexts (e.g., one or two frogs shown), in order to guide their interpretation of phrases such as, *Put the frog on the napkin* (one-frog context, destination interpretation) and *Put the frog on the napkin in the box* (two-frog context, modifier interpretation). While older children (8-9-year-olds) generally behaved like adults, differentiating between the two interpretations correctly, younger children (4-5-year-olds) repeatedly followed a destination interpretation of the phrase, regardless of referential context. Furthermore, a subset of the older children behaved in a similar manner to the 5-year-olds, incorrectly interpreting the modifier interpretation of the phrase (Trueswell et al., 1999). More recent work has demonstrated that difficulties in correctly carrying out the request did not stem from an inability to comprehend referents (Hurewitz et al., 2000). When asked, "Which frog goes in the box?," children correctly responded by saying, "the one on the napkin" (Hurewitz et al., 2000). Incorrect interpretations instead were postulated to result from children's inability to hold alternative interpretations in mind over an extended period of time (Hurewitz et al., 2000; Trueswell et al., 1999). These results could be interpreted using theories of working memory already discussed, suggesting this subset of children's limited resources were already overtaxed, leading to inefficient processing (Just & Carpenter, 1992).

Interestingly, working memory may also take into account differences in childhood ERP components elicited by complex sentential structure, such as passive voice (SLC, 2001). As King and Kutas (1995) noted, LAN effects may be more pronounced in response to sentences that involve substantial working memory load, such as SO sentences that violate word order expectations. Similarly, passive voice also involves a change in subject and object order, substantially adding to working memory load for children (SLC, 2001). This interpretation of the LAN could account for Hahne et al.'s (2004) finding that children aged 7-12 comprehend passive voice sentences, yet do not generate adult like early LANs. Instead, the children tested demonstrated a sustained bilateral anterior negativity. This response could be indicative of increased syntactic working memory demands in these younger lower capacity children (Oberecker, et al., 2005). These studies of children seem to suggest that syntactic ability may be mediated somewhat by working memory capacity. Further research in this area could shed light on the interaction between these two variables in developmental dyslexia research. For that reason, the current study aimed to utilize relative clause sentence structures in order to investigate the interaction between syntactic processing ability and working memory capacity in children with dyslexia.

Relative Clause Sentence Processing in Adults with Dyslexia

The ability to store items in working memory is believed to be related to a number of factors, such as level of education, age, and reading ability (SLC, 2001). For those with dyslexia, working memory impediments are due to lower-level deficits in phonological processing because the storage of information in working memory involves the use of phonological codes (Chiappe et al., 2004; Gottardo et al., 1996; SLC, 2001).To date electrophysiological research published, specifically targeting working memory difficulties in dyslexics, is limited. However, ERP studies specifically looking at this measure can help to either support or disprove the PSA and CLA.

The current research is part of a larger ongoing study investigating working memory differences in both adults and children with and without dyslexia. Preliminary results examining adults using the same paradigm employed in the current study, suggest differences in the ways adults with and without dyslexia utilize working memory during SO and SS sentence reading (Brown et al., unpublished data). As has been previously demonstrated in the literature in typical adults, both groups elicited significantly more negative LANs in response to the main clause verb of aurally presented SO rather than SS sentences. However, in contrast to the aural modality, in the visual modality dyslexic adults displayed a very different pattern of LAN effects at the same word location. While typical adults demonstrated a similar LAN pattern as was observed in the aural modality, dyslexics demonstrated no significant difference between sentence types. These preliminary findings seem to suggest that sentences may have been too difficult to comprehend in the visual modality. However, dyslexic adults performed above chance on questions related to the sentences, suggesting that while thematic role assigning may be taking place, this is not an automatic process (Hahne et al., 2004).

SCPs were also examined across the duration of the sentence in both groups (Brown et al., unpublished data). However, there were no significant effects, perhaps due to a limited number of participants. However, visual inspection of SCPs elicited during auditory sentence processing demonstrated that SO sentences produced relatively more negativity than SS sentences, for both adults with and without dyslexia. This difference again illustrates that while listening, both groups found SO sentences more difficult to integrate than SS sentences. When reading, typical adult readers also demonstrated relatively more negativity in response to SO compared with SS sentence types. Adults with dyslexia, however, actually demonstrated an unexpected waveform flip; SCPs elicited during SS sentence reading were more negative than those elicited during SO sentence reading. This suggests dyslexic readers may have exerted increased effort during the easier SS sentences, but did not when reading SO sentences because they were simply too difficult to integrate (i.e., they eventually give up; Brown et al., unpublished data). Correlations between SCP amplitudes in both sentence type and behavioural measures taken suggested differences in the abilities utilized in both groups. As would be expected, for typical readers, vocabulary and verbal working memory measures produced strong correlations with electrodes at the frontal and central regions of the head, for both sentence types. In contrast, for readers with dyslexia, strong correlations were shown among the reading fluency measures. Differences between the measures correlated with visual SCP waves suggest typical adult readers were actively interpreting the sentences, retrieving relevant information and holding sentence phrases in working memory. Readers with dyslexia, on the other hand, seemed to use all their resources simply trying to decode and identify words, with no resources left for comprehension. Overall, these preliminary findings suggest that it is not complicated syntax or working memory load that bog down readers with dyslexia. Instead, it seems that it is phonological processing that makes reading difficult.

Purpose of the Current Study

ERP is rarely employed when studying developmental dyslexia, most likely due to technical challenges, such as constraints on mobility and the number of trials necessary for enhancing signal-to-noise ratio (Phillips, 2005). Nevertheless, it is imperative that research with children be completed. Many adults with dyslexia eventually achieve functional reading ability through various compensatory strategies (Lyytinen et al., 2005). These learned skills and the effects they cause sometimes make it difficult to tease out factors purely associated with dyslexic language deficits. During the early school years, cognitive tasks such as reading, profoundly influence neuronal structures and vice versa. In order to truly focus on the skills important to reading achievement, children must be studied to document reading ability, or lack thereof, as it emerges. Children in this early transitional stage represent a developmental trajectory between word-level and automatic fluent reading. For these reasons, this study focused on children from the ages of 8 to 12, an age group still developing reading and complex syntactic abilities, as well as working memory capacity.

The current experiment utilized relative clause sentence structures known to vary in syntactic complexity and in the working memory load they induce (*SO* > *SS*). Examples of the sentence structures can be found in Table 1. A modality comparison was employed in order to assess the ability of children with and without dyslexia to process these complex syntactic structures with (i.e., *visual*) and without (i.e., *auditory*) the added phonological processing burden of converting graphemes to phonemes. The experimental design was created with three main purposes in mind. First, by comparing complex syntactic processing in children while listening and reading, assessments could be made between two prevalent theories regarding the underlying nature of linguistic deficits in dyslexia (i.e., *PSA, CLA*). The brainwave potentials elicited by control children were utilized as an indication of the prototypical waveform latency, amplitude, and topography associated with the specific age group of children. If children with dyslexia have a specific syntactic deficit unassociated with phonological processing limitations, in comparison to the waveforms elicited by controls, it was presumed they would demonstrate atypical waveform patterns in both modality presentations of the relative clause sentences, since the syntactic difficulty of the sentences is held constant between the two modalities. However, if the linguistic deficit demonstrated by dyslexics is phonological in nature, it was presumed that children with dyslexia would elicit atypical waveforms solely in response to visually presented sentences, thus demonstrating that syntactic processing does not play an independent role in the linguistic deficits associated with dyslexia.

A second study objective was to expand upon the limited literature in the field of developmental sentential processing. In the past it has been shown that childhood brain potentials vary in amplitude and latency from adult versions of the same component. Further research suggests topographic differences in certain components indicate the development from unaware and inexperienced in a particular linguistic skill to automatic and efficient processor of linguistic information. In particular, work in the field has focused on one-two word priming studies and auditory sentential studies. Little research has been completed on the developmental timing and sequencing of sentential processing. A third purpose was to specifically index SCPs in children. To the knowledge of the researcher, there has been no work on the development of this component in childhood. Valuable information could be gathered regarding its early manifestation in children, specifically it's amplitude, timing, and lateralization.

Hypotheses

Hypotheses regarding the outcomes demonstrated by children with dyslexia were made from the perspective of both theories of interest, the PSA and the CLA. Previous sentential processing research has demonstrated two main regions of interest within relative clause sentences that reflect increased processing demands: the 2nd article and main verb (King & Just, 1992; King & Kutas, 1995; Müeller et al., 1997). Based on relative clause processing results in adults, it was expected that an N400 effect would be elicited in response to the 2nd article of aurally presented SO sentences (Brown et al., unpublished data; Müeller et al., 1997). Though this effect is generally only generated by adult poor readers or comprehenders, it was predicted that even typical children would not possess the linguistic abilities of an average adult, thus behaving in a similar manner to lower level adult comprehenders. For the dyslexic group, the PSA would predict a result similar to those elicited by typical children while aurally processing the 2nd article of SS and SO sentences because, while the task involves syntactic complexity, it does not particularly tax phonological processing skills. However, the CLA would predict differences in the brain potentials elicited by the two groups indicating the dyslexic group's increased difficulty with the syntactic processing task. It is expected that increased difficulty (if shown) would be demonstrated by a more negative N400 amplitude in response to the 2nd article of SO sentences in comparison to the controls.

Additionally it was thought that, similar to adults, typical children would elicit more negative LAN effects at the main verb of aurally presented SO rather than SS sentences, indicating the added working memory load involved in these sentence types compared to SS sentences (Brown et al., unpublished data, Müller et al., 1997). Again, the PSA would assume that dyslexic and typical children perform similarly. Differences between groups would support the CLA, unless differences in brainwaves could be conclusively attributed to a skill influenced by phonological awareness, such as phonological working memory. In the past, differences in the amplitude of the LAN component elicited by typical adults at the main verb region have been tied to differences in working memory capacity (Müller et al., 1997). If children with dyslexia do demonstrate increased difficulties with syntactic processing or working memory load at the main verb region, the effect should be manifested as a decrease in the amplitude of the LAN or absence of the effect relative to controls, indicating difficulty holding the working memory information in store during relative clause sentence processing.

It has been shown that the brainwave components elicited in response to auditory relative clause sentences in typical adults follow the same pattern during the visual presentation of the sentences (Brown et al., unpublished data; King & Kutas, 1995; Müller et al., 1997). Therefore, it is expected that typical children will again elicit a N400 effect in response to the 2nd article and a LAN effect in response to the main verb of visually presented SO sentences. It is hypothesized that children with dyslexia instead will be overwhelmed by the visual task. The PSA and CLA would both predict this outcome, however, for different underlying reasons. According to the PSA, the increased difficulty of the visual task is caused by the added phonological processing demands of grapheme to phoneme conversion. Since the syntactic complexity of the task is held constant across both modalities, difficulty cannot be ascribed to syntactic processing deficits not demonstrated in the aural modality. The CLA, on the other hand, posits that children with dyslexia should demonstrate difficulty compared with controls in the visual modality, as well the auditory modality, because of deficits related to both phonological and syntactic processing.

Additionally, it was expected that SCP analysis would further elucidate differences between the groups related to phonological working memory capacity across the duration of the relative clause sentences. As has been demonstrated in relative clause studies in adults, it was assumed that typical children would elicit more negative SCPs in response to SO sentences, when compared with SS sentences, in both the aural and visual modalities, because of the increased processing demands inherent in comprehending their structure (Brown et al., unpublished data; King & Kutas, 1995; Muller et al., 1997). It was hypothesized that children with dyslexia would be overtaxed by both the aural and visual tasks, if in fact the underlying cause of dyslexia fits the profile configured by the CLA. This result would be manifested as a lack of differentiation between the SCPs elicited between SO and SS sentences. In contrast, if the underlying cause of dyslexia fits the profile hypothesized by the PSA, children with dyslexia should perform similar to controls during the auditory task. However, with the added difficulty of the visual task (related to decoding and increased phonological working memory), the PSA would also assume that the children would be overtaxed.

The correlational analyses were conducted in order to solidify exactly which language abilities were related to performance on the syntactic tasks for dyslexic and control children. It was also a method of investigating which skills either enhanced or limited sentential comprehension for each group. Previous research on adults with and without dyslexia has shown that typical adults rely on vocabulary and working memory when comprehending SS sentences (Brown et al., unpublished data). However, when reading SO sentences, more foundational reading skills, such as reading accuracy, are also important (Brown et al., unpublished data). In contrast, reading in adults with dyslexia is most closely related to reading fluency, suggesting dyslexic adults simply attempt to keep up with reading tasks while controls also are able to actively store sentential information in working memory. It was hypothesized that typical children presented with SS sentences would demonstrate similar correlations between SCPs and language skills as overtaxed adults (i.e., during SO processing). However, during SO processing, it was expected that typical children would demonstrate lower correlations with working memory. It was expected that children with dyslexia would demonstrate correlations with even lower level language skills, such as phonological awareness.

METHOD

Participants

The participants were forty-one (24 boys, 16 girls) children between the ages of 8-12 years. See Table 2 for a summary of the group characteristics. All children were native English speakers with no history of speech or hearing difficulties. The groups were roughly matched on age, gender, and handedness. The twenty children in the dyslexic group all had a previous clinical diagnosis of a reading impairment that was not co-morbid with any other disability. The twenty children in the control group all had a history of typical to above average academic achievement. Children were recruited from: a local private school for children with learning disabilities, the local Learning Disabilities Association, through referral from a local clinical psychologist, the region's public and catholic school boards, the Laurier Child Memory and Learning Lab, and by word of mouth. One child's data was lost due to technical difficulties with the ERP equipment.

Materials

Measures

Behavioural Baseline Measures

Reading comprehension. Reading comprehension was measured using the Gray Oral Reading Test, 4th Edition (GORT-4) (Wiederholt & Bryant, 1992). The GORT consists of fourteen reading passages, sequentially ordered according to difficulty. Each passage is accompanied by five comprehension questions. Children were asked to orally read the passages to the best of their ability. A Fluency Score was determined based on the combined factors of Rate (time in seconds to read each passage) and Accuracy (number of deviations from print made in each passage). An Oral Reading Comprehension Score was calculated based on the number of correct responses given to the comprehension questions. Once reading rate and accuracy fell below a specified level (fluency score of two or less) the task was discontinued. Comprehension questions were also discontinued when the child answered less than three correctly. In addition to reporting the scores separately, the Fluency and the Oral Reading Comprehension Scores were also combined to obtain an Oral Reading Quotient, or overall measure of reading ability.

Reading accuracy. Reading accuracy was measured using the Word Attack and Word Identification subtests of the Woodcock Reading Master Test Revised (Woodcock, 1991). The Word Attack assesses decoding skills, while the Word ID assesses word identification skills. Both subtests were included in order to differentiate those readers who have difficulty recognizing familiar words, from those who have difficulty with unfamiliar word decoding. It has been noted in the literature, that many children with reading difficulties proficiently read familiar words, yet still struggle with decoding (Olson, Wise, Conners, Rack, & Fulker, 1989). Text reading accuracy was assessed using the GORT Accuracy score (Wiederholt & Bryant, 1992).

Reading fluency: Words and text. Even though children with dyslexia often can identify single words, or even accurately decode, reading times are sometimes slowed to a point where fluency and comprehension are compromised (Frith, Wimmer, & Landerl, 1998; Wolf & Bowers, 1999). Word reading fluency was measured using the Sight Word Efficiency (SWE) and Phonetic Decoding Efficiency (PDE) subtests of the Tests of Word Reading Efficiency (TOWRE) (Torgesen, Wagner, Rashotte, 1999). The SWE assesses the number of words that can be correctly identified from a given list within 45 seconds. The PDE, in contrast, measures the number of pronounceable nonwords that can be read from a given list within the same time window (i.e., 45 sec.). Text reading fluency was assessed using the GORT Rate and Fluency scores (Wiederholt & Bryant, 1992).

Rapid automatized naming (RAN). RAN speed is associated with automaticity in word reading. Rapid automatized naming was measured using two RAN subsets from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999). This assesses how quickly and efficiently a list of numbers (subset a) or letters (subset b) can be read from a given list. RAN is also linked to phonological processing performance (Wagner et al., 1999).

Print exposure. A general measure of each child's print exposure was taken using the Title Recognition Test (TRT; Cunningham & Stanovich, 1997). Children were given a list of popular children's books and foil titles. They were asked to indicate which titles they recognized. The instructions made it clear to the children that they only had to recognize the title of the book and that this did not necessitate having read the book. Children were informed of the foils within the list in order to discourage guessing. Incorrect responses were subtracted from correct responses in order to determine TRT scores.

Phonological awareness. Phonological awareness was measured using three subtests from the Comprehensive Test of Phonological Processing (CTOPP): Segmenting Words, Segmenting Pseudowords, and Elision (Wagner et al., 1999). During the segmenting tasks children were asked to say a word or pseudoword, in the case of the Segmenting Pseudowords task, then say it one sound at a time. Both the Segmenting Words and Segmenting Pseudowords tasks increase in difficulty over the course of the test (e.g., Segmenting Words: Say "no." Say "no" one sound at a time. Say "graduate." Say graduate one sound at a time. Segmenting Nonwords: Say "ta." Say "ta" one sound at a time. Say "voostam." Say "voostam": one sound at a time). During the Elision task, children listened to a word, then repeated it back to the experimenter. Next, they were asked to pronounce the word with a specified sound deleted. Items in this task start at syllable deletion, then increase in difficulty to phoneme deletion (e.g., Say "popcorn." Now say "popcorn" without saying "corn." Say "tiger." Now say "tiger" without saying "/g/").

Vocabulary. Receptive vocabulary was measured using the Peabody Picture Vocabulary Test-III (PPVT-III; Dunn & Dunn, 1997). Children were presented with four pictures and asked to select the one that most closely matched the spoken word given. Vocabulary words given gradually increased in difficulty (e.g., Show me: "baby." Show me "descending"). When eight or more vocabulary words (in a set) were incorrectly matched with a picture, the task was discontinued.

Nonverbal reasoning. Nonverbal reasoning was assessed using four subtests of the Matrix Analogies Test (MAT), in order to ensure that all children fell within the normal cognitive abilities range (Naglieri, 1989). Subtests included Pattern Completion, Reasoning Analogy, Serial Reasoning, and Spatial Visualization. In each subtest, children were presented with an incomplete pattern and given five-six possible completions. Children were asked to point to the best pattern completion.

Working memory. Verbal working memory was assessed using two separate measures. The first was adapted from a Daneman and Carpenter (1980) task (Gottardo et al., 1996). Children were asked to identify a series of statements as true or false. After each series, children were asked to recall the final word of each statement. Series varied in length from two-four statements. The Digit Span subset of the Weschler Abbreviated Scale of Intelligence (WASI-III-

DS) was also given as a measure of verbal working memory (Weschler, 1992). Children were orally given a series of digits, then asked to repeat them either forwards (subtest a) or backwards (subtest b). (e.g., Experimenter: "4, 1, 7, 9." Child: Forwards Subtest: "4, 1, 7, 9." Backwards Subtest: "9, 7, 1, 4"). Digit series began at two (e.g., "4,1") and increased in length every two trials. The test was ended when the child could no longer correctly recite the series for both trials at that particular length.

Syntactic ability. Syntactic ability was assessed using The Sentence Assembly subtest of the Clinical Evaluation of Language Fundamentals- 3rd Ed. (CELF-3) (Semel, Wiig, & Secord, 1995). Children were given written syntactic fragments and then asked to correctly organize them into coherent sentence structures. For each set of fragments, children were asked to attempt two different structures (e.g., "the girl" "the boy" "an ice-cream cone" "bought" Child: 1. "The girl bought the boy an ice-cream cone." 2. "The boy bought the girl an ice cream cone"). The test ended when the child could no longer provide both sentences for five consecutive items.

ERP Stimuli

There were two experimental conditions, the subject-object relative (SO) clause sentences and the subject-subject (SS) relative clause sentences. Each condition contained 30 sentences, for a total of 60 sentences in each modality (auditory and visual). Sentence stimuli were all nine words in length (for both modalities). Refer to the Appendix for a complete list of the sentences used in the current study.

Procedure

Testing consisted of two sessions. Session I involved all standardized behavioural testing (see Materials). These measures served as baseline measures for each child, in order to ensure all participants were appropriate members of the population they represented (control vs. dyslexic groups). Session I took approximately 1.5-2 hrs to complete. Session II involved all electrophysiological recordings. This session consisted of two parts, auditory and visual sentence presentation. The order of presentation modality was counterbalanced.

Session II

During setup of the electrode cap children watched a movie in order to limit boredom prior to the experimental task and also to ensure they sat still during the process. After set-up, children were moved into an electrically shielded room where they sat in a comfortable chair in front of a computer monitor. An experimenter sat beside the child throughout the duration of the session in order to monitor for eye blinks and movement and also to assess frustration levels and need for breaks. Children were instructed to sit as still as possible. The experiment began with one practice stimulus in order to ensure participants were prepared. The stimulus onset was defined as the onset of the first word in the sentence. The presentation of each sentence, in both modalities, was preceded by a row of crosses, lasting approximately 2000 ms with an SOA of 2500 ms. During the visual task, sentences were presented on a 44 cm (17 inch) computer monitor positioned 60 cm away. The text stimuli were presented one word at a time with a duration of 300 ms per word and an SOA of 500 ms. Words were centered, in white letters (40 pt. font/ Times New Roman) on a black background. Prior to the auditory task, children were instructed to focus on a fixation point located on the center of the computer screen, in an attempt to limit blinks. Sentences presented in the auditory modality (and all questions) were presented bi-aurally through Hardon Karmon speakers positioned 60 cm away. The stimuli were digitized from the natural speech of a female speaker at a normal rate with natural intonation using the NeuroScan Inc. software (NeuroScan Inc., 2003).

Following the completion of each sentence, participants were aurally presented with a comprehension question pertaining to the previous sentence through the aforementioned speakers. Due to the difficulty of the task, it was determined that comprehension questions should be presented aurally for both the visual and auditory sentence presentations. This was done to limit frustration, particularly in the dyslexic group, as the reading task was quite demanding. It was also done to ensure that incorrect responses were due to a difficulty comprehending the target sentence, not the question. Participants were instructed to give the experimenter a simple yes or no answer following each question and also told that they had unlimited time to answer. During this time, participants were allowed to blink or move around. Periodic breaks were given at the experimenter's discretion, in order to ensure children were focused on the task at hand. After part one of Session II, participants were given a 15-minute break. At this time a snack and drink was provided. When ready, participants began part two. The total ERP session took approximately two hours to complete.

Electrophysiological recording

The electroencephalogram (EEG) activity was recorded from a 64-channel cap from the NeuroScan Synamps2 system with all AgCl electrodes referenced on-line to a mid-sagital/mid-coronal electrode site. All electrodes were distributed evenly over the scalp in accordance with the international 10/20 system (Jasper, 1958). For a schematic representation of the electrode layout, see Figure 1. Vertical and horizontal eye movements and blinks were monitored via an electrooculogram (EOG). This was recorded by additional electrodes placed on the outer canthus and infraorbital ridge of each eye. Electrode impedances were kept at or below 10 $K\Omega$. EEG was processed through a Neuroscan Synamps2 amplifier set at a bandpass of 0.05-100 Hz, and digitized at 250 Hz.

RESULTS

Behavioural Baseline Measures

The behavioural data was first analysed using a series of one-way ANOVAs in order to make group comparisons. Correlations and multiple regression analyses were conducted in order to determine the variables most strongly related to the measures of reading ability. Next, hierarchical regression analyses were conducted in order to determine the variables that accounted for unique variance in the measures of reading ability. Because of the age range of the sample (8-12 years), standardized scores were used for all analyses. For those measures that were not previously adjusted for age (Working Memory: Recall and T/F Questions, TRT), a series of linear regression analyses were conducted with the raw scores for each given measure using age in months as the dependent variable. The standardized residuals were saved as variables from each of these three analyses and used in all later statistics.

Table 2 summarizes the group characteristics of children with dyslexia and typical children. Compared with controls, children with dyslexia had significantly lower scores on all reading measures, phonological awareness, automaticity, working memory, syntax awareness, and vocabulary. For the dyslexic children, scores on these measures fell 1-2 standard deviations below the mean. The groups did not differ significantly in nonverbal reasoning, print exposure or age. These results indicate that children were representative of their respective groups.

Table 3 presents the bivariate intercorrelations among all the standardized behavioural measures for each of the groups separately. Fluency ($r = .79, p < .01$) and overall reading ability ($r = .46, p < .05$) were correlated with phonological awareness for the children with dyslexia. This same relationship was not observed for the typical children. Instead, typical children's reading measures were correlated with working memory ($r = .54, p < .05$) and vocabulary measures ($r = .58, p < .01$). A relationship was observed between comprehension ($r = .88, p <$

.01) and total reading ability (as measured by the GORT) for the children with dyslexia. However, comprehension was not necessarily related to reading ability in typically reading children. Syntactic awareness was related differently to the reading measures in each group. While for the typical children syntax ability was correlated with accuracy measures (pseudoword-level: $r = .46, p < .05$; word-level: $r = .47, p < .05$; text-level: $r = .58, p < .01$), it was instead correlated with fluency measures (pseudoword-level fluency: $r = .50, p < .05$; word-level fluency: $r = .59, p < .01$; text-level fluency: $r = .53, p < .05$; rate: $r = .63, p < .01$) in children with dyslexia.

In order to get a full picture of the relationship between reading ability and the test measures, bivariate intercorrelations were also conducted for all the standardized behavioural measures collapsed across groups (see Table 4). All variables, with the exception of the TRT, showed moderate to high levels of correlation with most of the reading ability measures. For the phonological awareness measures, it was found that elision standard scores ($r = .69, p < .01$) led to more robust correlations with reading measures than segmenting standard scores (Words: $r = .46, p < .01$; Nonwords: $r = .21, p > .09$). For the working memory scores, memory for digits (All reading measures: $r = .60$ to $.76, p < .01$) and working memory recall (Accuracy measures: $r = .44$ to $.51, p < .01$; Fluency measures: $r = .34$ to $.51; p < .05$) were more highly correlated with reading measures than working memory T/F (Accuracy measures: $r = .38$ to $.47, p < .01$; word-level fluency: $r = .21$ to $.28, p > .05$; text-level fluency: $r = .42$ to $.49, p < .01$). Automaticity, memory for digits, and working memory recall were also highly correlated with most reading measures. Overall, it appeared that syntactic awareness, phonological awareness, automaticity, and working memory were all constructs that seemed to have the strongest relationship to reading ability. Though automaticity, phonological decoding, and working memory are all related to phonological ability, the three areas seemed to have different patterns of correlations in this sample and therefore appeared to be separate constructs worthy of further exploration.

Based on the results of the correlational analyses, four constructs were chosen for further exploration in a series of multiple regression analyses. Automaticity, phonological awareness, working memory, and syntactic awareness were used as predictors of reading ability (as quantified by the following measures of overall reading ability: 1) word-level reading accuracy, 2) text-level reading accuracy, 3) word-level reading fluency, 4) text-level reading fluency, 5) reading comprehension, 6) rate of reading and 7) overall reading ability. All of the regression analyses were conducted for the whole sample collapsed across groups due to the small number of participants in each group. In order to reduce the number of variables in the analyses, composite scores were calculated for three variables. The composite score for automaticity was created by taking the sum of the standard scores for rapid digit and rapid letter naming. The number of variables for phonological awareness and working memory were reduced by computing means of principal components factor analysis with varimax rotation. Individual measures were considered representative of a specific factor if their loadings were .60 or greater. Separate factor analyses confirmed that the three phonological measures all loaded onto a single factor (with an eigenvalue >1). The loadings for elision, segmenting words and segmenting non words scores were .81, .87, and .83 respectively. Two working memory measures also loaded onto a single factor (eigenvalue >1). The loadings for WISC digit scores and working memory recall were .83 and .83 respectively. The multiple regression analyses were completed with the CTOPP elision measure as representative of phonological awareness and alternatively, with the phonological awareness composite as representative of phonological awareness. Analyses were also completed with the WISC digits measure as representative of working memory and again with the working memory composite. Only the model that accounted for the highest percentage of variance in reading ability measures is reported. This model contained the following predictor variables: phonological awareness (as measured by the CTOPP elision scores), working memory (as measured by the working memory composite), syntactic awareness (as measured by the CELF sentence assembly scores), and automaticity (as measured by the automaticity composite).

The Woodcock Word ID and Word Attack subtests (Woodcock, 1991) were used as indicators of word level reading accuracy. When measured by the Word ID, the four predictor variables accounted for 82% of the variance in reading accuracy. Inspection of the β weights indicated that phonological awareness was a major contributor to this model, while both automaticity and syntactic awareness were moderate predictors of reading accuracy (see Table 5). When reading accuracy was measured by Word Attack scores, the regression was slightly less effective, describing 75% of the variance. Both automaticity and phonological awareness were significant contributors to the model (see Table 5). For text level reading accuracy, as measured by the GORT accuracy measure, the model was a good fit; 86% of the variance was explained by the predictors. All four predictor variables accounted for significant variance in text-level reading accuracy. However, phonological awareness was the strongest predictor. Both automaticity and working memory moderately contributed to the model, while syntactic awareness seemed to have the least predictive strength (see Table 6).

Word level reading fluency was measured by both the Sight Word Efficiency and Phonetic Decoding subtests of the TOWRE (Torgesen, Wagner, & Rashotte, 1999). The model predicted 84% of the variance when measured by the Sight Word Efficiency subtest. Inspection of the β weights suggested that automaticity was a major contributor to the model, while phonological awareness was a minor contributor, as is shown in Table 7. The model predicted

83% of the variance when measured by the Phonetic Decoding subtest. Again, inspection of the β weights suggested that automaticity was a major contributor to the model, while phonological and syntactic awareness were moderate contributors (see Table 7). For predicting text level reading fluency, as measured by the GORT Fluency measure, 83% of the variance was explained by the model (Wiederholt & Bryant, 1992). All variables seemed to contribute to the model, however, phonological awareness and automaticity were stronger predictors than working memory and syntactic awareness (see Table 8). The GORT Rate measure was used to measure text reading rate. The model was a good fit, describing 86% of the variance in reading rate. As is shown in Table 8, both automaticity and syntactic awareness were major contributors to the model. Phonological awareness also seemed to play a moderate role (Wiederholt & Bryant, 1992).

For predicting reading comprehension, as measured by the GORT Comprehension measure, the four predictor variables accounted for 60% of the variance (Wiederholt & Bryant, 1992). Inspection of the β weights indicated that both phonological awareness and working memory were major contributors to the model (see Table 9; Wiederholt & Bryant, 1992). Finally, overall reading ability was measured using the GORT Total Standard Score. The model accounted for 83% of the variance. Phonological awareness was a strong predictor but working memory also seemed to play a moderate role (see Table 9; Wiederholt & Bryant, 1992).

In summary, the multiple regression analyses indicated that phonological awareness and automaticity were major contributors for reading accuracy measures. In contrast, the most important contributor to reading fluency seemed to be automaticity. Fluency measures were also predicted by phonological awareness. Syntactic awareness seemed to play a more important role in predicting fluency than accuracy measures. Furthermore, different trends were noticed between word and text-level measures. For both, phonological awareness and automaticity appeared to be the most important contributors; however syntactic awareness seemed to play more of a predictive role in text-level reading compared to word-level reading. Working memory was generally a more moderate predictor of the reading measures, however it did seem to predict more variance in comprehension and overall reading ability.

Taking into consideration the results of the above findings and the current research question, next a series of hierarchical regression analyses were carried out in order to determine the unique variance attributable to phonological and (or) syntactic awareness in the model of reading ability. These results are displayed in Tables 10-14. Again, elision scores were used as the phonological awareness measure and the composite variables were used for both automaticity and working memory measures. Because working memory was a weaker predictor of reading ability, in comparison to the other phonological measures, it was always entered first in the forced orderings. Phonological awareness and syntactic awareness were each entered last in the analyses. Because in past literature automaticity has been shown to be an aspect of a larger phonological processing, these variables were always entered one after the other (Wagner et al., 1999).

In all the word and text-level reading and comprehension measures, phonological awareness accounted for significant unique variance after working memory, syntax, and automaticity were entered into the model. Nine percent of the unique variance on the measure of overall reading ability (GORT) was contributable to this factor. Phonological awareness also explained considerable unique variance in the word (8%) and text-level (9%) accuracy measures, as well as in the comprehension measure (9%). Less unique variance was explained in the rate (4%) and fluency measures (word-level = 3-4%; text-level = 7%).

In contrast, syntactic awareness did not account for significant unique variance in several of the reading and comprehension measures, specifically, syntactic awareness did explain a significant portion of unique variance in a number of text-level measures, such as text-level rate (5%), accuracy (2%) and fluency (3%). Syntactic awareness also accounted for 4% of the unique variance in the word ID scores and 5% of the variance in the TOWRE fluent phonetic decoding scores. While these results suggest the importance of phonological awareness to reading ability, syntactic awareness also predicted significant unique variance in a number of the reading measures.

ERP Measures

All ERP data were re-referenced off-line to the average of the left and right mastoid electrodes. High frequency noise was removed by applying a low-pass filter set at 30 Hz. Brain potential amplitudes were examined over both multiple (i.e., SCP) and single words in the sentence. SCPs were measured from 200 ms before the first word to 500-550 ms after the final words onset (visual: -200-4500 ms; auditory: -200-3893ms). This multiword epoch was then divided into nine single word regions for the purpose of statistical analysis. The single word boundaries in the auditory SCPs were determined by computing the average endpoint of each word across all auditory sentence recordings. Single word analysis was completed in two different latency windows: the N400 and LAN were examined from 300-500 ms post stimulus onset, and a later latency window from 500-900 ms post stimulus onset. This later time window was utilized in order to ensure no delayed effects were missed, particularly in the dyslexic group. As well, the P600, a component associated with arduous syntactic processing, occurs during this time window. Therefore, later differences could potentially inform evaluations of the syntactic deficits seen in children with dyslexia. Any trials that were contaminated by blinks, lateral eye-movements or muscle artifacts were rejected off-line before averaging. In the control group, 49.92% of auditory and 52.34% of visual trials were lost due to artifacts in the slow wave regions and 58.75% of the auditory and 57.83% of the visual trials were lost in the single word regions. For the dyslexic group, 52.34% of auditory and 41.09% of visual of slow cortical potential trials were lost and 60.04% of the auditory and 55.83% of the visual single word trials were taken out due to artifacts. In each latency region, for each participant, the remaining trials were averaged for both sentence types. These individual averages were then averaged across participants in order to create a grand average of the brainwave amplitudes for each respective time window. Amplitudes for each region were then analyzed in a series of 2 (task: auditory or visual) x 2 (group: typical or dyslexic) x 2 (sentence type: SS and SO) x 2 (stimuli list: 1 or 2) x 62 (electrode site). The between subjects factor, List, was used to stabilize variance that may have been caused by rotating participants between the two stimuli lists. These analyses were collapsed over the entire age range. These task analyses were followed up with 2 (sentence type: SS and SO) x 2 (stimuli list: 1 or 2) x 62 (electrode site) repeated measures ANOVAS. Again, these analyses were collapsed over the entire age range but completed for both participant groups (dyslexic and typical) separately. Comparisons were later made between the groups by completing a series of 2 (group: typical or dyslexic) x 2 (sentence type: SS and SO) x 2 (stimuli list: 1 or 2) x 62 (electrode site) repeated measures ANOVA. Results of the group comparison analyses were reported only in the case of a significant main effect or interaction. Topographic distribution was only examined when an interaction between electrode site and sentence type in one of the aforementioned analyses was significant. For the distribution analysis, a subset of electrodes were chosen consisting of: F7, FT7, P7, CB1, FP1, F1, P3, O1, F8, FT8, P8, CB2, FP2, F2, P4, and O2. These electrodes are all representative of different topographical regions of the scalp. Distribution analyses were computed in a 2 (sentence type: SS and SO) x 2 (hemisphere: left and right) x 2 (laterality: lateral and medial) x 4 (anteriority: prefrontal, frontal, parietal, and occipital) ANOVA. Distribution analyses that examined results of the direct group comparisons also included the bivariate factor of participant group (typical and dyslexic). All p values were reported after Epsilon correction (Huyn-Feldt) for repeated measures with greater than one degree of freedom.

ERP Comprehension Questions

A 2 (group; dyslexic, typical) x 2 (task; auditory, visual) mixed model ANOVA on the ERP comprehension questions revealed a significant main effect of Group, $F(1,38) = 19.27, p = .000$, because typical children ($M = 93.58$) answered a significantly greater percentage of questions correctly than did dyslexic children ($M = 86.62$). There was also a main effect of task, $F(1,38) = 56.30, p = .000$. Overall, children answered a significantly greater percentage of questions correctly during the auditory task ($M = 95.33$) compared with the visual task ($M = 84.87$). However, these findings were qualified by a significant Group x Task interaction, $F(1,38) = 14.42, p = .001$. Post-hoc comparisons of the means using the Bonferroni correction indicated that although groups performed similarly on comprehension questions during the auditory task (*Typ* $M = 96.16$; *Dys* $M = 94.50$; $t\ (38) = 0.842, p > .30$), during the visual task, typical children ($M = 91.00$) correctly answered a significantly greater percentage of questions correctly than did the children with dyslexia ($M = 78.75$; $t\ (38) = 6.216, p = < .001$).

Multi-word ERPs

Task Comparison for Slow Cortical Potential Averages

An interaction between task and electrode was sustained throughout the 9 word sentence. Furthermore, a significant interaction between task, group, and electrode developed at the second word, continuing to the end of the sentence. During the early relative clause, at the 4th and 5th word regions, there was also a significant task x sentence type x group interaction. For a summary of the task analysis for the SCPs see Table 15.

Auditory Slow Cortical Potential Averages (-200-3893 ms)

Control group. In the typical children, the auditory SCPs in response to SS and SO sentences began to diverge late into the relative clause. Results for the nine word regions confirmed that the main effect of sentence type was not significant until the 6th word of the sentence, $F(1,18) = 4.26, p < .05$), where amplitudes for SO sentences became significantly more negative ($M = -5.65$ µV) than amplitudes for SS sentences ($M = 2.58$ µV). This effect was both sustained and became larger over the duration of the sentence, particularly after the relative clause was encountered (i.e., during the main verb phrase). For a summary of the auditory SCPs for both dyslexics and controls see Table 16. Figure 2 presents a schematic diagram of the auditory SCP grand average ERPs for both sentence types in each group.

Dyslexic group. The auditory SCPs in the dyslexic children followed a similar trajectory as in the typical children. Amplitudes in response to SO sentences became significantly more negative ($M = -4.90$ µV) than amplitudes for SS sentences ($M = -2.17$ µV) in exactly the same word region, $F(1,18) = 7.97, p < .05$). Again these effects were sustained throughout the rest of the sentence. Unlike in the controls, a significant interaction between sentence type and electrode was confirmed at the last word of the sentence, $F(1,18) = 2.40, p < .05$).

In order to investigate this effect, a distribution analysis was performed comparing the mean amplitude of SO sentences to SS sentences at various topographical scalp regions. As is presented in Table 17, this analysis demonstrated a significant two-way sentence type x anteriority interaction $F(3,54) = 5.18, p < .05$). Comparisons revealed SO sentences elicited significantly more negative amplitudes ($M = -5.21$) than SS ($M = -0.01$ μV) sentences at the prefrontal region of the scalp ($F(1,18) = 23.31, p < .001$). At frontal electrode sites, amplitudes in response to SO sentences ($M = -6.07$ μV) were again significantly more negative than those for SS sentences ($M = .08$ μV), $F(1,18) = 32.67, p < .001$). In contrast, no effect of sentence type was observed at either the parietal ($F(1,18) = 3.68, p = .08$) or occipital scalp regions, $F(1,18) = 0.93, p = .27$). These findings are comparable to previous studies that have found the differences between brainwave amplitudes evoked by SO and SS sentences tend to taper off late in the sentence in typical adults who have poor comprehension due to working memory limitations (Müller et al., 1997).

For a graphic representation of the differences between auditory SCPs for both groups at a single electrode site from the frontal, central, and parietal region, see Figure 3. For specific comparisons between SO and SS sentences for controls and for dyslexics at the same frontal, central, and parietal locations, see Figure 4.

Visual Slow Cortical Potential Averages (-200-4500ms)

In contrast to the auditory SCPs, the brainwave amplitudes for both sentence types gradually became more positive. However, the visual SCPs did follow the same trend as the auditory data in that the amplitudes in response to SO sentences became progressively more negative than the SS amplitudes, particularly after the main verb clause. This effect was more robust in typical children than dyslexic children. For a summary of the visual SCPs in both groups, see Table 16. See Figure 5 for a schematic diagram of the grand average SCPs in response to visual SS and SO sentences at each of the sixty-two electrode sites.

Control group. Results for the nine word regions in typical children revealed a main effect of sentence type beginning early in the relative clause, at the 5th word of the sentence, $F(1,18) = 9.25, p < .01$. This result was caused by significantly more negative brainwave amplitudes in response to SO sentences (M = -5.65 μV) rather than SS sentences (M = -2.58 μV). This difference occurred just one word after the divergence in sentence type (at the beginning of the relative clause), slightly delayed in comparison to adult readers (King & Kutas, 1995). This main effect of sentence type was sustained until the 8th word of the sentence. A significant interaction between sentence type and electrode site also developed at this point and continued to the end of the sentence. Distribution analyses and further comparisons at each word region revealed that these effects were due to several variations in anteriority, laterality and hemisphere. As is typical for SCP topography, amplitude differences between the sentence types were most robust at anterior locations on the scalp (Brown et al., unpublished data; King & Kutas, 1995). This effect was mediated by laterality effects; for the most part, differences in sentence type amplitudes were stronger over medial sites when contrasted with lateral sites. Furthermore, beginning at the relative clause typical children also developed a left hemispheric asymmetry, a result not found in past studies with adult readers (Brown et al., unpublished data; King & Kutas, 1995). The left hemisphere was reliably more dominant in every word region except that of the main verb. At this region, effects appeared particularly frontal, medial and bilateral. See Table 17 for a summary of all SCP topographic distribution results in both groups.

Dyslexic group. Dyslexic children, in contrast, only showed a significant effect of sentence type at the 6th word. At this point in the sentence, amplitudes evoked by SO sentences (M = -1.76 μV) were significantly more negative than those evoked by SS sentences (M = 0.82 μV). However, differences between the two sentence types approached significance at the 4th, 7th, and 8th words, indicating that a subset of the dyslexic children may have been differentiating between the SO and SS sentences. There were no reliable interactions at any word region. In comparison to the brain amplitudes of typical children, dyslexic children demonstrated a more uniform pattern of amplitudes across various scalp regions over both hemispheres.

Group (typical and dyslexic) comparisons. The group comparison analyses indicated a significant interaction at the last word of the visually presented sentences between group, sentence type, and electrode site, $F(61, 2196) = 2.03, p < .05$. This finding was further investigated through a distribution analysis which demonstrated a significant 3-way interaction involving group, sentence type, and anteriority, $F(3,108) = 6.12, p < .01$. Planned comparisons revealed that SCPs elicited by controls (Typ) in response to SS sentences were more positive than those elicited by the dyslexic group (Dys) at both prefrontal (M Typ = 3.99 µV, M Dys = 0.16 µV; $t(108) = 2.76, p < .01$),and frontal sites (M Typ = 3.57 µV, M Dys = 0.24 µV; $t(108) = 2.39, p < .05$). For a summary of the visual SCP results in both participant groups refer to Table 16. For a graphic representation of the differences between the visual SCPs for both groups, compared together and separately at a frontal, central, and parietal electrode site, see Figures 6 and 7 respectively.

Single Word ERPs.

Task Comparison

Task Comparison at 2nd Article: 300-500 ms.

Results in the 300-500 ms time window indicated a significant main effect of task, $F(1,37) = 4.96, p < .05$, which occurred because brainwave amplitudes generated in response to the visual task ($M = 0.14$ µV) were more negative than those in response to the auditory task ($M = 1.49$ µV). There was also a significant sentence type x group interaction, $F(1,37) = 11.08, p < .01$.

Task Comparison at 2nd Article: 500-900 ms.

Results in the 500-900 ms time window indicated a significant main effect of task, $F(1,37) = 11.80, p < .01$, because amplitudes in response to the visual task ($M = -0.36$ μV) were more negative than those in response to the auditory task ($M = 1.18$ μV). There was also a significant task x electrode interaction, $F(61, 2196) = 4.71, p < .001$.

Task Comparison at Main Verb: 300-500 ms.

Results in the 300-500 ms time window indicated a significant interaction between task and electrode site, $F(61,2257) = 4.13, p < .001$.

Task Comparison at Main Verb: 500-900 ms.

Results in the 500-900 ms time window indicated a significant interaction between task and electrode site, $F(61,2257) = 2.56, p < .05$.

Auditory

Auditory 2nd Article

Auditory N4/Left Anterior Negativity (300-500 ms).

Control group. Results in this time window for the typical children demonstrated a significant main effect of sentence type, $F(1,18) = 21.20, p < .001$, which occurred because amplitudes for SO sentences ($M = -1.85$ μV) were significantly more negative than amplitudes for SS sentences ($M = 2.04$ μV).

Dyslexic group. Dyslexic children also showed a significant main effect of sentence type, $F(1,18) = 6.47, p < .05$, because amplitudes for SO sentences ($M = -1.17$ μV) were significantly more negative than amplitudes for SS sentences ($M = 1.54$ μV).

Auditory Late Latency Window (500-900 ms).

Control group. Results for the 500-900 ms epoch revealed a significant main effect of sentence type for typical children, $F(1,18) = 20.04$, $p < .01$, which occurred because amplitudes in response to SO sentences ($M = -2.14$ µV) were more negative than amplitudes in response to SS sentences ($M = 1.62$ µV).

Dyslexic group. This time region also yielded a significant effect of sentence type in children with dyslexia, $F(1,18) = 13.03$, $p < .01$, because amplitudes generated in response to SO ($M = -2.21$ µV) sentences were more negative than those generated in response to SS sentences ($M = 1.28$ µV).

For a summary of all single word effects in both typical and dyslexics, see Table 18. For a schematic diagram of the single word ERPs in response to the 2nd article of aurally presented SO and SS sentences, see Figure 8. See Figure 9 for a graphic illustration comparing the groups' brainwave responses together in one image at a frontal, central, and parietal electrode site. See Figure 10 for a graphic demonstrating each groups' brainwave responses to SO and SS sentences separately at the same frontal, central, and parietal locations.

Auditory Main Verb

Auditory N4/Left Anterior Negativity (300-500 ms).

Control group. Amplitudes elicited in response to SO sentences ($M = -0.05$ µV) in this time window were significantly more negative than those elicited by SS sentences ($M = 1.48$ µV), $F(1,18) = 4.52$, $p < .05$.

Dyslexic group. While children with dyslexia did demonstrate a trend for more negative amplitudes in response to SO sentences ($M = -0.33$ µV) rather than SS sentences ($M = 1.17$ µV), unlike controls, there was no reliable difference between sentence type in the 300-500 ms time window, $F(1,18) = 1.14$, $p = .30$.

Auditory Late Latency Window (500-900 ms).

Control group. Results for this time window for the typical children demonstrated a significant main effect of sentence type, $F(1,18) = 6.25$, $p < .05$, because amplitudes evoked by SO sentences ($M = -0.20$ µV) were significantly more negative than those evoked by SS sentences ($M = 1.59$ µV).

Dyslexic group. Again, at the main verb there were no significant differences between the mean amplitudes of SS ($M = 0.86$ µV) and SO sentences ($M = -0.26$ µV) for the 500-900 ms time window, $F(1,18) = 1.19$, $p = .29$.

For a schematic diagram of the single word ERPs in response to the main verb of aurally presented SO and SS sentences, see Figure 11. See Figure 12 for a graphic illustration comparing the groups' brainwave responses together in one image at a frontal, central, and parietal electrode site. See Figure 13 for a graphic demonstrating each groups' brainwave responses to SO and SS sentences separately at the same frontal, central, and parietal locations.

Visual

Visual 2nd Article

Visual N4/Left Anterior Negativity (300-500 ms).

Control group. For the typical children, the overall ANOVA for this time window demonstrated a main effect of sentence type, $F(1,18) = 16.59$, $p < .001$, which occurred because amplitudes in response to SO sentences ($M = -0.44$ µV) were more negative than those evoked by SS sentences ($M = 3.76$ µV). There was also a significant sentence type x electrode interaction, $F(61, 1098) = 2.17, p < .05$. Distribution analysis revealed that there was a marginally significant sentence type x laterality interaction, $F(1,18) = 3.88, p = .06$, which occurred because differences in the brainwave amplitudes between SO and SS sentences tended to be slightly larger over medial (*M* difference = 3.89 μV), $F(1,18) = 178.21, p < .001$, regions of the scalp in comparison to lateral regions (*M* difference = 3.09 μV), $F(1,18) = 111.61, p < .001$.

Dyslexic group. While there was a trend for more negative amplitudes in response to SO (*M* = 0.85 μV) sentences rather than SS sentences (*M* = 1.79 μV), in the visual 300-500 ms latency window the dyslexic children did not demonstrate reliable differences in amplitudes evoked by each sentence type, $F(1,18) = 1.34, p = .26$.

Group comparisons. The overall ANOVA for this latency window at the 2nd article indicated a significant interaction involving group and sentence type, $F(1,36) = 6.25, p < .05$. A distribution analysis revealed a marginal interaction between group and sentence type, $F(1,36) = 3.79, p < .059$. However, planned comparisons demonstrated no difference between the brainwave amplitudes elicited by controls and dyslexics during SS sentence presentation (*M* Typ = 3.15 μV, *M* Dys = 1.49 μV; $t(36) = 0.45, p > .05$) and during SO presentation, *M* Typ = -0.35 μV, *M* Dys = 0.55 μV; $t(36) = 0.24, p > .05$.

Visual Late Latency Window (500-900 ms)

Control group. For the typical children, this time region yielded a significant main effect of sentence type, $F(1,18) = 29.22, p < .001$, due to more negative amplitudes in response to SO sentences (*M* = -1.20 μV) than to SS sentences (*M* = 3.75 μV). A significant two-way interaction between sentence type and electrode was also observed $F(1,18) = 2.68, p < .05$. In order to investigate this relationship in more detail, a distribution analysis was performed. Results showed a marginally significant interaction between sentence type and laterality, $F(1,18) = 4.38$, $p < .06$, due to larger differences between sentence types at medial (M difference = 4.41 μV; $F(1,18) = 361.76$, $p < .001$), rather than lateral sites (M difference = 3.73 μV; $F(1,18) = 257.95$, $p < .001$). Results also showed a significant three-way interaction between sentence type, laterality and anteriority, $F(3,54) = 2.99$, $p < .05$. This interaction occurred because differences between sentence type at both medial and lateral sites were larger over the medial prefrontal (M difference = 4.44; $F(1,18) = 151.38$, $p < .001$), lateral prefrontal (M difference = 4.19, $F(1,18) = 134.85$, $p < .001$), medial frontal (M difference = 5.80; $F(1,18) = 258.15$, $p < .001$) and lateral frontal (M difference = 3.84; $F(1,18) = 113.23$, $p < .001$) regions of the scalp compared with the medial parietal (M difference = 4.18; $F(1,18) = 134.21$, $p < .001$), lateral parietal (M difference = 3.61; $F(1,18) = 100.14$, $p < .001$), medial occipital (M difference = 3.23; $F(1,18) = 80.15$, $p < .001$) and lateral occipital regions; M difference = 3.26; $F(1,18) = 81.69$, $p < .001$).

Dyslexic group. This time region also yielded a significant effect of sentence type in the children with dyslexia, $F(1,18) = 7.20$, $p <.05$, because SO ($M = 0.12$ μV) sentences were more negative than SS sentences ($M = 2.06$ μV).

Group comparisons. The overall ANOVA comparing groups indicated a significant interaction between group and sentence type, $F(1,36) = 6.69$, $p < .05$. A distribution analysis revealed a Group x Sentence Type interaction, $F(1,36) = 5.09$, $p < .05$. However, planned comparisons demonstrated no differences between the brainwave amplitudes generated by controls and dyslexics during SS (M Typ = 3.08 μV, M Dys = 1.41 μV; $t(36) = 0.52$, $p > .05$) and SO sentence processing(M Typ = -0.99 μV, M Dys = -0.07 μV; $t(36) = 0.28$, $p > .05$). For a schematic diagram of the single word ERPs in response to the 2nd article of visually presented

SO and SS sentences, see Figure 14. See Figure 15 for a graphic illustration comparing the groups' brainwave responses together in one image at a frontal, central, and parietal electrode site. See Figure 16 for a graphic demonstrating each groups' brainwave responses to SO and SS sentences separately at the same frontal, central, and parietal locations. Table 19 summaries the single word topographic distribution findings.

Visual Main Verb

Visual N4/Left Anterior Negativity (300-500 ms).

Control group. There was no main effect of sentence type during the 300-500 ms latency window ($F < 1$). However, this was qualified by a significant interaction between sentence type and electrode site, $F(1,18) = 3.90$, $p < .01$. A distribution analysis was then conducted, revealing a significant interaction between sentence type and laterality, $F(1,18) = 5.79$, $p < .05$. The interaction between sentence type and anteriority was also significant, $F(1,18) = 6.12$, $p < .05$. Finally, a significant three-way interaction was also found between sentence type, anteriority, and laterality, $F(3,54) = 5.04$, $p < .01$.

Planned comparisons revealed that amplitudes elicited in response to SO sentences were significantly more negative than those elicited in response to SS sentences at both lateral prefrontal (M SO = -0.04 μV, M SS = 1.28 μV; $F(1,18) = 20.20$, $p < .001$) and medial prefrontal (M SO = -1.90 μV, M SS = 1.29 μV; $F(1,18) = 116.75$, $p < .001$) sites and both lateral frontal (M SO = 0.25 μV, M SS = 1.37 μV; $F(1,18) = 14.29$, $p < .001$) and medial frontal (M SO = -0.96 μV, M SS = 1.48 μV; $F(1,18) = 68.68$, $p < .001$) sites. These frontal differences between sentence type were also larger over medial prefrontal (M difference = 4.26 μV) and medial frontal sites (M difference = 3.18 μV) when compared with lateral prefrontal (M difference = 2.50 μV) and lateral frontal (M difference = 2.01 μV) sites. Smaller differences between sentence types were seen at the posterior region of the scalp. However, in contrast to the anterior sites, amplitudes in response to SS sentences were actually more negative than those in response to SO sentences at medial parietal (*M* SO = 0.52 μV, *M* SS = -0.84 μV; $F(1,18) = 21.32$, $p < .001$) and medial occipital sites (*M* SO = -0.02 μV, *M* SS = -0.91 μV; $F(1,18) = 9.01$, $p < .01$) and lateral parietal (*M* SO = 0.18 μV, *M* SS = -0.99 μV; $F(1,18) = 15.59$, $p < .001$) and lateral occipital sites (*M* SO = 0.32 μV, *M* SS = -0.89 μV; $F(1,18) = 16.72$, $p < .001$).

Dyslexic group. Unlike the controls, during the visual 300-500 ms latency window the dyslexic children did not demonstrate reliable differences in amplitudes evoked by SO (*M* = 0.46 μV) and SS (*M* = 1.33 μV) sentences, $F(1,18) = 1.20$, $p = .29$. There was also no interaction with electrode site, $F(1,18) = 1.02$, $p = .42$.

Group comparisons. The comparison ANOVA revealed a 3-way Group x Sentence Type x Electrode interaction, $F(61,2196) = 2.21$, $p < .05$. A distribution analysis indicated a marginal Group x Sentence Type x Anteriority interaction, $F(3,108) = 3.60$, $p = .056$. However, planned comparisons showed no differences in the brainwave amplitudes generated by controls and dyslexics in response to SS and SO sentences.

Visual Late Latency Window (500-900 ms)

Control group. No main effect of sentence type was found at this latency region, $F(1,18)$ 2.05, $p = .17$. However, a significant interaction between sentence type and electrodes site was detected, $F(1,18) = 5.21$, $p < .001$. A distribution analysis was performed on the mean amplitudes from the latency window. Results from this analysis showed a significant interaction between sentence type and anteriority, $F(3,54) = 9.21$, $p < .01$. There was also a significant interaction between sentence type and laterality, $F(1, 18) = 11.16$, $p < .01$. Lastly, a three-way interaction was detected between sentence type, anteriority, and laterality, $F(3,54) = 9.55, p < .001$.

Planned comparisons revealed that brainwave amplitudes elicited in response to SO sentences were more negative than those elicited in response to SS sentences at the anterior regions of the scalp, including: lateral prefrontal (*M* SO = 1.24 μV, *M* SS =3.74 μV), medial prefrontal (*M* SO = -0.32 μV, *M* SS = 4.87 μV), lateral frontal (*M* SO = 1.41 μV, *M* SS =3.45 μV), and medial frontal (*M* SO = 0.87 μV, *M* SS =5.06 μV) regions. Furthermore, these differences were largest at medial prefrontal (*M* difference = 5.26 μV; $F(1, 18) = 257.86, p < .001$) and medial frontal (*M* difference = 4.18 μV; $F(1, 18) = 167.59, p < .001$) sites in comparison to lateral prefrontal (*M* difference = 2.50 μV; $F(1, 18) = 60.04, p < .001$) and lateral frontal sites (*M* difference = 2.03 μV; $F(1, 18) = 39.63, p < .001$. In contrast, the amplitudes generated in response to SS sentences were actually significantly more negative than the amplitudes generated in response to SO sentences at the posterior scalp locations, including: lateral parietal (*M* SS = -1.55 μV, *M* SO = -0.71 μV; $F(1, 18) = 6.72, p < .05$) and medial parietal (*M* SS =-1.23 μV, *M* SO = -0.40 μV; $F(1, 18) = 7.42, p < .01$) locations, as well as lateral occipital (*M* SS =-1.26 μV, *M* SO = -0.28 μV; $F(1, 18) = 9.17, p < .01$) and medial occipital (*M* SS = -0.79 μV, *M* SO = .14 μV; $F(1, 18) = 8.37, p < .01$) locations. As the F values suggest, differences between sentence types were largest at the front, as opposed to the back, of the head.

Dyslexic group. Again, the dyslexic group did not show significant differences between visually presented SO (*M* = 0.91 μV) and SS sentences (*M* = .22 μV) at the main verb region, $F < 1$.

Group comparisons. The main ANOVA indicated a 3-way Group x Sentence type x Electrode interaction, $F(61,2196) = 2.80, p < .05$. A distribution analysis revealed a significant

Group x Sentence Type x Anteriority interaction, $F(3,108) = 4.36$, $p < .05$, as well as a significant Group x Sentence Type x Laterality x Anteriority interaction, $F(3,108) = 4.44$, $p < .01$. Planned comparisons demonstrated several differences between groups at various regions of the scalp. Brainwave amplitudes elicited by controls in response to SS sentences were more positive than those elicited by the dyslexic group at lateral prefrontal (*M* Typ = 3.74 μV, *M* Dys = 2.26 μV; $t(108) = 2.78$, $p < .01$) and lateral frontal sites (*M* Typ = 3.45 μV, *M* Dys = 2.36 μV; $t(108) = 2.04$, $p < .05$), as well as medial prefrontal (*M* Typ = 4.87 μV, *M* Dys = 2.15 μV; $t(108) = 5.09$, $p < .001$) and medial frontal sites (*M* Typ = 5.06 μV, *M* Dys = 2.91 μV; $t(108) = 4.02$, $p < .001$). On the other hand, brainwave amplitudes elicited by controls in response to SO sentences were more negative than those generated by the dyslexic group at medial prefrontal (*M* Typ = -0.32 μV, *M* Dys = 1.28 μV; $t(108) = 3.01$, $p < .01$) and medial frontal sites (*M* Typ = 0.87 μV, *M* Dys = 2.36 μV; $t(108) = 2.77$, $p < .01$). In contrast, the brainwave amplitudes generated by controls in response to SO were actually more positive than those demonstrated by the dyslexic group at the posterior regions of the scalp, including: the lateral parietal (*M* Typ = -0.71 μV, *M* Dys = -2.08 μV; $t(108) = 2.58$, $p < .001$), medial parietal (*M* Typ = -0.40 μV, *M* Dys = -2.41 μV; $t(108) = 3.77$, $p < .001$), lateral occipital (*M* Typ = -0.28 μV, *M* Dys = -2.28 μV; $t(108) = 3.65$, $p < .001$), and medial occipital regions (*M* Typ = 0.14 μV, *M* Dys = -1.65 μV; $t(108) = 3.36$, $p < .01$). For a schematic diagram of the single word ERPs in response to the main verb of visually presented SO and SS sentences, see Figure 17. See Figure 18 for a graphic illustration comparing the groups' brainwave responses together in one image at a frontal, central, and parietal electrode site. See Figure 19 for a graphic demonstrating each groups' brainwave responses to SO and SS sentences separately at the same frontal, central, and parietal locations.

Correlational Analysis

In order to get a more detailed picture of which abilities were accessed during the interpretation of complex sentence structures, partial correlations were conducted between SCP amplitudes at the 2nd article region (4th word) and all raw behavioural scores. Correlations were also examined between behavioural scores and SCP amplitudes at the main verb region (7th word). Because of the age range, age and gender were entered as control variables. This analysis was conducted between groups. The 2nd article and main verb regions were both chosen for further inspection because of past research suggesting these two regions of relative clause sentences are where differences in working memory load between sentences (or participant groups) are most apparent (King & Kutas, 1995). Correlations between specific reading measures and SCP amplitudes were only reported if the reading measure was significantly correlated with several (minimum of five-six) electrode amplitudes in the particular topographic region of interest. This was done in order to limit the possibility of Type I errors. After a set of correlations was identified between a particular behavioural measure and a number of electrode sites from a given scalp region, scatter plots of the data were created in order to assess the relevance of the correlations' directionality, as well as the details of the relationship between the two variables. Refer to Table 20 for a summary of the correlations between the amplitudes evoked in response to the 2nd article (4th word) of the SCPs and behavioural scores. Refer to Table 21 for a summary of those correlations between the main verb (7th word region) of the SCPs and behavioural scores.

Auditory 2nd Article

Control Group

Subject-subject 2nd article. There were no substantial groups of significant correlations between SCP amplitudes at any scalp location and behavioural measures.

Subject-object 2nd article. With the increased difficulty of the task, positive correlations were noted between central and posterior SCPs and phonological awareness (as measured by the CTOPP Segmenting Nonwords subtest). SCPs generated at the posterior scalp region were also positively correlated with comprehension. Inspection of the scatter plots indicated that higher levels of phonological awareness and comprehension ability increased as SCPs increased in amplitude. This finding suggests that the more skilled typical comprehenders utilized less effort than less skilled typical comprehenders when processing SO sentences.

Dyslexic Group

Subject-subject 2nd article. The dyslexic group demonstrated significant positive correlations between working memory questions and posterior and centrally generated SCPs, a finding absent in typical children. Inspection of the scatter plots indicated that for dyslexic children, higher scores on working memory questions was related to more positive SCPs, suggesting dyslexic children with stronger working memory demonstrated less effortful processing of auditory SS sentences in comparison to those with weaker working memory.

Subject-object 2nd article. Similar to the auditory SO correlations demonstrated by controls, for dyslexics, SCPs generated at frontal and posterior regions were positively correlated with measures of phonological awareness (CTOPP: Segmenting Nonwords and Elision subtests). SCPs generated at the posterior regions were also positively correlated with working memory recall scores. In each of these correlations, dyslexic children with higher behavioural scores demonstrated more positive SCPs at the 2nd article, demonstrating an ease in processing SO sentences in comparison to dyslexic children with lower behavioural scores. However, negative correlations were also noted between SCPs generated at the 2nd article, reading rate and text-level fluency. Inspection of the scatter plots indicated that in these cases, more negative amplitudes in response to SO sentences were significantly related to better reading speed and fluency scores. This finding suggests that the most fluent dyslexic readers exhibited the most effort when processing auditory SO sentences, most likely because less fluent readers were overwhelmed by the task.

Visual 2nd Article

Control Group

Subject-subject 2nd article. Negative correlations were noted between frontal SCPs and pseudo-word reading accuracy and also between posterior SCPs and phonological awareness (as measured by the CTOPP: Elision subtest). Both sets of correlations suggested that controls with better phonological awareness scores exerted more effort when reading (as demonstrated by more negative SCPs) than controls with lower phonological awareness scores. This suggests children with the lowest scores may have been overwhelmed by the task. Since age was controlled for during this analysis, it may be concluded that, while less proficient, these readers were not necessarily the youngest children.

Subject-object 2nd article. Controls demonstrated negative correlations between SCPs generated at the central and posterior regions of the scalp and phonological awareness (as measured by the CTOPP: Segmenting Words). There were also negative correlations between pseudo-word fluency and central SCPs. Inspection of the scatter plots indicated that higher scores on phonological awareness and reading fluency were related to more negative SCP amplitudes. This finding suggests that controls with better phonological awareness and fluency skills were utilizing more effort when reading than those with less phonological awareness and fluency skills most likely because those with less skill were overwhelmed by the task.

Dyslexic Group

Subject-subject 2^{nd} article. Similar to controls, children with dyslexia also demonstrated negative correlations between SCPs and phonological awareness (as measured by the CTOPP: Segmenting Words subtest). As indicated by more negative SCPs, dyslexics who exerted the most effort on the reading task were most likely to have a higher level of phonological awareness.

Subject-object 2^{nd} article. Indicative of the difficulty of the task, for the children with dyslexia there were no substantial groups of significant correlations between behavioural scores and SCP amplitudes. Smaller groups of positive correlations were noted between SCP scores, reading rate and fluency measures, suggesting that the more fluent dyslexic readers utilized less effortful processing than less fluent readers. However, negative correlations between SCPs generated at the 2^{nd} article and decoding ability (as measured by the Word Attack) indicated that lower decoding ability limited sentential processing. Dyslexic children with less decoding skills were also less likely to exert processing effort than dyslexic children with more decoding skill.

Auditory Main Verb

Control Group

Subject-subject main verb. For the control group, significant positive correlations were noted between SCPs generated in response to the main verb region of aurally presented sentences and phonological awareness (as measured by the CTOPP: Segmenting Words subtest). Control children with higher levels of phonological awareness demonstrated less effortful processing (as demonstrated by the relative positivity of their SCPs) than control children with lower levels of phonological awareness.

Subject-object main verb. The increased difficulty of processing the main verb of aurally presented SO sentences lead to several positive correlations between SCPs at more frontal regions, nonverbal reasoning and print exposure. SCPs generated across scalp locations were also significantly positively correlated with various measures of phonological awareness. Inspection of the scatter plots suggested that the controls who demonstrated the least difficulty with the task (as demonstrated by relatively more positive SCPs) had more reading experience, higher nonverbal reasoning ability and also higher levels of phonological awareness than controls who demonstrated more effortful processing when faced with the listening task.

Dyslexic Group

Subject-subject main verb. In the dyslexic group, significant positive correlations were noted between SCPs generated over the posterior region of the scalp and scores on working memory questions. Children with higher working memory question scores also generated more positive SCPs, indicating less effortful processing than children with lower working memory question scores.

Subject-object main verb. Similar to controls, for the dyslexic group, the increased difficulty of the SO processing task led to further positive correlations with SCPs generated at the main verb and phonological awareness (as measured by the CTOPP: Elision subtest), vocabulary, and working memory (as measured by the WISC Digits subtest). However, unlike the controls, the dyslexic group also demonstrated negative correlations between SCPs and text-level reading rate, accuracy, and comprehension. Inspection of the scatter plots indicated that children with higher levels of text-reading ability were also more likely to demonstrate more effortful processing when listening to the main verb of SO sentences.

Visual Main Verb

Control Group

Subject-subject main verb. Significant positive correlations were noted between SCPs generated at the front of the scalp and several measures of reading speed, fluency, and overall reading ability. Controls also demonstrated positive correlations between working memory capacity (as measured by the Working Memory Recall test) and centrally generated SCPs. The most fluent readers in the control group also generated the most positive SCPs.

Subject-object main verb. For typical children, SCPs generated at the frontal and central regions of the scalp were positively correlated with word-level reading accuracy and vocabulary. Controls with higher scores demonstrated relatively more positive SCPs in comparison to controls with lower scores. As previously mentioned, the elicitation of more positive SCPs demonstrates less effortful processing.

Dyslexic Group

Subject-subject main verb. Similar to controls during SS sentence reading, the dyslexic group demonstrated positive correlations between SCPs and fluency measures. Dyslexics also demonstrated correlations between working memory and SCPs. However, unlike the control group, the relationship between working memory and SCP amplitude was negative. Investigation of the scatter plots suggested that dyslexic children with more working memory capacity exerted more effortful processing than dyslexic children with less working memory capacity, suggesting lower working memory ability contributed to children's likelihood of becoming overwhelmed by the task.

Subject-object main verb. Negative correlations were noted between posterior SCPs generated in response to the main verb of visually presented SO sentences and working memory capacity (as measured by the Working Memory Questions test).

In summary, the dyslexic and control groups demonstrated fairly similar correlational relationships between behavioural scores and SCPs generated at the 2nd article and main verb of aurally presented SS and SO sentences. In contrast, the groups seemed to use somewhat different resources during the processing of visually presented sentences. For both groups, auditory SCPs were positively correlated with phonological awareness, reading experience and working memory. Reading fluency seemed to be a more relevant skill for the children with dyslexia, when compared with controls, particularly during the processing of the main verb region. The negative correlations between SCPs generated by the dyslexic group and fluency measures, suggests that dyslexic children with lower level reading fluency demonstrated less effortful processing than those with higher levels of reading fluency. While reading the relative clause sentence structures, both groups demonstrated negative correlations between brainwave amplitudes and phonological awareness. This finding indicates that a subset of less able readers in both groups demonstrated less effortful processing when reading than did readers with high phonological awareness. However, the significant correlations in each group particularly diverged when the children reached the main verb of visually presented sentences. While the control group demonstrated positive correlations primarily with measures of fluency, children with dyslexic demonstrated negative correlations with phonological awareness and working memory.

GENERAL DISCUSSION

Utilizing ERP measures, the present study investigated auditory and visual relative clause sentential processing in children with and without developmental dyslexia. Specifically, the comparison of SS and SO sentences was designed to disentangle how working memory capacity is deployed when faced with processing demands caused by varying levels of syntactic complexity. The research question was posed whether reading deficits seen in developmental dyslexia are totally attributable to difficulty with phonological processing, or if not, what the contribution of other abilities, such as syntactic awareness, is to reading ability. Since the working memory deficit in dyslexia can be accounted for by the degree of one's phonological limitation (Gottardo et al., 1996; Wagner & Torgesen, 1987), a focus of the study was to examine whether working memory capacity could account for differences between groups in syntactic sensitivity. Children were tested on a variety of standardized measures that tapped into levels of phonological sensitivity, automaticity (another facet of phonological processing), working memory capacity, syntactic sensitivity, vocabulary, print exposure, general word and text level reading accuracy, fluency, and comprehension, rate of reading, and overall reading ability. These tests were used as a baseline method of ensuring the children's linguistic ability fit their respective grouping. Results of these behavioural tests were also compared in multiple and hierarchical regression analyses, in order to test the unique variance in each reading measure that was accounted for by one of the primary abilities necessary for efficient reading: 1) working memory, 2) automaticity 3) syntactic awareness and 4) phonological awareness. Next, the brainwaves for each group were measured as they were elicited to SS and SO sentences in both the visual and aural modality. This modality comparison was constructed in order to disentangle those delays specifically attributable to working memory capacity, versus those specific to syntactic processing ability. While the sentences presented in the aural modality represent the same complex syntactic structure as those given in the visual modality, they involve less working memory capacity because they do not involve the added phonological processing task of converting graphemes to phonemes.

Behavioural Data

The correlational and multiple regression analyses indicated that out of the numerous reading related skills the children were tested on, phonological sensitivity, automaticity, working memory, and syntactic sensitivity were the measures that most contributed to reading success. Further hierarchical regression analyses were difficult to interpret in that results both supported and conflicted with past findings that presented evidence in favour of either the PSA or CLA.

Converging with past research, at the text-level, significant unique variance was attributable to both phonological processing and syntactic processing ability for several variables. This is an expected finding at the text-level because passage reading is a more intricate process than word reading in that it involves both phonetic and sentential level integration (Compton, Appleton, & Hosp, 2004). Even with the expected influence of syntactic sensitivity at the text-level, however, phonological sensitivity was a much stronger unique predictor. In fact, syntactic sensitivity did not account for significant unique variance in reading comprehension or in overall reading ability. These findings conflict with past research that has shown syntactic and phonological processing ability to be equal predictors in reading achievement (see Tunmer & Hoover, 1992). In fact, the findings seem to give reasonable support toward the phonological processing limitation hypothesis (Shankweiler et al., 1992), in that even at the text-level where it could be expected that syntactic sensitivity may play more of a role in reading ability, phonological sensitivity was still a much stronger independent predictor of reading skill for this sample of children.

Word reading, on the other hand, does not involve the multifaceted confound of sentential integration. Here, results should be more readily interpretable. In support of the phonological processing limitation hypothesis put forth by Shankweiler et al. (1992), only phonological sensitivity was a unique predictor of pseudo-word reading accuracy and word reading fluency. However, more problematic for this theory, syntactic sensitivity was found to predict a small portion of unique variance in word reading accuracy and pseudo-word reading fluency. In fact, comparable to the findings of Tunmer and Hoover (1992), for the pseudo-word reading fluency measure, the percent of unique variance accounted for by phonological and syntactic sensitivity was statistically equal. These results may point to the importance of other linguistic factors, aside from phonological sensitivity, in reading ability. However, the fact that syntactic sensitivity was such an inconsistent contributor in reading ability, only accounting for unique variance in two of the four word-level reading measures in the present data, suggests that interpretations should be made with caution.

The results should also be interpreted within the framework of test measurement validity. As has been documented in past literature, many tasks inadvertently measure more than the specific construct of interest (Gottardo et al., 1996). While the validity of measures of phonological sensitivity, such as the CTOPP subtests used in the present study, have been studied and documented extensively (Wagner et al., 1999), less work has been done on measures of syntactic sensitivity (Bowey, 1994). In fact, a specific complaint regarding these measures is that often they are confounded by working memory demands, and therefore unintentionally tap into further facets of phonological ability (Bowey, 1994). Upon closer examination of the measure used in the current study, the CELF sentence assembly, the test relies heavily on working memory capacity. For example, during the test children are shown four-five sentence fragments at once. Each fragment is specifically one-two words in length. Children must rearrange the fragments in their head, eventually verbalizing the correct sentence structure. In order to limit some of the phonological complexities inherent to the task (such as decoding the words), the fragments are first read to the children (Semel et al., 1995). However, the task can still become taxing to working memory, particularly for the poorer readers, who have potentially more difficulty keeping these sentence fragments in mind while working on their response. Furthermore, typical readers may actually have been rereading the lists multiple times. This would suggest method variance between the groups; while dyslexic children relied on memory, the typical children instead used reading skill, thereby freeing resources to focus on the task at hand.

ERP Effects

Single Word Effects

Both current working memory theory and earlier ERP studies on SS and SO sentential processing in adults has shown two specific points of divergence between these sentence types, the 2^{nd} article (4^{th} word) and the main verb (7^{th} word). These areas of interest serve as a frame of the area where the two sentences differ in processing demand, the relative and main verb clause (King & Just, 1991; King & Kutas, 1995; Müller et al., 1997; Brown et al., unpublished data). At these points in both aurally and visually presented sentences, adults elicit significantly more negative amplitudes in response to SO sentences than SS sentences between roughly 300-500 ms (King & Kutas, 1995; Müller et al., 1997; Brown et al., unpublished data). This effect is larger for those with poor comprehension or those with reading difficulties such as dyslexia (Brown et al., unpublished data; Neville et al., 1993. In the current study, single word analyses were undertaken at the same two word regions, the 2nd article (4th word) and main verb (7th word), for both aurally and visually presented sentences. These analyses occurred within two separate time windows, 300-500 ms and 500-900 ms. As was previously mentioned, the later time window was chosen as an area of interest because of the potential for delayed N400 and LAN effects, or the occurrence of the P600, a component associated with syntactic comprehension difficulties. As expected, across single word time windows both groups demonstrated more negative amplitudes in response to visually presented rather aurally presented sentences, indicating the increased difficulty of the reading task, compared with the listening task.

Auditory 2nd Article

In the auditory modality, both children with and without dyslexia performed similarly at the 2nd article, eliciting more negative amplitudes in response to SO rather than SS sentences in both time windows. In both groups, differences between sentence types were evenly distributed across the scalp. This suggests that at this early point in the sentence, both groups were processing the sentential information in a similar fashion. This finding is consistent with past research indicating that children with and without dyslexia respond similarly to semantic integration tasks when presented in an aural format (Bonte & Blomert, 2004; Sabisch et al., 2006).

Additionally, all the children seemed to interpret the beginning of the relative clause in much the same manner as adults with poor comprehension. In the ERP literature, the level of surprise at encountering the 2nd article is manifested by the negativity of the N400 response to

SO sentences relative to that produced by SS sentences (King & Kutas, 1995; Müller et al., 1997; Brown, unpublished data). It is here, at the 4th word of these sentence types, that listeners first realise they are encountering either a SS or SO structure (indicated by either a verb or an article respectively). As has been seen in the adult literature, poor comprehenders tend to be caught off guard by SO sentence structures (Brown et al., unpublished data; King & Kutas, 1995). Similarly, children in the present study elicited large differences between sentence types indicative of their surprise at encountering the less frequent SO structure. For poor comprehenders, the increased unexpectedness of the SO sentence type may be due to a failure to hold alternative sentence possibilities in mind while actively interpreting. It has been suggested that the reason for this difficulty is limited available working memory resources (King & Kutas, 1995). Given the limited working memory resources of all children compared to adults, it seems expected that they would behave in a similar manner as adults with limited working memory capacity in King and Kutas` study (1995).

The beginning of the relative clause could be a potentially overwhelming region for those with low working memory capabilities, such as children. Upon recognizing the SO sentence structure, listeners (or readers) must now be prepared to allocate resources toward storing previously encountered sentential information in working memory longer than anticipated. This can be problematic for those with no resources to spare. Because of these limitations, it is tempting to suggest that children may not possess the capacity to fully understand these sentence types. However, the pattern of ERP in response to the 2nd article suggests otherwise. If children were not able to adopt the SO interpretation of the sentence, presumably the resulting structure would be syntactically anomalous. Past studies in children and adults indicate that sentences containing syntactic violations elicit a P600 component at the region of ambiguity (Kaan et al., 2000; Oberecker et al., 2005; Sabisch et al., 2006). However in the current study, both groups instead demonstrated prolonged negativity throughout both time windows, indicating all children were able to generate and continue on with the alternate SO sentence structure.

One further note of consideration involves the topographic distribution of the N400 in children relative to adults. As has been reviewed, substantial relative clause studies in adults indicate that a processing difference between sentence types at the beginning of the relative clause should be manifested as a N400 effect (Brown et al., unpublished data; King & Kutas, 1995). In the present study, a N400 type effect was demonstrated in the expected word region, even though the topographical distribution of this effect was not prototypical of the adult component. While adult N400s tend to have a central-parietal distribution, in children the effect is more often reported as a frontal distribution or, as was found in the present study, a broad distribution across all regions of the scalp (Atchley et al., 2006; Holcomb et al., 1992). In both cases of child N400 distributions, the difference in topography in comparison to adults, suggests children employ considerably more resources when processing linguistic information.

Auditory Main Verb

At both latency periods of the aurally presented main verb, control children again demonstrated more negative amplitudes for SO than SS sentences. These effects were evenly distributed across the scalp, however visual inspection of the waveforms suggested a trend toward larger effects over the left anterior region. In contrast, children with dyslexia did not demonstrate differences between sentence types. In past relative clause research with adults, the difference between sentence types demonstrated at the main verb was hypothesized to be indicative of thematic role assignment (Friederici, 1995; 2002; Friederici, Hahne, & Mecklinger, 1996; King & Kutas, 1995; van den Brink & Hagoort, 2004). Upon hearing the 7th word (ie., the main verb) of either SS or SO sentences, listeners must determine who or what is the subject of the verb encountered. While both sentence types involve this assignment, working memory load should be greater in the case of the SO sentence structure, due to the increased duration of time the head noun of the sentence is held in working memory. Past studies have specifically implicated the LAN as an indication of the degree of load posed by a sentence type, with more negative amplitudes signifying greater working memory demand (King & Kutas, 1995). Again, the processing capacity of children, who were typical readers for their age, seemed comparable to adult poor comprehenders.

While generally memory load is indicated by larger LAN amplitudes, the lack of a LAN effect for the children with dyslexia deserves further consideration. One explanation, suggested by Hahne et al. (2004), is that the absence of a particular component in children may indicate processing is not taking place at an automatic level, though some integration and comprehension could be taking place. For example, these results would be consistent with findings that while 6-year-olds do not elicit early LAN components in response to passive sentence structures, they are able to correctly respond to questions regarding their content (Hahne et al., 2004). Similarly, adults with dyslexia who did not produce LANs in response to the main verb of SO sentences still performed at above 80% on related comprehension questions (Brown et al., unpublished data). A second and not necessarily exclusive hypothesis is that by the time the dyslexic children reached the main verb of the sentence, the group was simply overwhelmed by the complex sentence structures. However, given the dyslexic group's performance on the ERP comprehension questions, it is suggested that the children have not reached an automatic level of processing.

Visual 2nd Article

In comparison to the auditory single word results, a different trend was observed in response to visually presented sentences. At the 2nd article, control children demonstrated more negative amplitudes in response to SO rather than SS sentences in both time windows. Early on, these effects were particularly strong over medial sites across the scalp. However, in the later latency region, effects were strongest over medial anterior sites. These effects are in line with research that suggests that ERP components generally become more lateralized with experience and therefore with automaticity of processing (Morris, unpublished). As was previously mentioned, the N400 topography in children tends to vary substantially from that seen in adults, particularly in challenging tasks (Atchley et al., 2006; Holcomb et al., 1992). The frontal N400 elicited here is fairly prototypic of the childhood version of this component. Reasons for the frontal distribution have been speculated on (Holcomb et al., 1992). Generally, throughout adult and child ERP literature, frontal negativities have been associated with taxing levels of processing (Hahne et al., 2004; King & Kutas, 1995; Kluender & Kutas, 1993). In fact, it has been suggested that frontally distributed N400s in children may actually reflect the presence of a second overlapping negative waveform, particularly when tasks involve substantial processing difficulty or attention (Holcomb et al., 1992). The present results support this suggestion. Not only is the current study's relative clause task particularly demanding for children, the present task involves the further difficulty of reading, compared to the aural version. Interestingly, the frontal distribution of the N400 was only present for the more demanding task of reading (rather than in response to the listening task), further supporting the notion that the anterior topography of the N400 in children is associated with attentive and effortful semantic integration.

In contrast to typical children, children with dyslexia did not demonstrate reliable differences between sentence types in the 300-500 ms time window. However, they did elicit the expected negativity to SO sentences relative to SS sentences in the 500-900 ms region, suggesting a latency delay in the development of the effect in comparison to control children of the same age. Latency differences between adult and child waveforms are a common finding in the childhood ERP literature, particularly in children with dyslexia or other reading disabilities. These differences are generally indicative of slower processing speed (due to the difficulty of the task for these children) rather than qualitatively different methods of sentential processing (Atchley et al., 2006; Holcomb et al., 1992; Neville et al., 1993; Taylor & Baldeweg, 2002).

Visual Main Verb

For the visual main verb analyses, there were no main effects of sentence type for either the control or dyslexic children. However, for the controls, brainwaves elicited by SO sentences were more negative than those elicited by SS sentences only at medial, anterior sites. In contrast, at posterior regions, the waves in response to relative clause sentences were actually flipped, with amplitudes elicited in response to SS sentences occurring more negatively than those elicited by SO sentences.

While this was not an expected outcome, information gained from adult relative clause research suggests this effect does not necessarily conflict with past findings. Müller et al. (1997) found that in certain waves collected, poor comprehenders performed in a similar fashion. For example, while good comprehenders demonstrated a sustained negativity in waves generated in response to SO sentence structures, it was reported that this particular sample of poor comprehenders actually demonstrated more of a relative positivity, particularly at the back of the head. Müller et al. (1997) note that positivity in waveforms is sometimes generated in response to syntactically ambiguous sentences where the preferred interpretation (in this case an SS completion of the sentence) produces an incomplete sentence fragment. An example of one such positive waveform is the P600. As has already been discussed, the P600 generally occurs in response to syntactically anomalous sentences (Atchley et al., 2006; Kaan et al., 2000; Sabisch et al., 2006). A P600 response would suggest, that at this level of working memory load, typical children were unable to adopt the unexpected SO interpretation of the sentence, or at the very least, demonstrated effortful processing (Friederici, 1995; 2002; Friederici et al., 1996). In the present study the positivity demonstrated by typical children does not resemble a prototypic P600 component. Generally, the effect is manifested as a positive deflection with a very specific latency (usually at 600 msec post stimulus onset). In contrast, the positivity seen in the present results was continuously sustained from roughly 100-1000 msec after presentation of the main verb. While prolonged child P600 components have been noted in the literature, these effects generally do not start early in the time window (Friederici & Hahne, 2001). Furthermore, in the present study, the effect only occurred at the most posterior regions of the scalp, while the typical SO negativity was still seen at anterior regions. The negativity elicited by SO sentences at the front of the scalp suggests the typical children were successfully interpreting the sentence, or at the very least, eliciting the processing load indicative of successful integration. However, it is suggested that the positivity seen in the present study may denote difficulty in switching sentential interpretation 'gears.' In line with this hypothesis, some researchers have begun to suggest that P600-like positivities may simply reflect effortful syntactic processing more generally and not necessarily anomalous sentential interpretations (Kaan et al., 2000).

Multi-word ERPs

The previously presented single word analyses demonstrate substantial information regarding specific regions of interest, as suggested by working memory theory. However, when studying working memory, word by word analyses do not reach the heart of the issue, capacity for information storage over time. For this reason, SCPs were measured over the full duration of the sentence in order to shed light on the working memory capacity of dyslexics and children more generally. As in the single word analyses, as expected, both groups demonstrated more negative amplitudes in response to the visual task rather than the auditory task, thus indicating the increased complexity of reading compared to listening.

Auditory SCPs

As is suggested by the SCPs generated in response to aurally presented relative clause sentences, both groups had the ability to efficiently hold sentential information in active store, while interpreting the remainder of the sentence. In both groups the effect was evenly distributed across all regions of the scalp. However, for dyslexics, differences between sentence types at the final word were only displayed at anterior regions of the scalp. In past studies completed with both adults and children, more frontal distributions generally attest to the increased difficulty of processing demands (Hahne et al., 2004; Muller et al., 1997). Taking past findings into consideration, it is likely that by the 9th word of the sentence, dyslexic children's working memory capacity was over taxed in comparison to controls.

In contrast to past research on adults that has found slight right hemisphere asymmetry in response to aurally presented relative clauses, all effects were bilateral. While the right hemisphere may be specifically implicated in auditory processing, a hemisphere effect in children is an unlikely occurrence. Work completed on early component development in children suggests that brainwaves actually have different maturation rates depending on scalp location. This research suggests a more precocious development of the left hemisphere in comparison to the right, particularly when tasks involve linguistic processing (Taylor & Baldeweg, 2002). Furthermore, right hemispheric asymmetries are particularly unusual in tasks that are difficult, such as relative clause processing, both because of the advanced development of the left hemisphere and because in children difficult tasks typically generate greater negativity in both hemispheres, indicating the use of multiple resources (Hahne et al., 2004).

Visual SCPs

In contrast to the similarities observed during the auditory task, visual SCPs elicited while reading were distinctly different between groups. In dyslexic children, the SCPs elicited in response to SO sentences were only reliably more negative than those elicited in response to SS sentences at the 6th word of the sentence, during the demanding relative clause. Differences between sentence types approached significance at the 4th, 7th, and 8th word. These marginal amplitude differences between sentence types could suggest that a small subset of the children with dyslexia could read efficiently enough to differentiate both sentence types, while the others were overwhelmed, thus diminishing the strength of the result. These subsets of dyslexic readers are likely differentiated by age or severity of reading deficits, whereby older children or those with less severe difficulties could perform the task while younger or more disadvantaged readers could not. The behavioural scores of the dyslexic group support the suggestion that differences in the severity of some of the children's symptoms may have played a role in the visual SCP effect. While all children assessed fit the dyslexic profile, the behavioural scores of the group as a whole demonstrated a bimodal distribution where approximately half of the children were 1 standard deviation below mean reading ability and the other half were performing at 2 standard deviations below the mean. Visual inspection of the SCP amplitudes suggested that the better dyslexic readers elicited a greater difference between SS and SO sentences then did the most severely limited readers. Unfortunately, the size of the sample in the present study does not allow for closer inspection of age or symptom severity effects. As a group, the limited differences in SCP amplitude generated between sentence types suggests the inefficient and limited storage of sentential items in working memory in children with dyslexia (King & Kutas, 1995; Müller et al., 1997).

Control children on the other hand, demonstrated a significant difference between sentence types early in the relative clause that continued until the 8th word of the sentence. Several interactions with electrode site indicated that effects were largest at medial anterior sites over the left hemisphere. As has been previously discussed, these interactions attest to the extreme load on working memory for typical children while reading relative clause sentences (Hahne et al., 2004; Holcomb et al., 1992) Furthermore, as is indicated by the strong effects at medial electrodes, the children lacked automaticity of processing (Morris, unpublished). The absence of automaticity during visual presentation, but not aural presentation, demonstrates that the medial effect while reading was not due to inexperience with the sentence types or syntactic difficulty, but rather the excess load placed on working memory. In fact, reminiscent of dyslexic children's processing in the auditory modality, control children seem to reach their resource capacity by the last word of the visually presented sentence. Similar to dyslexics, controls only demonstrated differences between sentence types at the medial anterior region of the scalp. These results demonstrate the utility of multi-word ERPs in investigating working memory capacity. Many of the detailed effects just discussed were not apparent during single word measures. Single word components do not pick up on the specific demands caused by prolonged storage of information across the duration of the sentence.

The hemisphere asymmetry observed for typical children is interesting in that these effects have not been observed in adults (King & Kutas, 1995; Brown et al., unpublished). As was discussed in the previous section, these effects are most likely attributable to the general maturation asymmetry between the advanced development of the left hemisphere in relation to the right in children (Taylor & Baldeweg, 2002). Potentially, children utilize these resources when faced with difficult linguistic processing tasks, such as relative clause processing. This suggestion remains speculative, however, other single word ERP components related to phonological working memory, such as the LAN, document left specialization during taxing working memory load (Kluender & Kutas, 1993). It stands to reason that a similar effect might be observed across longer epochs.

Correlational Findings

Significant Correlations during Auditory Sentential Processing

During auditory sentence processing, dyslexic and control groups demonstrated similar patterns of correlations between behavioural measures and SCPs generated in response to the 2nd article and also in response to the main verb of SS and SO sentences. For both groups auditory SCPs were associated with working memory capacity and measures related to language experience (exposure to print and vocabulary measures). Children with greater working memory capacity and more experience with reading elicited relatively more positive SCP amplitudes, demonstrating less effortful sentential processing in comparison to children with lower working memory capacity or less reading experience. Both children with dyslexia and controls also demonstrated strong positive correlations between phonological awareness and SCP amplitudes at both sentence regions (2nd article and main verb). For both groups, children with higher levels of phonological awareness demonstrated relatively more positive SCP amplitudes, indicative of their less effortful linguistic processing in comparison to children with lower levels of phonological awareness. These findings further emphasize the importance of phonological awareness in oral language development. As was previously mentioned, ERP has shown the early occurring relationship between infant and toddler language ability and later phonological awareness (Espy et al., 2004; Friederici, 2005). These findings in infants and young children suggest phonological awareness is very much related to one's ability to segment words from a stream of speech. The more detailed representation provided by ERPs in the present study further demonstrates the importance of phonological awareness in auditory language processing, even in older children who are faced with a linguistically complex task.

While groups performed similarly in some regards while listening to complex sentences, their patterns of correlations also differed, particularly during SO sentence presentation. Specifically, reading fluency skill was more strongly related to auditory processing for the children with dyslexia, compared to controls. Inspection of the negative correlations between fluency and SCP scores suggests that more fluent reading in the dyslexic group was related to more effortful processing of SO sentences. This finding suggests that children below a certain level of reading fluency may have been overwhelmed by the auditory sentence complexity, therefore giving up on attempts at comprehension. A comparison of the various fluency measures correlated with SCPs at the two regions of interest suggests that more children with dyslexia were hindered by fluency deficits at the main verb than at the 2nd article of the aurally presented sentences. For example, more basic word-level reading fluency was negatively correlated with

SCPs generated in response to the 2nd article, while higher order text-level measures were negatively correlated with SCPs generated in response to the main verb.

Significant Correlations during Visual Sentential Processing

Similar to correlational patterns in the aural modality, both controls and children with dyslexia demonstrated negative correlations between SCPs generated in response to the 2nd article of visually presented SS sentences and measures of phonological awareness. In both groups, children with higher levels of phonological awareness exerted more effortful processing when encountering the 2nd article than children with lower levels of phonological awareness. This finding suggests that children below a certain phonological skill level were limited by their deficit to the point where the processing task was overwhelming. Children with more efficient phonological processing skills were able to complete the task, though their SCPs indicate it was especially taxing to do so. In the control group, the subset of children unable to efficiently complete the task was the most inexperienced readers, which was possibly related to age. For the dyslexic group this subset may also have included younger readers. However, as indicated by the bimodal distribution of language skills in the dyslexic group, the children overwhelmed by the task were actually those with the most severe reading disabilities.

During visual presentation of SO sentences however, the pattern of correlations between the groups markedly differed. Interestingly, when overtaxed the controls demonstrated similar negative correlations between fluency and SCPs in response to SO sentences as the dyslexic group did during the auditory task. This finding suggests that at the 2nd article of SO sentences, controls with more reading fluency generated more negative SCPs, indicative of increased processing strain than did controls with less reading fluency. This negative relationship again suggests that the youngest (or least fluent) typical readers were overwhelmed by the processing demands of SO sentences, while more fluent readers were able to comprehend the sentences, but exerted considerable effort in order to do so. For dyslexics, there was also a trend toward a relationship between visual SCPs at the 2nd article and fluency measures. However, this was limited to a small number of central electrode sites. This may suggest that a subset of more fluent dyslexic readers were able to keep up with the processing demands of the SO sentences, however most were overwhelmed by the task. One note of consideration is necessary when interpreting findings related to reading fluency. In the current study, both groups demonstrated correlations between brainwave amplitudes and reading fluency. The method of ERP presentation likely inflates the importance of reading fluency compared with typical reading situations because words are presented one at a time at a predetermined rate. Children with less efficient reading fluency skills may have difficulty keeping up with the rate of word presentation.

As was previously mentioned, during the visual presentation of relative clause sentences groups still displayed similar patterns of correlations between SCPs and behavioural measures at the 2nd article. However, the linguistic skills utilized by the two groups markedly diverged at the main verb of visually presented sentences. During SS sentence presentation, typical readers demonstrated positive correlations between SCPs and reading fluency, overall reading ability, and working memory. In contrast, for the dyslexic group, SCPs elicited at the main verb of SS sentences were negatively correlated with phonological awareness and working memory capacity. These relationships suggest that, as a group, typical children were able to actively read the SS sentences and hold sentential information in mind for comprehension, while dyslexic children were specifically limited by their lower levels of phonological awareness and phonological working memory.

During visual presentation of the main verb of SO sentences, both groups demonstrated substantial difficulty. For typical children, SCPs were positively correlated with vocabulary and word-reading accuracy measures. These correlations suggest that during the processing of the more complex SO sentences, even typical children were reduced to simply attempting to correctly identify each word as it appeared on the computer screen, with few resources left for holding the sentential information in working memory. For dyslexic children, the negative correlations between SCPs and working memory questions demonstrate that this group was also limited by working memory capacity. Lack of correlations with other reading measures suggests that a large portion of the dyslexic group did not have enough resources to effectively decode and comprehend at this late point in the sentence.

Implications for Theories Regarding the Underlying Cause of Dyslexia

The results of this study contribute to the debate regarding the underlying cause of developmental dyslexia. As mentioned previously, the phonological processing limitation hypothesis posits that all linguistic deficits demonstrated in dyslexia are caused by a low-level phonological processing deficit which impedes any higher level process that builds upon information obtained at this fundamental level (Shankweiler et al., 1992). When applied to the current study, the theory would predict that any syntactic or grammatical deficits demonstrated by dyslexics, when processing the SS and SO sentences, must be clearly attributable to phonological processing through working memory. Deficits solely found in the visual modality can be conclusively tied to phonological working memory decoding deficits because both the auditory and visual presentation of SS and SO sentences involve the exact same level of syntactic complexity and only differ in working memory demands. In the aural modality, it may be more difficult to disentangle those deficits caused by working memory capacity or syntactic deficits. Aural relative clause sentences carry the same level of syntactic complexity as the visual version and, though less taxing to working memory, still utilize a high level of working memory resources. The CLA on the other hand, suggests that processing in dyslexia is stilted by an even more rudimentary level of linguistic processing that therefore causes separate deficits in a multitude of areas (Dickenson et al., 2003). Deficits demonstrated when processing aurally presented sentences or the elicitation of components suggestive of syntactic difficulty would refute the phonological processing limitation hypothesis, thereby giving credence to the CLA.

In support of the PSA, results of the current study demonstrated that early in the auditory presentation of SS and SO sentences, mainly at the beginning of the relative clause, children with dyslexia performed in a similar manner to typical children, showing no suggestion of a syntactic deficit. Therefore, at this point, children with dyslexia did not seem any more surprised by the SO sentences than controls and also seemed no less likely than typical children to generate alternative sentence possibilities when faced with SO sentence structures.

In contrast, results elicited by children at the main verb of the aurally presented SS and SO sentences are at first less conclusively in favour of either the PSA or CLA. A clear result in favour of the PSA would involve children in both groups continuing to process this area of the sentence in a similar manner. In support of this theory, it has been demonstrated that adults with dyslexia process aurally presented sentences in the same manner as typical adults (Brown et al., unpublished data). However, this was not the case in children with dyslexia. In comparison with controls, the dyslexic group had substantially more difficulty at the main verb region, becoming either overtaxed by the complexity of the sentences by this point, or showing delayed levels of automaticity in comparison to age matched typical children. These findings could be the result of either syntactic or working memory related difficulties. At this late point in the sentence (the 7th

of nine words) it could be tempting to suggest working memory was most likely becoming overtaxed, since phonological working memory deficits have been long documented in the dyslexia research (Bowey, 2005; Brown et al., unpublished; Gottardo et al, 1996). This seems particularly likely considering the fact that differences between dyslexic and control groups demonstrated during the processing of aurally presented complex sentences eventually dissipates by adulthood (Brown et al., unpublished data). Furthermore, the component utilized in the current study, as a method of comparison between the groups, is more a measure of working memory demands than syntactic processing (Kluender & Kutas, 1993; King & Kutas, 1995; Kaan et al., 2000; but see Friederici, 1995; 2002; Friederici et al., 1996). However, this area of aurally presented relative clause sentences does not afford the clear disentanglement of working memory and syntactic processing.

One way of elucidating those deficits specifically attributable to either working memory or syntactic difficulty is to attempt to utilise specific ERP components distinctly associated with each area of linguistic processing in question. As has already been discussed, the P600 component is one associated with the processing of syntactically anomalous sentence structures (Friederici, 1995; Oberecker et al., 2005), need for syntactic re-analysis when reading garden-path sentences, and more generally, difficulty with syntactic processing (Kaan et al., 2000). Presumably, the development of a P600 component would be demonstrated during single word analyses if at any time the children were unable to syntactically interpret the relative clause sentences or simply had a particular difficulty processing the syntactic aspects of the sentences. However, during this time window, generally children with dyslexia generated the opposite trend, prolonged negativities. An area worthy of further consideration, and the closest example of syntactic difficulties in the present study, was the posterior positive response elicited by typical children in response to visually presented SO sentences. It was suggested that this effect may have been caused by effortful syntactic processing. The fact that this effect was not seen in the (syntactically identical) aural modality suggests that syntactic difficulty was in fact mediated by working memory, a finding consistent with the PSA.

Interestingly, the modality comparison utilized in the present experiment also emphasizes the similarity in linguistic processing between the two groups of children when phonological sensitivity was controlled. While typical children displayed no difficulties in processing the aurally presented sentences, once the added demands of phoneme to grapheme conversion were involved, the group seemed to mirror many of the difficulties previously demonstrated in the aural modality by children with dyslexia. For example, SCPs demonstrated by children with dyslexia in the aural modality almost identically matched the SCPs demonstrated by controls in the visual modality. For both groups, though information was stored over the duration of the sentence, overburdened working memory capacity became apparent at the last word, where differences between sentence types were only significant at the front of the head. In general, both groups seemed to generate more anterior effects when working memory was specifically taxed.

As was just reviewed, groups performed quite similarly in some regards. However, there were differences in their trends of topographical distribution. Throughout various effects investigated, typical children repeatedly demonstrated stronger effects at medial rather than lateral sites, particularly when processing resources were overburdened. As was previously discussed, it has been suggested that more medial effects demonstrate lack of experience in a given processing task, or lack of automaticity at that given skill (Morris, unpublished). Interestingly, a similar trend was not observed in the children with dyslexia. Intuitively, one would assume that dyslexics would be more likely than controls to display this effect, instead of vice versa. One possible explanation is that dyslexics are processing at a stage below pre-automaticity. For example, it has been shown that children often elicit precursors (to) or topographic manipulations of adult waveforms when at a pre-automatic stage of processing (Hahne et al., 2004). In comparison to adults, these components generally involve extremely large amplitudes or the involvement of added regions of the scalp (Hahne et al., 2004; Holcomb et al., 1992; Taylor & Baldeweg, 2002). However, it has also been demonstrated that young children sometimes perform above chance on behavioural questions prior to their generation of precursor effects (Hahne et al., 2004). These variations in medial electrode trends between groups do not necessarily insinuate qualitative differences in the development of automaticity. Though these effects are related to experience, in typical children they were specifically generated in response to the more challenging visual modality rather than the aural modality. Following working memory theory postulated by Just and Carpenter (1992), these findings suggest it is the added resources needed for phonological working memory (because of the grapheme to phoneme conversion) that lead to decreased efficiency, causing typical children to behave as if they were less experienced readers. Therefore, automaticity differences can also be related to phonological processing limitations.

A finding worthy of further consideration is the group differences found in hemispheric laterality during the processing of visual SCPs. In the current study, typical children displayed stronger effects over the left hemisphere, while children with dyslexia instead demonstrated a bilateral distribution during the elicitation of SCPs in response to visually presented SS and SO sentences. Because of the lack of research on SCPs in children, the implications of this finding are unclear. Due to the low level of significance found between sentence types for the dyslexic group, the findings could be the result of considerable variance in SCP amplitudes, potentially caused by either young children or the most severely impaired readers who were overwhelmed by the processing task. However, variation within the dyslexic group may also signify that a skill, such as syntactic processing, differs between controls and dyslexics, or potentially even within specific subsets of dyslexic readers.

There is the possibility that the varying hemispheric trends between groups could shed further light on aspects of syntactic sensitivity. In the past, a small number of ERP studies have found lateralization differences between dyslexics and controls (Khan, Frisk, & Taylor, 1999; Landwehrmeyer, Gerling, & Wellesch, 1990; Neville et al., 1993). In particular, it has been found that reading impaired children who also demonstrate severe syntactic deficits tend to display right hemisphere asymmetry while performing linguistic tasks (Neville, 1993). It has been suggested that these hemisphere differences demonstrate a syntactic processing abnormality, at least in specific subsets of reading impaired children (Neville, 1993). The current group of dyslexic readers and the group previously discussed by Neville et al. (1993) differed in their level of syntactic deficits. In the present study, dyslexic readers did not demonstrate more pronounced deficits in syntactic processing compared with other reading related skills. However, this discrepancy between the two dyslexic groups could simply point to inaccuracies in behavioural test measures, not in actual levels of syntactic sensitivity. While the current study's dyslexia group did not demonstrate a right hemisphere effect while reading, the lateralization of their results still differed from typical readers. There is the potential that the present hemispheric differences found between control and dyslexic groups could still be indicative of specific syntactic deficiencies in dyslexia not detected by behavioural tests. However, the current study was not designed to focus on such differences in lateralization. Therefore, while the findings of the current study generally substantiate the PSA, further consideration of hemispheric differences between typical and dyslexic readers is necessary.

The results of the current study are consistent with the PSA, in that the differences in linguistic processing between groups were for the most part limited to the visual modality, suggesting phonological working memory deficits, not syntactic deficits were the underlying problem for this group of dyslexic children. Furthermore, the investigation of the time window of the P600, an ERP component elicited specifically during arduous syntactic processing, confirms that this positivity was absent during auditory processing of syntactically complex sentences. This result suggests that it was not syntactic complexity that overburdened children with dyslexia. With this in mind, differences that were noted in several ERP components associated with working memory limitations, demonstrate that working memory capacity was the specific deficit that led to the inefficient processing of syntactic structures in comparison to age matched controls. These findings are of course qualified by differences found between groups in topographic distributions. However, these differences were only noted in the visual modality where phonological processing deficits were exacerbated. Potentially these differences in laterality could be related to differences in phonological processing. However, since at the present time interpretations of this effect are unclear, there is still the possibility that they may relate to a different process or set of processes than phonological development.

Differences and Similarities Between the Sentential Processing of Adults and Children with and without Dyslexia

As was previously mentioned, the current study undertaken with children with and without dyslexia is part of a larger ongoing project designed to focus not only on the differences between sentential processing in dyslexic and typical reading children, but also on the differences in linguistic strategies undertaken by adults and children with and without reading impairment. When the present results in children were considered in light of those found in adults, several relationships emerged indicating the relevance of age and reading group (dyslexic or typical) in the development of linguistic skills. At the visually presented 2nd article, superior syntactic processing seemed more reflective of age (and therefore, linguistic experience) than reading ability. For example, in adult readers, only the dyslexic group demonstrated surprise or difficulty at generating an alternative SO sentence structure, as indexed by an N400 effect (Brown et al., unpublished data). In contrast, both control and dyslexic children demonstrated difficulty at the 2nd article of visually presented SO sentence structures. In other words, both groups of children behaved similar to less competent adult readers when faced with syntactically complex sentential processing. In contrast, when processing the main verb of visually presented relative clause sentences, differences were more related to reading group, as opposed to age. In both adult and child readers, only controls elicited LAN effects, indicating that dyslexic readers struggled with holding sentential information related to thematic role assignment in working memory. This is a particularly strong finding when it is considered that phonological working memory limitations inherent in dyslexia reduced the processing capabilities of adults with the deficit to a level below that of the typical 8-12-year-olds in this study. All together, single word effects elicited while reading indicate that phonological working memory (or phonological skills more generally) is an explicit area of difficulty for dyslexics of any age.

Single word effects elicited by adults and children during aural sentence presentation also suggest that difficulty lies at the level of phonological working memory. Though in the visual modality typical children demonstrated stronger phonological working memory capacity than adults with dyslexia, during the same syntactic task in the aural modality, dyslexic and typical adults performed similarly, both producing LANs at the main verb of SO sentences. The discrepancy between the processing capabilities of dyslexic adults from the visual to aural modality demonstrates the scope of the phonological deficit inherent in dyslexia, even in compensated adults. This finding provides strong support for the PSA, in that adults performed equally on the syntactic task after added complexity caused by phonologically related skills was controlled (i.e., during the listening task). Furthermore, regardless of modality, *all* children demonstrated more difficulty generating the uncommon SO sentence, as indicated by the N400 elicited in response to the 2nd article. In contrast, neither adult group demonstrated this surprise at encountering the alternative SO relative clause sentence. These findings again suggest that syntactic awareness is more related to age than reading ability because the skill seems to follow a similar developmental trajectory in both groups of children.

Furthermore, the correlations between SCPs elicited in response to the main verb of relative clause sentences and various behavioural measures indicate the linguistic skills most utilized by each group. Typical children generally demonstrated the same relationships as adults, employing vocabulary, reading accuracy and working memory when reading. This suggests controls decoded and kept pace with the individual words as they were displayed on the computer screen, while actively storing sentential information in working memory for comprehension. Notably, when processing the more complex SO sentences, typical children behaved similar to dyslexic adults. When overtaxed, both dyslexic adults and typical children relied on reading fluency, simply attempting to read each individual word with no resources left to hold information in working memory. While both dyslexic adults and children demonstrated strong relationships with fluency, children also demonstrated negative correlations with phonological awareness and working memory, specifically indicating that phonological deficits limit the processing capabilities of dyslexic readers.

Limitations of the Current Study and Future Directions

Although the results of the current study inform theories regarding the underlying cause of dyslexia, there are certain limitations to the research. For example, the behavioural measure of syntactic sensitivity utilized in the current study potentially confounded the two separate constructs of syntax and working memory. Therefore, the contribution of syntactic sensitivity may have been inflated. This should be considered when interpreting the hierarchical regression analyses and the correlations between SCPs and the syntactic measure. The confound of working memory and syntactic ability in behavioural tests is a common problem in the field (Bowey, 1994). Thus, future research should be designed to evaluate the validity of various measurements of syntactic awareness.

While the current research demonstrates the relationship between dyslexia and various aspects of linguistic processing, there are limitations to its generalizability. This study includes a wide age range of boys and girls. Therefore, while the results broadly illustrate differences between children with and without dyslexia, these findings do not elucidate the specific maturational changes in the development of adult-like ERP components related to linguistic processing. Further research in large samples of children is needed in order to elucidate the specific timing and sequencing of sentential processing in both child clinical and typical populations.

The current study noted differences in the hemispheric lateralization of the visual SCP in children with and without dyslexia. Further research on the prototypic topographic distribution of this waveform would help to elucidate the meaning of the hemispheric differences between typical and dyslexic children. Once this is clarified, researchers may be able to create experimental paradigms that target specific aspects of linguistic processing, such as syntactic processing or phonological processing. This may help in elucidating the processes represented by the hemisphere effects found in the present study.

Conclusion

The results of the current study indicate that the syntactic deficits seen in dyslexia are mediated by phonological working memory capacity. This specific research project was designed to test two opposing theories regarding the underlying cause of dyslexia, the CLA and the PSA. The findings suggest that it is a low-level phonological processing limitation, which in turn affects higher level processes such as phonological working memory and syntax, that accounts for all deficits seen in dyslexia.

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Appendix

Sentences Used in the ERP Component of the Experiment

Item	Modality	Sentence Type	Sentence
1.	visual	SS	The parents who paid the babysitter ate the food.
	visual	SO	The babysitter who the parents paid ate the food.
	auditory	SS	The mayor who introduced the speaker sang the song.
	auditory	SO	The speaker who the mayor introduced sang the song.
2.	visual	SS	The monster that scared the child went to sleep.
	visual	SO	The child who the monster scared went to sleep.
	auditory	SS	The rabbit that sniffed the mouse dug the hole.
	auditory	SO	The mouse that the rabbit sniffed dug the hole.
3.	visual	SS	The child who sent the grandma hit the car.
	visual	SO	The grandma who the child sent hit the car.
	auditory	SS	The dinosaur that spotted the bird guarded the eggs.
	auditory	SO	The bird that the dinosaur spotted guarded the eggs.
4.	visual	SS	The t-rex that escaped the caveman ate the meat.
	visual	SO	The caveman that the t-rex escaped ate the meat.
	auditory	SS	The robber who hit the runner hid the watch.
	auditory	SO	The runner who the robber hit hid the watch.
5.	visual	SS	The donkey that kicked the man climbed the hill.
	visual	SO	The man who the donkey kicked climbed the hill.
	auditory	SS	The fireman who lifted the girl won the medal.
	auditory	SO	The girl who the fireman lifted won the medal.
6.	visual	SS	The kid who fought the brother kicked the bike.
	visual	SO	The brother who the kid fought kicked the bike.
	auditory	SS	The man who questioned the star held the book.
	auditory	SO	The star who the man questioned held the book.
7.	visual	SS	The lion that cleaned the cubs played the game.
	visual	SO	The cubs that the lion cleaned played the game.
	auditory	SS	The doctor who healed the child took the pills.
	auditory	SO	The child who the doctor healed took the pills.
8.	visual	SS	The reporter who attacked the man told the lie.
	visual	SO	The man who the reporter attacked told the lie.
	auditory	SS	The student who hated the teacher hid the answers.

	auditory	SO	The teacher who the student hated hid the answers.
9.	visual	SS	The chef who helped the girl washed the dishes.
	visual	SO	The girl who the chef helped washed the dishes.
	auditory	SS	The child who bit the dentist carried the doll.
	auditory	SO	The dentist who the child bit carried the doll.
10.	visual	SS	The man who chose the banker added the numbers.
	visual	SO	The banker who the man chose added the numbers.
	auditory	SS	The sheriff who guarded the convict told the lie.
	auditory	SO	The convict who the sheriff guarded told the lie.
11.	visual	SS	The man who fired the lawyer missed the meeting.
	visual	SO	The lawyer who the man fired missed the meeting.
	auditory	SS	The dad who heard the boy stopped the car.
	auditory	SO	The boy who the dad heard stopped the car.
12.	visual	SS	The doctor who cured the mother picked the flowers.
	visual	SO	The mother who the doctor cured picked the flowers.
	auditory	SS	The mother who washed the baby had the party.
	auditory	SO	The baby who the mother washed had the tantrum.
13.	visual	SS	The child who ignored the mother broke the lamp.
	visual	SO	The mother who the child ignored broke the lamp.
	auditory	SS	The hunter who shot the deer ate the bread.
	auditory	SO	The deer that the hunter shot ate the bread.
14.	visual	SS	The boy who chased the girl caught the fish.
	visual	SO	The girl who the boy chased caught the fish.
	auditory	SS	The woman who brushed the horse saw the pony.
	auditory	SO	The horse that the woman brushed saw the pony.
15.	visual	SS	The nanny who trusted the child cleaned the house.
	visual	SO	The child who the nanny trusted cleaned the house.
	auditory	SS	The father who held the boy passed the ball.
	auditory	SO	The boy who the father held passed the ball.
16.	visual	SS	The traveler who followed the guide missed the bus.
	visual	SO	The guide who the traveler followed missed the bus.
	auditory	SS	The girl who bothered the sister rode the bike.
	auditory	SO	The sister who the girl bothered rode the bike.
17.	visual	SS	The boy who picked the player liked the game.
	visual	SO	The player who the boy picked liked the game.
	auditory	SS	The jogger who passed the man enjoyed the park.
	auditory	SO	The man who the jogger passed enjoyed the park.

18.	visual	SS	The waitress who served the grandpa liked the game.
	visual	SO	The grandpa who the waitress served liked the game.
	auditory	SS	The mom who watched the children liked the sunshine.
	auditory	SO	The children who the mom watched liked the sunshine.
19.	visual	SS	The son who visited the dad hugged the family.
	visual	SO	The dad who the son visited hugged the family.
	auditory	SS	The coach who carried the boy cheered the team.
	auditory	SO	The boy who the coach carried cheered the team.
20.	visual	SS	The boy who lost the dog walked the streets.
	visual	SO	The dog that the boy lost walked the streets.
	auditory	SS	The doctor who saw the patient gave the candy.
	auditory	SO	The patient who the doctor saw gave the candy.
21.	visual	SS	The child who liked the star followed the crowd.
	visual	SO	The star who the child liked followed the crowd.
	auditory	SS	The child who patted the bunny ate the carrots.
	auditory	SO	The bunny that the child patted ate the carrots.
22.	visual	SS	The policeman who grabbed the robber climbed the stairs.
	visual	SO	The robber who the policeman grabbed climbed the stairs.
	auditory	SS	The farmer who milked the cow helped the calf.
	auditory	SO	The cow that the farmer milked helped the calf.
23.	visual	SS	The girl who gave the puppy held the leash.
	visual	SO	The puppy that the girl gave held the leash.
	auditory	SS	The boy who bugged the girl moved the chair.
	auditory	SO	The girl who the boy bugged moved the chair.
24.	visual	SS	The nurse who treated the patient visited the family.
	visual	SO	The patient who the nurse treated visited the family.
	auditory	SS	The mom who promised the kids made the cookies.
	auditory	SO	The kids who the mom promised made the cookies.
25.	visual	SS	The witch who cursed the lady waved the wand.
	visual	SO	The lady who the witch cursed waved the wand.
	auditory	SS	The dad who missed the grandpa rocked the baby.
	auditory	SO	The grandpa who the dad missed rocked the baby.
26.	visual	SS	The mommy who tickled the baby held the bottle.
	visual	SO	The baby who the mommy tickled held the bottle.
	auditory	SS	The dog that smelt the boy ate the meat.
	auditory	SO	The boy who the dog smelt ate the meat.

27.	visual	SS	The bully who tripped the boy held the lunch.
	visual	SO	The boy who the bully tripped held the lunch.
	auditory	SS	The cat that scratched the girl watched the rain.
	auditory	SO	The girl who the cat scratched watched the rain.
28.	visual	SS	The lady who rode the horse ate the apple.
	visual	SO	The horse that the lady rode ate the apple.
	auditory	SS	The mom who hugged the boy baked the cake.
	auditory	SO	The boy who the mom hugged baked the cake.
29.	visual	SS	The vet who fixed the puppy saved the day.
	visual	SO	The puppy that the vet fixed saved the day.
	auditory	SS	The horse that licked the girl kicked the fence.
	auditory	SO	The girl that the horse licked kicked the fence.
30.	visual	SS	The father who changed the baby liked the toy.
	visual	SO	The baby who the father changed liked the toy.
	auditory	SS	The parent who cuddled the boy read the story.
	auditory	SO	The boy who the parent cuddled read the story.
31.	visual	SS	The runner who impressed the fans enjoyed the race.
	visual	SO	The fans that the runner impressed enjoyed the race.
	auditory	SS	The child who wrote the writer drank the juice.
	auditory	SO	The writer who the child wrote drank the juice.
32.	visual	SS	The father who fed the hens took the nap.
	visual	SO	The hens that the father fed took the nap.
	auditory	SS	The jogger who walked the dog ran the track.
	auditory	SO	The dog that the jogger walked ran the track.
33.	visual	SS	The father who drove the kids cleaned the house.
	visual	SO	The kids who the father drove cleaned the house.
	auditory	SS	The swimmer who stopped the boy visited the beach.
	auditory	SO	The boy who the swimmer stopped visited the beach.
34.	visual	SS	The principal who blamed the girl met the parents.
	visual	SO	The girl who the principal blamed met the parents.
	auditory	SS	The boy who pushed the sister hurt the cat.
	auditory	SO	The sister who the boy pushed hurt the cat.
35.	visual	SS	The winner who bet the loser finished the race.
	visual	SO	The loser who the winner bet finished the race.
	auditory	SS	The boy who bumped the girl scored the goal.
	auditory	SO	The girl who the boy bumped scored the goal.
36.	visual	SS	The clown who tricked the children told the joke.

	visual	SO	The children who the clown tricked told the joke.
	auditory	SS	The girl who dried the dog grabbed the stick.
	auditory	SO	The dog that the girl dried grabbed the stick.
37.	visual	SS	The worker who wanted the boss closed the box.
	visual	SO	The boss who the worker wanted closed the box.
	auditory	SS	The mailman who found the dog drank the water.
	auditory	SO	The dog that the mailman found drank the water.
38.	visual	SS	The bully who hurt the boy rode the bike.
	visual	SO	The boy who the bully hurt rode the bike.
	auditory	SS	The grandpa who caught the fish liked the water.
	auditory	SO	The fish that the grandpa caught liked the water.
39.	visual	SS	The mother who greeted the guest dropped the purse.
	visual	SO	The guest who the mother greeted dropped the purse.
	auditory	SS	The artist who drew the child made the picture.
	auditory	SO	The child who the artist drew made the picture.
40.	visual	SS	The brother who knocked the sister hid the book.
	visual	SO	The sister who the brother knocked hid the book.
	auditory	SS	The mother who hired the nanny carried the baby.
	auditory	SO	The nanny who the mother hired carried the baby.
41.	visual	SS	The scientist who knew the boy won the prize.
	visual	SO	The boy who the scientist knew won the prize.
	auditory	SS	The grandma who cooked the lobster touched the water.
	auditory	SO	The lobster that the grandma cooked touched the water.
42.	visual	SS	The mother who calmed the child made the tea.
	visual	SO	The child who the mother calmed made the tea.
	auditory	SS	The student who told the teacher finished the homework.
	auditory	SO	The teacher who the student told finished the homework.
43.	visual	SS	The mommy who rocked the child sang the song.
	visual	SO	The child who the mommy rocked sang the song.
	auditory	SS	The girl who teased the sister held the doll.
	auditory	SO	The sister who the girl teased held the doll.
44.	visual	SS	The dad who coached the team won the game.
	visual	SO	The team who the dad coached won the game.
	auditory	SS	The nurse who married the farmer planted the corn.
	auditory	SO	The farmer who the nurse married planted the corn.
45.	visual	SS	The boy who tapped the teacher wrote the note.
	visual	SO	The teacher who the boy tapped wrote the note.

	auditory	SS	The dragon that saved the king started the fire.
	auditory	SO	The king who the dragon saved started the fire.
46.	visual	SS	The aunt who named the baby liked the visit.
	visual	SO	The baby who the aunt named liked the visit.
	auditory	SS	The scientist who taught the boy ate the apple.
	auditory	SO	The boy who the scientist taught ate the apple.
47.	visual	SS	The bride who kissed the father chose the song.
	visual	SO	The father who the bride kissed chose the song.
	auditory	SS	The captain who watched the crew sailed the sea.
	auditory	SO	The crew who the captain watched sailed the sea.
48.	visual	SS	The swimmer who left the swimmer felt the sand.
	visual	SO	The girl who the swimmer left felt the sand.
	auditory	SS	The aunt who quieted the baby rolled the ball.
	auditory	SO	The baby who the aunt quieted rolled the ball.
49.	visual	SS	The owner who ordered the worker earned the money.
	visual	SO	The worker who the owner ordered earned the money.
	auditory	SS	The witch who poked the frog cast the spell.
	auditory	SO	The frog that the witch poked cast the spell.
50.	visual	SS	The son who met the grandpa cut the turkey.
	visual	SO	The grandpa who the son met cut the turkey.
	auditory	SS	The builder who called the man fixed the problem.
	auditory	SO	The man who the builder called fixed the problem.
51.	visual	SS	The boy who cheered the player hit the homerun.
	visual	SO	The player who the boy cheered hit the homerun.
	auditory	SS	The soldier who copied the general swept the floor.
	auditory	SO	The general who the soldier copied swept the floor.
52.	visual	SS	The woman who dressed the model took the picture.
	visual	SO	The model who the woman dressed took the picture.
	auditory	SS	The family who thanked the mover carried the table.
	auditory	SO	The mover who the family thanked carried the table
53.	visual	SS	The baby who loved the mother hugged the bear.
	visual	SO	The mother who the baby loved hugged the bear.
	auditory	SS	The dad who surprised the kids gave the candy.
	auditory	SO	The kids who the dad surprised gave the candy.
54.	visual	SS	The babysitter who believed the child told the lie.
	visual	SO	The child who the babysitter believed told the lie.
	auditory	SS	The cousin who hid the child opened the door.

	auditory	SO	The child who the cousin hid opened the door.
55.	visual	SS	The baby who loved the mother hugged the bear.
	visual	SO	The mother who the baby loved hugged the bear.
	auditory	SS	The friend who fooled the girl took the picture.
	auditory	SO	The girl who the friend fooled took the picture.
56.	visual	SS	The boy who shared the kittens drank the milk.
	visual	SO	The kittens that the boy shared drank the milk.
	auditory	SS	The runner who raced the uncle crossed the finish.
	auditory	SO	The uncle who the runner raced crossed the finish.
57.	visual	SS	The mommy who touched the daddy wore the ring.
	visual	SO	The daddy who the mommy touched wore the ring.
	auditory	SS	The child who climbed the dad held the doll.
	auditory	SO	The dad who the child climbed held the doll.
58.	visual	SS	The librarian who aided the students carried the books.
	visual	SO	The students who the librarian aided carried the books.
	auditory	SS	The grandpa who timed the runner held the watch.
	auditory	SO	The runner who the grandpa timed held the watch.
59.	visual	SS	The child who pulled the bunny dug the hole.
	visual	SO	The bunny that the child pulled dug the hole.
	auditory	SS	The detective who spied the con hid the money.
	auditory	SO	The con who the detective spied hid the money.
60.	visual	SS	The girl who brought the friend watched the TV.
	visual	SO	The friend who the girl brought watched the TV.
	auditory	SS	The boy who invited the kids gave the gifts.
	auditory	SO	The kids who the boy invited gave the gifts.

Table 1
Example of relative clause sentences used in the current ERP experiment.

	Sentence Regions		
Sentence Type	*Pre Relative Clause*	*Relative Clause*	*Main Verb Phrase*
Subject Relative (SS)	The girl who	chased the boy	crossed the street.
Object Relative (SO)	The girl who	the boy chased	Crossed the street.

Table 2

Between group participant characteristics.

	Reading Condition				
	Typical		Dyslexic		
Standardized Measures	M	SD	M	SD	F
	Phonological Awareness/Sensitivity				
CTOPP Elision	11.45	2.62	6.10	2.22	48.394***
CTOPP Segmenting Words	11.10	1.59	8.30	2.25	20.69***
CTOPP Segmenting Nonwords	11.30	1.38	9.20	2.35	11.85***
	Automaticity				
CTOPP Rapid Digit Naming	9.47	2.09	6.70	2.56	13.667***
CTOPP Rapid Letter Naming	10.15	2.43	7.70	2.58	9.55**
	Reading Accuracy				
Word Level:					
Word ID	107.55	9.80	77.05	11.90	78.28***
Word Attack	103.85	10.46	77.70	9.90	65.94***
Text Level:					
GORT Accuracy Subscale	10.55	2.09	3.40	2.14	114.44***
	Reading Fluency				
Word Level:					
TOWRE Sight Word Efficiency					
TOWRE Phonemic Decoding	104.70	10.06	82.00	12.83	38.77***
Text Level:					
GORT Fluency Subscale	11.35	3.42	3.20	2.46	74.73***
GORT Rate Subscale	11.50	2.72	4.85	3.18	50.38***
	Reading Comprehension				
GORT Total Reading Ability	23.30	3.69	10.40	4.07	110.36***
GORT Passage Comprehension	11.90	2.04	7.20	2.04	52.79***
	Working Memory				
WISC Digits	9.6	2.28	6.7	2.22	16.56***
Verbal Working Memory: Recall	0.42	0.98	-0.48	0.77	10.39**
Verbal Working Memory: Questions	0.33	0.98	-0.46	0.64	8.93**
	Syntax Awareness/Sensitivity				
CELF	9.90	1.86	6.50	1.70	36.36***
	Vocabulary				
PPVT	114.45	9.99	95.60	23.55	10.86**
	Print Exposure				
Title Recognition Questionnaire	0.27	0.91	-0.27	1.01	3.20
	Nonverbal Reasoning				
MAT	106.50	9.50	104.05	7.10	0.853
Age in years	10.36	1.40	10.82	1.47	1.033
Gender	12 boys, 8 girls		13 boys, 7 girls		
Handedness	15 RH, 5 LH		15 RH, 5 LH		

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 3

Intercorrelations among the behavioural standard scores for children with and without dyslexia.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Reading Accuracy																					
1. Word Attack st. Score	-	.927**	.789**	.529*	.725**	.763**	.814**	.635**	-.114	.392	.252	.280	.460*	.503*	.697**	.068	.184	.462*	.397	.382	.348
2. Word ID st. score	.636**	-	.817**	.568**	.685**	.811**	.827**	.764**	.047	.344	.210	.224	.343	.360	.665**	.135	.105	.468*	.465*	.231	.493*
3. GORT Accuracy	.566**	.740**	-	.732**	.771**	.951**	.883**	.838**	-.060	.279	.173	.086	.618**	.542*	.756**	.416	.400	.583**	.240	.224	.569**
Reading Fluency																					
4. TOWRE Sight Word Efficiency	.626**	.917**	.737**	-	.765**	.739**	.820**	.607**	-.116	.282	.078	-.012	.702**	.742**	.325	.280	.143	.339	.103	.351	.391
5. TOWRE Phonemic Decoding st. score	.714**	.791**	.555*	.789**	-	.775**	.812**	.607**	-.177	.361	.363	.359	.683**	.649**	.490*	.231	.104	.553*	.101	.328	.469*
6. GORT Fluency	.696**	.883**	.814**	.828**	.793**	-	.900**	.842**	-.130	.333	.139	.010	.537*	.442	.606**	.373	.384	.510*	.260	.243	.640**
7. GORT Rate	.708**	.849**	.760**	.883**	.805**	.917**	-	.812**	-.009	.364	.195	.140	.601**	.583**	.517*	.348	.360	.529*	.432	.347	.447*
Reading Comprehension																					
8. GORT Reading	.604**	.824**	.815**	.742**	.626**	.921**	.829**	-	.422	.241	.202	.043	.450	.247	.510*	.654**	.447*	.503*	.579**	.225	.609**
9. GORT Comprehension	.365	.578**	.644**	.480*	.292	.630**	.547*	.883**	-	-.118	.149	.067	-.046	-.292	-.077	.582**	.173	.094	.632**	-.040	.027
Phonological Awareness/ Sensitivity																					
10. Elision	.169	.372	.479*	.270	.233	.352	.218	.455*	.483*	-	.203	.266	.181	.244	.181	-.078	-.041	.290	.126	.346	.313
11. Segmenting Words	-.168	-.093	.127	-.077	-.296	-.021	-.096	.084	.192	.246	-	.538*	.043	.241	.288	.351	.032	.538*	.010	.228	.185
12. Segmenting NonWords	-.277	-.264	-.174	-.420	-.485*	.793**	-.502*	-.218	.035	.187	-.296	-	-.053	.221	.157	-.203	-.247	.340	.177	.365	.080
Automaticity																					
13. RAN digits	.506*	.564**	.534*	.714**	.675**	.637**	.718**	.437	.103	.033	-.066	.619**	-	.704**	.481*	.433	.419	.249	.070	.283	.224
14. RAN letters	.650**	.675**	.568**	.740**	.718**	.673**	.758**	.479*	.142	-.042	-.347	-.545*	.736**	-	.400	.113	.204	.375	-.057	.444*	.026

Working Memory																					
15. WISC digits	.225	.434	.602**	.392	.147	.463*	.365	.548*	.535*	.198	-.107	.002	.270	.277	-	.279	.250	.598**	.103	.037	.428
16. WM recall	.238	.295	.030	.224	.197	.077	.052	.148	.203	.031	-.016	.083	-.225	.086	.039	-	.680**	.430	.294	-.028	.260
17. WM Questions	.225	-.018	-.067	.433	-.012	-.032	-.093	-.018	.003	.019	-.339	.069	-.525*	.004	-.072	.545*	-	.276	.229	.016	-.044
Syntactic Awareness/Sensitivity																					
18. CELF	.325	.641**	.449*	.586**	.504*	.528*	.627**	.502*	.364	-.042	-.069	-.316	.290	.324	.208	.348	.044	-	.150	.042	.271
Vocabulary																					
19. PPVT	-.071	.090	.083	.115	.067	-.047	-.059	.065	.186	.721**	.013	.017	-.131	-.225	-.077	.082	.033	-.045	-	.376	.226
Print Exposure																					
20. Title Recognition Questionnaire	.180	.133	-.061	.165	.246	.018	.003	.041	.059	-.041	.068	-.060	.106	.041	-.094	.607**	-.042	.250	-.001	-	.285
Nonverbal Reasoning																					
21. MAT SS	.332	.558*	.657**	.601**	.422	.532*	.554*	.578**	.511*	.433	.243	.135	.227	.349	.357	.144	-.130	.407	.192	-.102	-

*p < 0.05; **p < 0.01 Above diagonal – typical children, below diagonal – children with dyslexia

Table 4

Intercorrelations among the behavioural standard scores across all participants.

Behavioural Measures (SS)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Reading Accuracy																					
1. Word Attack	-	.918**	.895**	.811**	.878**	.904**	.900**	.876**	.654**	.713**	.478**	.356**	.662**	.668**	.676**	.444**	.454**	.729**	.412**	.383*	.321*
2. Word ID		-	.931**	.897**	.881**	.939**	.934**	.938**	.750**	.748**	.495**	.349*	.659**	.642**	.708**	.486**	.383*	.800**	.477**	.325*	.409**
3. GORT Accuracy			-	.872**	.861**	.960**	.921**	.956**	.756**	.771**	.572**	.389*	.690**	.636**	.760**	.509**	.472**	.791**	.461**	.276	.425**
Reading Fluency																					
4. TOWRE Sight Word Efficiency				-	.882**	.885**	.932**	.857**	.640**	.658**	.410**	.169	.794**	.782**	.602**	.336*	.214	.731**	.402*	.361*	.437**
5. TOWRE Phonemic Decoding					-	.904**	.907**	.840**	.570**	.687**	.441**	.286	.766**	.739**	.595**	.348*	.281	.770**	.386*	.390*	.413**
6. GORT Fluency						-	.951**	.690**	.954**	.740**	.509**	.300	.702**	.641**	.710**	.514**	.486**	.782**	.413**	.305	.466**
7. GORT Rate							-	.924**	.698**	.690**	.455**	.206	.767**	.736**	.653**	.467**	.422**	.798**	.395*	.306	.426**
Reading Comprehension																					
8. GORT Reading								-		.760**	.565**	.366*	.639**	.555**	.698**	.467**	.415**	.784**	.494**	.300	.420**
9. GORT Comprehension									-	.638**	.542**	.397*	.413**	.302	.542**	.538**	.370*	.636**	.528**	.220	.261
Phonological Awareness																					
10. Elision										-	.562**	.485**	.436**	.428**	.516**	.327*	.315*	.592**	.626**	.309	.346*
11. Segmenting Words											-	.6.6**	.292	.187	.366*	.383*	.161	.525**	.289	.265	.250
12. Segmenting NonWords												-	-.073	.012	.311	.198	.156	.306	.267	.207	.160
Automaticity																					
13. RAN digits													-	.790**	.544**	.320*	.226	.525**	.184	.295	.266
14. RAN letters														-	.499**	.287	.291	.537**	.081	.319*	.213
Working Memory																					
15. WISC digits															-	.280	.265	.632**	.245		.407**
16. WM recall																-	.721**	.491**	.234	.335*	.135

17. WM Questions	-	.379*	.219	.112	-.078
Syntactic Awareness					
18. CELF		-	.339*	.295	.333*
Vocabulary					
19. PPVT			-	.214	.224
Print Exposure					
20. Title Recognition Questionnaire				-	.143
Nonverbal Reasoning					
21. MAT SS					-

*p < 0.05; **p < 0.01

Table 5

Multiple regression analyses predicting word level reading accuracy using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Model	Total R^2	β	t value
Word ID SS	0.82		
1. Automaticity		0.26	2.85**
2. Phonological Awareness		0.35	3.83***
3. Working Memory		0.17	1.60
4. Syntactic Awareness		0.32	2.69*
Word Attack SS	0.75		
1. Automaticity		0.33	3.07**
2. Phonological Awareness		0.35	3.20**
3. Working Memory		0.17	1.30
4. Syntactic Awareness		0.22	1.58

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 6

Multiple regression analyses predicting text level reading accuracy using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Model	Total R^2	β	t value
GORT Reading Accuracy SS	0.86		
1. Automaticity		0.27	3.28**
2. Phonological Awareness		0.38	4.72***
3. Working Memory		0.27	2.86**
4. Syntactic Awareness		0.21	2.05*

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 7

Multiple regression analyses predicting word level reading fluency using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Model	Total R^2	β	t value
TOWRE Sight Word Efficiency SS	0.84		
1.Automaticity		0.57	6.49***
2. Phonological Awareness		0.23	2.58*
3. Working Memory		0.08	0.78
4. Syntactic Awareness		0.22	1.98
TOWRE Phonetic Decoding SS	0.83		
1. Automaticity		0.46	5.27***
2. Phonological Awareness		0.26	2.89**
3. Working Memory		0.01	.089
4. Syntactic Awareness		0.36	3.19**

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 8

Multiple regression analyses predicting text level reading rate and fluency using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Model	Total R^2	β	t value
GORT Reading Rate SS	0.86		
1. Automaticity		0.44	5.42***
2. Phonological Awareness		0.24	2.88**
3. Working Memory		0.05	0.49
4. Syntactic Awareness		0.38	3.58***
GORT Reading Fluency SS	0.83		
1. Automaticity		0.29	3.22**
2. Phonological Awareness		0.34	3.74***
3. Working Memory		0.23	2.12*
4. Syntactic Awareness		0.26	2.22*

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 9

Multiple regression analyses predicting reading comprehension and total reading ability using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Model	Total R^2	β	t value
GORT Reading Comprehension SS	0.60		
1. Automaticity		-0.09	-.64
2. Phonological Awareness		0.39	2.79**
3. Working Memory		0.44	2.72**
4. Syntactic Awareness		0.13	0.73
GORT Overall Reading SS	0.83		
1. Automaticity		0.16	1.78
2. Phonological Awareness		0.39	4.27***
3. Working Memory		0.33	3.08**
4. Syntactic Awareness		0.22	1.90

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 10

Hierarchical regression analyses predicting word level reading accuracy using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Step Variable	Mult R	Mult R^2	ΔR^2	F change
Word ID SS				
1. Working Memory	0.72	0.51	0.51	39.18***
2. Automaticity	0.81	0.65	0.14	14.39***
3. Phonological Awareness	0.89	0.78	0.13	21.06***
4. Syntactic Awareness	0.91	0.82	0.04	7.25*
2. Syntactic Awareness	0.83	0.68	0.17	18.64***
3. Automaticity	0.86	0.74	0.06	8.82**
4. Phonological Awareness	0.91	0.82	0.08	14.67***
Word Attack SS				
1. Working Memory	0.67	0.46	0.46	30.85***
2. Automaticity	0.79	0.62	0.17	15.89***
3. Phonological Awareness	0.86	0.73	0.11	14.83***
4. Syntactic Awareness	0.87	0.75	0.02	2.50
2. Syntactic Awareness	0.76	0.58	0.13	10.99**
3. Automaticity	0.82	0.68	0.10	10.38**
4. Phonological Awareness	0.87	0.75	0.08	10.25**

* $p < 0.05$; ** $p < 0.01$, *** $p < 0.001$

Table 11

Hierarchical regression analyses predicting text level reading accuracy using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Step Variable	Mult R	Mult R^2	ΔR^2	F change
GORT Reading Accuracy SS				
1. Working Memory	0.76	0.58	0.58	51.30***
2. Automaticity	0.84	0.71	0.13	16.10***
3. Phonological Awareness	0.92	0.84	0.13	29.76***
4. Syntactic Awareness	0.93	0.86	0.02	4.21*
2. Syntactic Awareness	0.84	0.70	0.12	14.52***
3. Automaticity	0.88	0.77	0.07	10.35**
4. Phonological Awareness	0.93	0.86	0.09	22.26***

* $p < 0.05$; ** $p < 0.01$, *** $p < 0.001$

Table 12

Hierarchical regression analyses predicting word level reading fluency using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Step Variable	Mult R	Mult R^2	ΔR^2	F change
Sight Word Efficiency				
1. Working Memory	0.65	0.43	0.43	27.49***
2. Automaticity	0.87	0.76	0.34	51.52***
3. Phonological Awareness	0.91	0.82	0.06	10.71**
4. Syntactic Awareness	0.92	0.84	0.02	3.90
2. Syntactic Awareness	0.76	0.57	0.15	12.42***
3. Automaticity	0.90	0.81	0.23	42.07***
4. Phonological Awareness	0.92	0.84	0.03	6.63*
Phonetic Decoding				
1. Working Memory	0.65	0.42	0.42	26.46***
2. Automaticity	0.84	0.70	0.28	34.14***
3. Phonological Awareness	0.89	0.79	0.08	13.69***
4. Syntactic Awareness	0.91	0.83	0.05	10.18**
2. Syntactic Awareness	0.79	0.63	0.21	20.78***
3. Automaticity	0.89	0.79	0.16	27.76***
4. Phonological Awareness	0.91	0.83	0.04	8.34**

* p < 0.05; ** p < 0.01, *** p < 0.001

Table 13

Hierarchical regression analyses predicting text level reading rate and fluency using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Step Variable	Mult R	Mult R^2	ΔR^2	F change
GORT Reading Rate SS				
1. Working Memory	0.68	0.46	0.46	31.24***
2. Automaticity	0.85	0.72	0.27	34.78***
3. Phonological Awareness	0.90	0.80	0.78	13.68***
4. Syntactic Awareness	0.93	0.86	0.05	12.85***
2. Syntactic Awareness	0.82	0.67	0.21	23.43***
3. Automaticity	0.91	0.82	0.15	29.27***
4. Phonological Awareness	0.93	0.86	0.04	8.26**
GORT Reading Fluency SS				
1. Working Memory	0.74	0.54	0.54	43.98***
2. Automaticity	0.83	0.69	0.15	16.75***
3. Phonological Awareness	0.90	0.80	0.11	20.06***
4. Syntactic Awareness	0.91	0.83	0.03	4.91*
2. Syntactic Awareness	0.82	0.69	0.14	15.33***
3. Automaticity	0.87	0.76	0.08	10.88**
4. Phonological Awareness	0.91	0.83	0.07	14.00***

* $p < 0.05$; ** $p < 0.01$, *** $p < 0.001$

Table 14

Hierarchical regression analyses predicting reading comprehension and total reading ability using automaticity, phonological awareness, working memory, and syntactic awareness measures across all participants (N = 40).

Step Variable	Mult R	Mult R^2	ΔR^2	F change
GORT Reading Comprehension SS				
1. Working Memory	0.69	0.47	0.47	32.67***
2. Automaticity	0.69	0.47	0.00	0.12
3. Phonological Awareness	0.77	0.59	0.12	10.41**
4. Syntactic Awareness	0.77	0.60	0.01	0.53
2. Syntactic Awareness	0.71	0.51	0.04	2.69
3. Automaticity	0.71	0.51	0.00	0.03
4. Phonological Awareness	0.77	0.60	0.09	7.79**
GORT Overall Reading SS				
1. Working Memory	0.77	0.60	0.60	54.30***
2. Automaticity	0.82	0.67	0.08	8.20**
3. Phonological Awareness	0.90	0.81	0.14	24.93***
4. Syntactic Awareness	0.91	0.83	0.02	3.60
2. Syntactic Awareness	0.84	0.70	0.11	12.68***
3. Automaticity	0.86	0.73	0.03	4.14*
4. Phonological Awareness	0.91	0.83	0.09	18.26***

* $p < 0.05$; ** $p < 0.01$, *** $p < 0.001$

Table 15

Summary of task analysis for each slow potential region with a significant interaction.

	Task Analysis - SCPs				
Word	1st	2nd	3rd	4th	5th
Task x Grp	F < 1	F < 1	F (1,37) = 3.40	F < 1	F < 1
Task x S	F < 1	F < 1	F < 1	F < 1	F < 1
Task x El	F (61,2257) = 14.59**	F (61,2257) = 9.58**	F < 1.60	F (61,2257) = 6.05**	F (61,2257) = 4.61***
Task x Grp x S	F < 1	F < 1	F < 1	F < 1	F (1,37) = 4.84*
Task x Grp x El	F < 1	F (61,2257) = 65.52**	F < 1.10	F < 1.10	F < 2.0
Task x S x El	F < 1	F < 1	F < 1	F < 1	F < 1.40
Tk x Grp x S x El	F < 1	F < 1	F < 1.20	F(61,2257) = 2.40*	F < 1.80

Word	6th	7th	8th	9th
Task x Grp	F < 1	F < 1	F < 1.68	F < 1
Task x S	F < 1	F < 1	F < 1	F (1,37) = 2.54
Task x El	F (61,2257) = 4.21**	F (61,2257) = 4.37**	F (61,2257) = 6.12**	F (61,2257) = 5.60**
Task x Grp x S	F < 1	F < 1	F < 1	F < 1
Task x Grp x El	F (61,2257) = 2.80*	F (61,2257) = 2.53**	F (61,2257) = 3.43***	F (61,2257) = 2.37
Task x S x El	F < 1	F < 1	F < 1	F < 1.03
Tk x Grp x S x El	F < 1.50	F < 1.85	F < 1.60	F (61,2257) = 2.65**

* p < 0.05; ** p < 0.01; *** p < 0.001

Table 16

Summary of slow cortical potential results by sentence type over each word region.

	Typical Children		Dyslexic Children	
Word	Sentence Type	Sentence Type x Electrode Site	Sentence Type	Sentence Type x Electrode Site
Auditory				
1st	F < 1	F < 1	1.38	F < 1
2nd	F < 1	F < 1	F < 1	F < 1
3rd	F < 1	F < 1	F < 1	F < 1
4th	F < 1	F < 1	F < 1	1.04
5th	2.68	F < 1	F < 1	F < 1
6th	4.26*	F < 1	7.97*	1.00
7th	6.49*	F < 1	7.02*	1.63
8th	6.59*	F < 1	7.03*	1.75
9th	5.96*	F < 1	9.87**	2.40*
Visual				
1st	F < 1	F < 1	F < 1	F < 1
2nd	F < 1	F < 1	F < 1	1.47
3rd	2.52	F < 1	1.07	1.05
4th	2.62	1.12	3.80	1.36
5th	9.25**	5.06***	F < 1	F < 1
6th	21.72**	3.79***	4.96*	1.66
7th	11.15**	2.09*	3.69	1.51
8th	15.65***	3.13**	3.44	1.10
9th	3.30	2.57**	1.10	F < 1

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 17

Summary of topographic distribution analysis for each slow potential word region with a significant interaction.

Dyslexics Children – Auditory Presentation					
Word	5th	6th	7th	8th	9th
S x H					F < 1
S x L					F < 1
S x A					F (3,54) = 5.18*
S x H x L					F < 1
S x H x A					F < 1
S x L x A					F (3,54) = 2.89
S x H x A x L					F < 1

Typical Children – Visual Presentation					
Word	5th	6th	7th	8th	9th
S x H	F (1,18) = 3.31	F < 1.99	F < 1	F < 1.08	F < 1
S x L	F < 1	F (1,18) = 6.02*	F (1,18) = 8.31**	F (1,18) = 9.37**	F (1,18) = 7.78*
S x A	F (3,54) = 19.97***	F (3,54) = 8.73**	F (3,54) = 5.90*	F (3,54) = 7.19**	F (3,54) = 9.24**
S x H x L	F (1,18) = 4.57*	F < 2.35	F < 1	F < 2.30	F (1,18) = 4.43*
S x H x A	F (3,54) = 4.27*	F (3,54) = 4.08*	F < 1	F (3,54) = 3.63*	F < 2.27
S x L x A	F < 1	F < 1	F < 1	F < 1.93	F < 1.60
S x H x A x L	F < 1.07	F < 1	F < 1.53	F < 2.05	F < 1.59

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 18

Summary of single word results for all word regions of interest.

	Typical Children		Dyslexic Children	
Effect Latency Region	N4/LAN 300-500 ms	Late Latency 500-900 ms	N4/LAN 300-500 ms	Late Latency 500-900 ms
Auditory				
2nd Article				
Sentence Type	21.20***	20.04***	6.47*	13.03**
Sentence Type x Electrode	1.16	1.77	1.21	1.91
Main Verb				
Sentence Type	4.52*	6.25**	1.14	1.19
Sentence Type x Electrode	1.98	2.07	F < 1	F < 1
Visual				
2nd Article				
Sentence Type	16.89***	29.22***	1.34	7.20*
Sentence Type x Electrode	2.17	2.68*	1.05	F < 1
Main Verb				
Sentence Type	F < 1	2.05	1.20	F < 1
Sentence Type x Electrode	3.90***	5.21***	1.02	F < 1

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 19

Summary of topographic distribution analysis for each single word region with a significant interaction.

Typical-Visual Presentation				
Latency Window	N4/LAN 300-500 ms	N4/LAN 300-500 ms	Late Latency 500-900 ms	Late Latency 500-900 ms
Word	2nd Article	Main Verb	2nd Article	Main Verb
S x H	F < 1	F < 1.60	F (1,18) = 3.34	F < 1
S x L	F (1,18) = 3.88	F (1,18) = 5.79*	F (1,18) = 4.38	F (1,18) = 11.16**
S x A	F < 1	F (3,54) = 6.12*	F < 1	F (3,54) = 9.21**
S x H x L	F < 1.82	F(1,18) = 4.29	F (1,18) = 4.31	F < 2.78
S x H x A	F < 1	F < 1.34	F < 1	F < 1.15
S x L x A	F < 1.45	F(3,54) = 5.04**	F (3,54) = 2.99*	F (3,54) = 9.56***
S x H x A x L	F < 1	F < 1	F < 1	F < 1

Table 20

Summary of correlations between behavioural measures and SCP amplitudes in response to sentence type at the 2nd article (4th word) . Directionality of each correlation is indicated by a + or – sign. The abbreviations PA = phonological awareness, & WM = working memory.

Auditory Condition	Typical Children		Children with Dyslexia	
Electrode Region	SS	SO	SS	SO
Anterior			(+)WM: questions	(-) Fluency: word, pseudoword-level, & text-level, (-)Rate, (+)PA: segmenting nonwds
Central		(+)PA: segmenting nonwords	(+) WM: questions	(+)WM: questions
Posterior		(+)PA: segmenting nonwords, (+)Comprehension	(+)WM: questions	(+)PA: elision, (+) WM: recall, questions
Visual Condition				
Anterior	Accuracy: pseudoword level			
Central		(-)PA: segmenting words		
Posterior	(-) PA: elision	(-) Fluency: pseudoword-level, (-) PA: segmenting words	(-) PA: segmenting words	

Table 21

Summary of correlations between behavioural measures and SCP amplitudes in response to sentence type at the main verb (7th word). Directionality of each correlation is indicated by a + or – sign. The abbreviations PA = phonological awareness, & WM = working memory.

Auditory Condition	Typical Children		Children with Dyslexia	
Electrode Region	SS	SO	SS	SO
Anterior	(+) PA: segmenting words	(+) PA: segmenting words & nonwords, (+) Nonverbal Reasoning		(-) Rate, (-) Text-level Accuracy & Fluency
Central		(+) PA: segmenting nonwords, (+) Print Exposure		(+) Vocabulary
Posterior			(+)WM questions	(+) Vocabulary, (+) Comprehension, (+) PA: elision, (+) WM: digits
Visual Condition				
Anterior	(+) Fluency: word, pseudoword-level, & text-level (+) Rate, (+) Total Reading, (+) WM: recall		(+) Fluency: pseudoword-level, (-) PA: segmenting nonwords	
Central			(+) Fluency: pseudoword-level, (-) WM: questions	
Posterior		(+) Vocabulary, (+) Accuracy: word-level		(-) WM: questions

Figure Captions

Figure 1. Schematic diagram representing 64 electrodes used in the study with each respective label name and scalp location. Circled sites are those shown in further figures.

Figure 2. At each electrode location: grand average of auditory SCP brainwave amplitudes (-200-3893 ms) for both sentence types (SS, SO) in each participant group (typical, dyslexic). Their location on the figure is indicative of their spatial location on the scalp. Negative amplitudes are plotted up in this and all further figures.

Figure 3. Mean amplitudes for the slow potentials evoked by auditory SS and SO sentences in each participant group (typical, dyslexic) at a (A) frontal, (B) central, and (C) parietal electrode site along the midline (FPZ, CZ, POZ).

Figure 4. Mean amplitude differences between auditory SS and SO sentences for dyslexic readers at a (A) frontal, (B) central, and (C) parietal midline scalp location (FPZ, CZ, POZ) during the SCP time window (-200-3893 ms). Mean amplitude differences between SS and SO sentences for typical readers at a (D) frontal, (E) central, and (C) parietal scalp location (FPZ, CZ, POZ) during the same time window.

Figure 5. Grand average of each SCP across scalp locations for visual SS and SO sentences in each participant group (typical, dyslexic).

Figure 6. Dyslexic and typical mean amplitudes evoked by each sentence type during the visual SCP latency region (-200-4500 ms) at a (A) frontal, (B) central, and (C) parietal electrode site along the midline (FPZ, CZ, POZ).

Figure 7. SCP mean amplitude differences between visual SS and SO sentences for dyslexic participants at a (A) frontal, (B) central, and (C) parietal scalp location (FPZ, CZ, POZ). Mean

amplitude differences for controls between SS and SO sentences for the same latency window at a (D) frontal, (E) central, and (F) parietal electrode (FPZ, CZ, POZ).

Figure 8. Typical and dyslexic single word grand averages for each electrode location across the scalp at the 2nd article (4^{th} word) of auditory SS and SO sentences.

Figure 9. Dyslexic and typical mean amplitude differences evoked by auditory SS and SO sentences during the 2^{nd} article (4^{th} word) single word region (-100-1000 ms) at a (A) frontal, (B) central, and (C) parietal scalp location (FPZ, CZ, POZ).

Figure 10. Mean amplitude differences between auditory SS and SO sentences at the 2^{nd} article word region (4^{th} word) for participants with dyslexia at a (A) frontal, (B) central, and (C) parietal electrode (FPZ, CZ, POZ) and for typical participants at the same (D) frontal, (E) central, and (F) parietal scalp locations.

Figure 11. Grand average of single word ERPs in response to the auditory main verb (7^{th} word) of SS and SO sentences. Averages are shown at each site for both participant groups (typical, dyslexic).

Figure 12. Dyslexic and typical mean amplitudes evoked by each sentence type during the auditory main verb (7^{th} word) region (-100-1000 ms) at a (A) frontal, (B) central, and (C) parietal electrode site along the midline (FPZ, CZ, POZ). Within this single word region, epochs were analyzed from 300-500 ms and from 500-90 ms.

Figure 13. Auditory single word mean amplitude differences between SS and SO sentences for dyslexic participants at the main verb (7^{th} word) at a (A) frontal, (B) central, and (C) parietal scalp location (FPZ, CZ, POZ). Mean amplitude differences for controls between SS and SO sentences for the same latency window at a (D) frontal, (E) central, (F) parietal electrode (FPZ, CZ, POZ).

Figure 14. Typical and dyslexic single word grand averages for each electrode location across the scalp at the 2nd article (4th word) of visual SS and SO sentences.

Figure 15. Dyslexic and typical mean amplitudes evoked by each sentence type during the visual 2nd article (4th word) region (-100-1000 ms) at a (A) frontal, (B) central, and (C) parietal electrode site along the midline (FPZ, CZ, POZ). Within this single word region, epochs were analyzed from 300-500 ms and from 500-900 ms.

Figure 16. Visual single word mean amplitude differences between SS and SO sentences at the 2nd article (4th word) for dyslexic participants at a (A) frontal, (B) central, and (C) parietal scalp location (FPZ, CZ, POZ). Mean amplitude differences for controls between SS and SO sentences for the same latency window at a (D) frontal, (E) central, (F) parietal electrode (FPZ, CZ, POZ).

Figure 17. Typical and dyslexic single word grand averages for each electrode location across the scalp at the main verb (7th word) of visual SS and SO sentences.

Figure 18. Dyslexic and typical mean amplitudes evoked by each sentence type during the visual main verb (7th word) region (-100-1000 ms) at a (A) frontal, (B) central, and (C) parietal electrode site along the midline (FPZ, CZ, POZ). Within this single word region, epochs were analyzed from 300-500 ms and from50-900 ms.

Figure 19. Visual single word mean amplitude differences between SS and SO sentences at the main verb (7th word) for dyslexic participants at a (A) frontal, (B) central, and (C) parietal scalp location (FPZ, CZ, POZ). Mean amplitude differences for controls between SS and SO sentences for the same latency window at a (D) frontal, (E) central, (F) parietal electrode (FPZ, CZ, POZ).

Figure 1

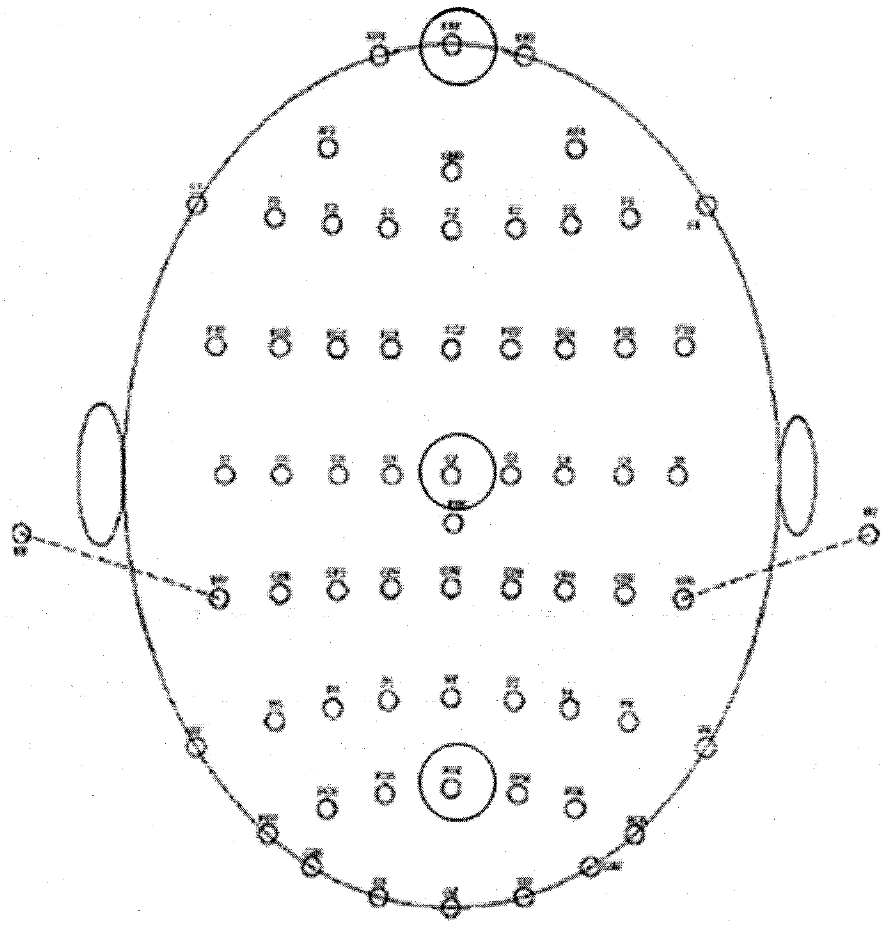


Figure 2

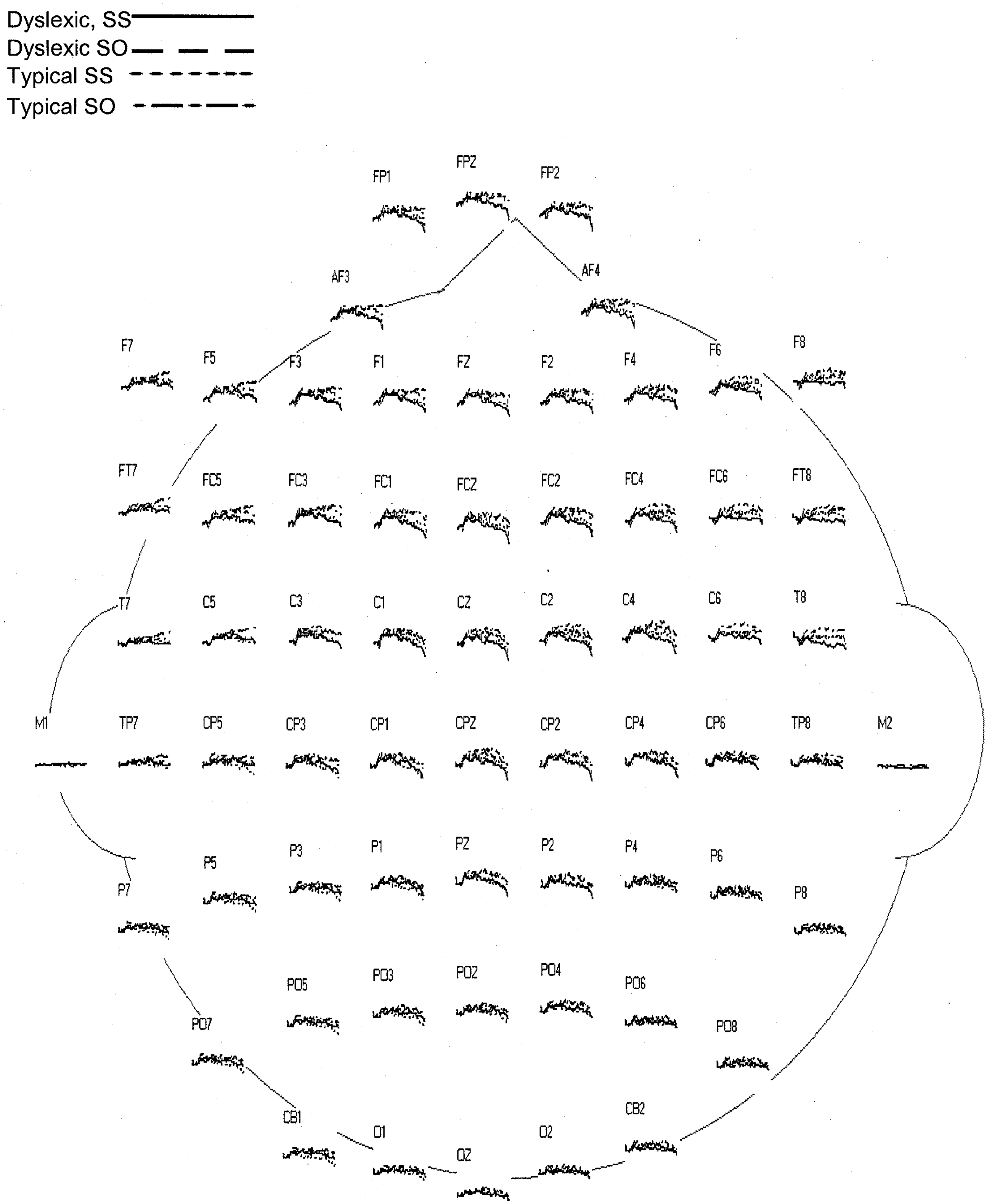

Dyslexic, SS
Dyslexic SO
Typical SS
Typical SO
FP1
FPZ
FP2
AF3
AF4
F7
F5
F3
F1
FZ
F2
F4
F6
F8
FT7
FC5
FC3
FC1
FCZ
FC2
FC4
FC6
FT8
T7
C5
C3
C1
CZ
C2
C4
C6
T8
M1
TP7
CP5
CP3
CP1
CPZ
CP2
CP4
CP6
TP8
M2
P7
P5
P3
P1
PZ
P2
P4
P6
P8
PO7
PO5
PO3
POZ
PO4
PO6
PO8
CB1
O1
OZ
O2
CB2

Figure 3

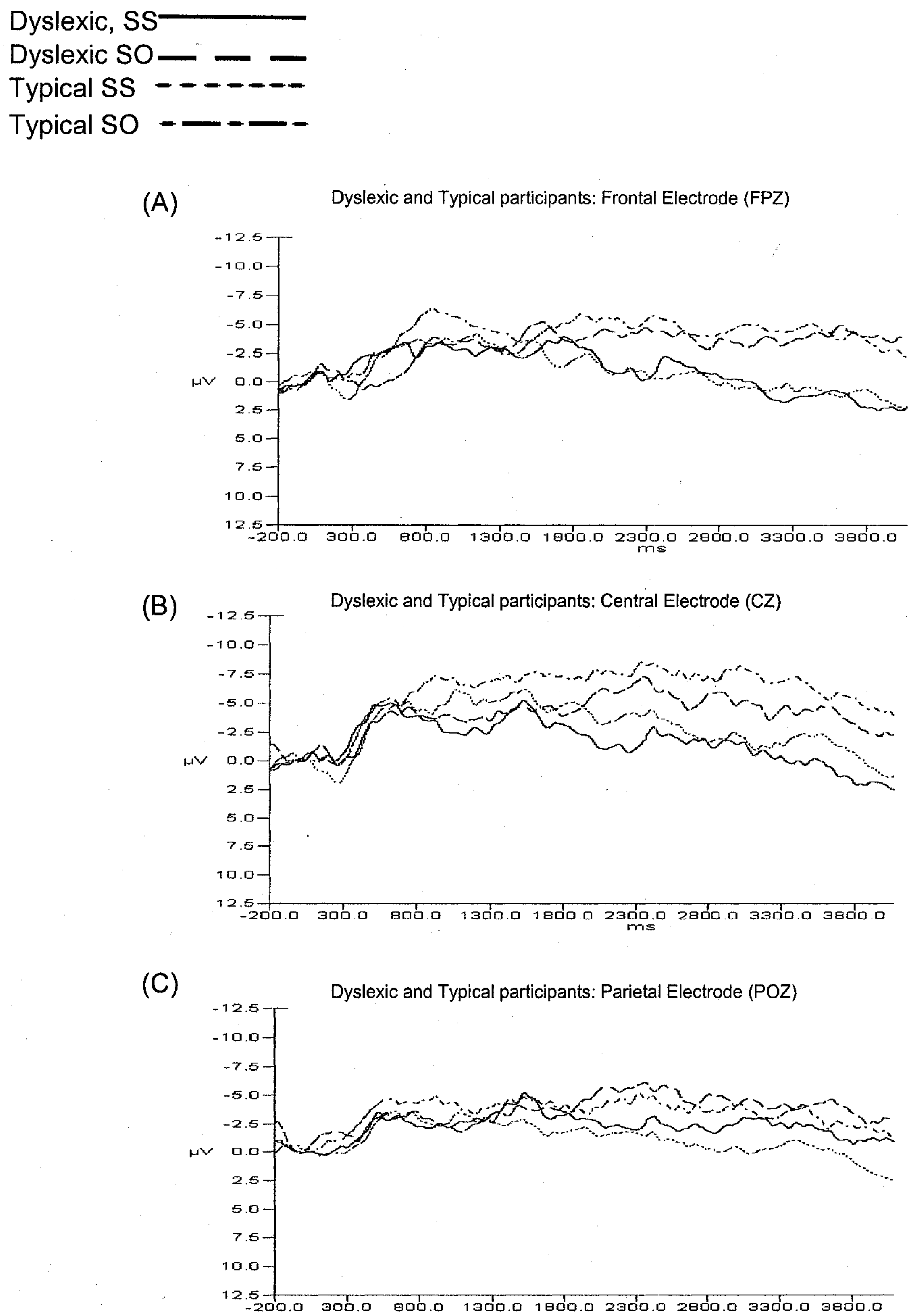
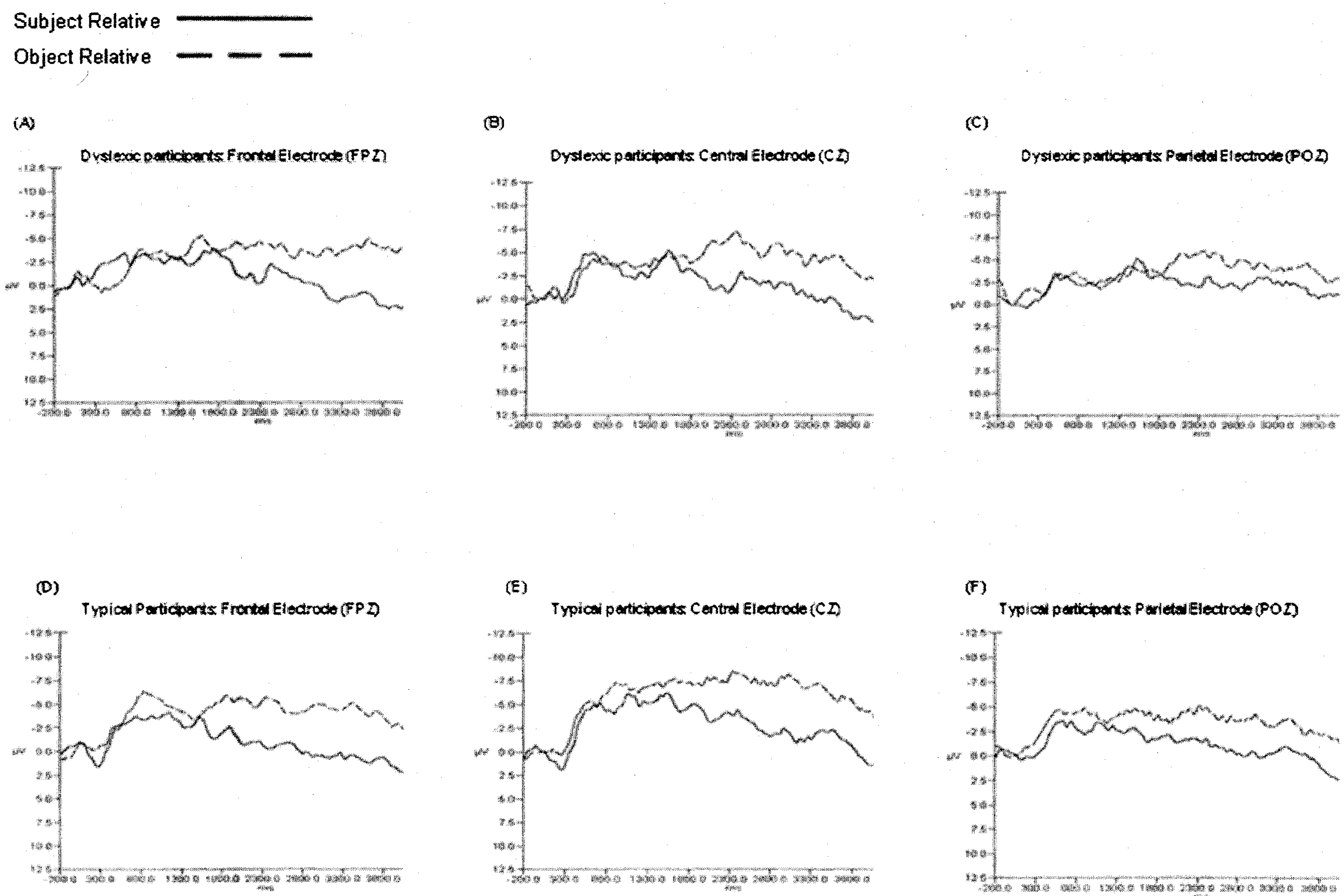

Dyslexic, SS
Dyslexic SO
Typical SS
Typical SO
(A)
Dyslexic and Typical participants: Frontal Electrode (FPZ)
µV
ms
-200.0 300.0 800.0 1300.0 1800.0 2300.0 2800.0 3300.0 3800.0
-12.5 -10.0 -7.5 -5.0 -2.5 0.0 2.5 5.0 7.5 10.0 12.5
(B)
Dyslexic and Typical participants: Central Electrode (CZ)
µV
ms
-200.0 300.0 800.0 1300.0 1800.0 2300.0 2800.0 3300.0 3800.0
-12.5 -10.0 -7.5 -5.0 -2.5 0.0 2.5 5.0 7.5 10.0 12.5
(C)
Dyslexic and Typical participants: Parietal Electrode (POZ)
µV
ms
-200.0 300.0 800.0 1300.0 1800.0 2300.0 2800.0 3300.0 3800.0
-12.5 -10.0 -7.5 -5.0 -2.5 0.0 2.5 5.0 7.5 10.0 12.5

Figure 4


Subject Relative
Object Relative
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Dyslexic participants: Frontal Electrode (FPZ)
(B)
Dyslexic participants: Central Electrode (CZ)
(C)
Dyslexic participants: Parietal Electrode (POZ)
(D)
Typical Participants: Frontal Electrode (FPZ)
(E)
Typical participants: Central Electrode (CZ)
(F)
Typical participants: Parietal Electrode (POZ)

Figure 5

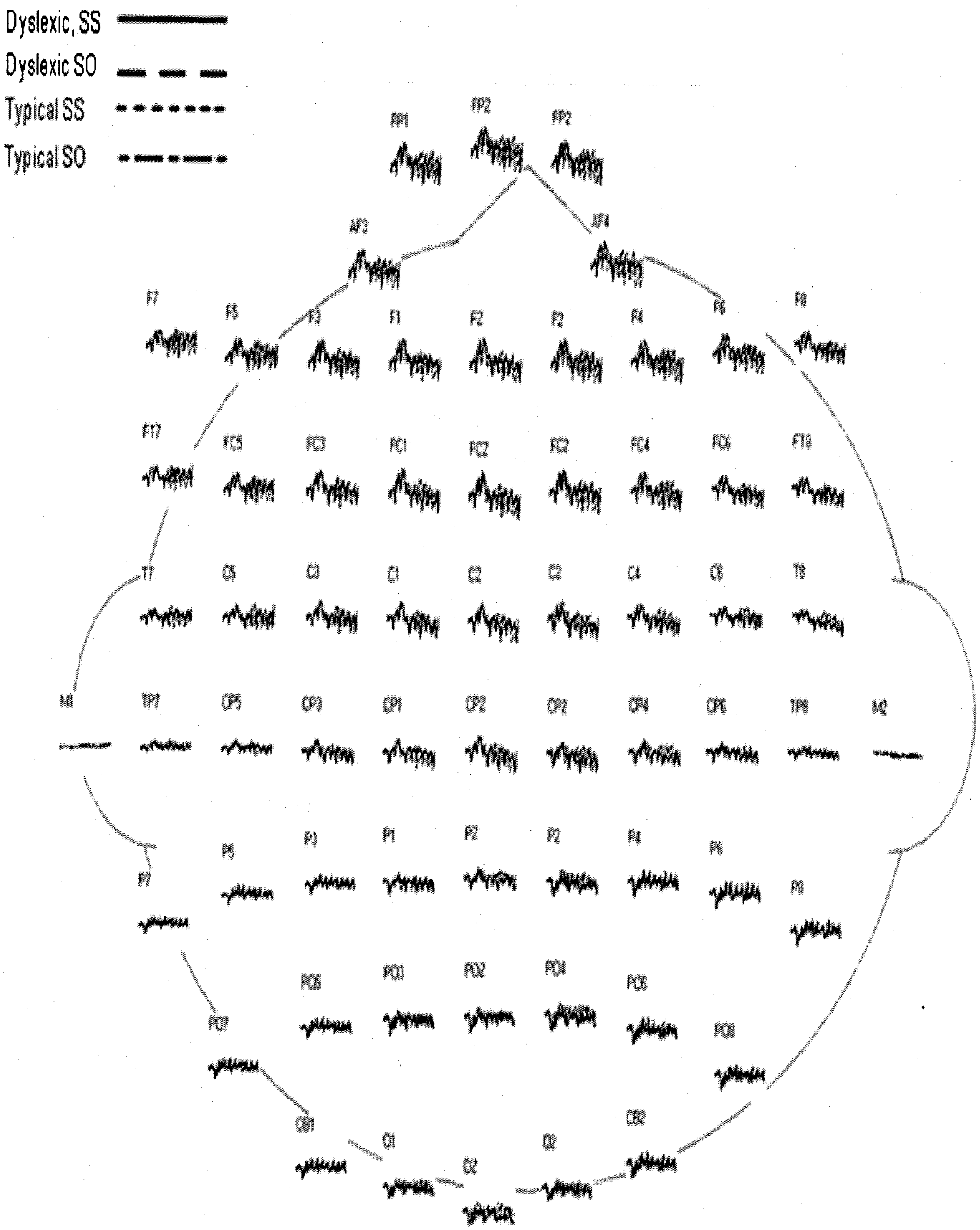


Figure 6

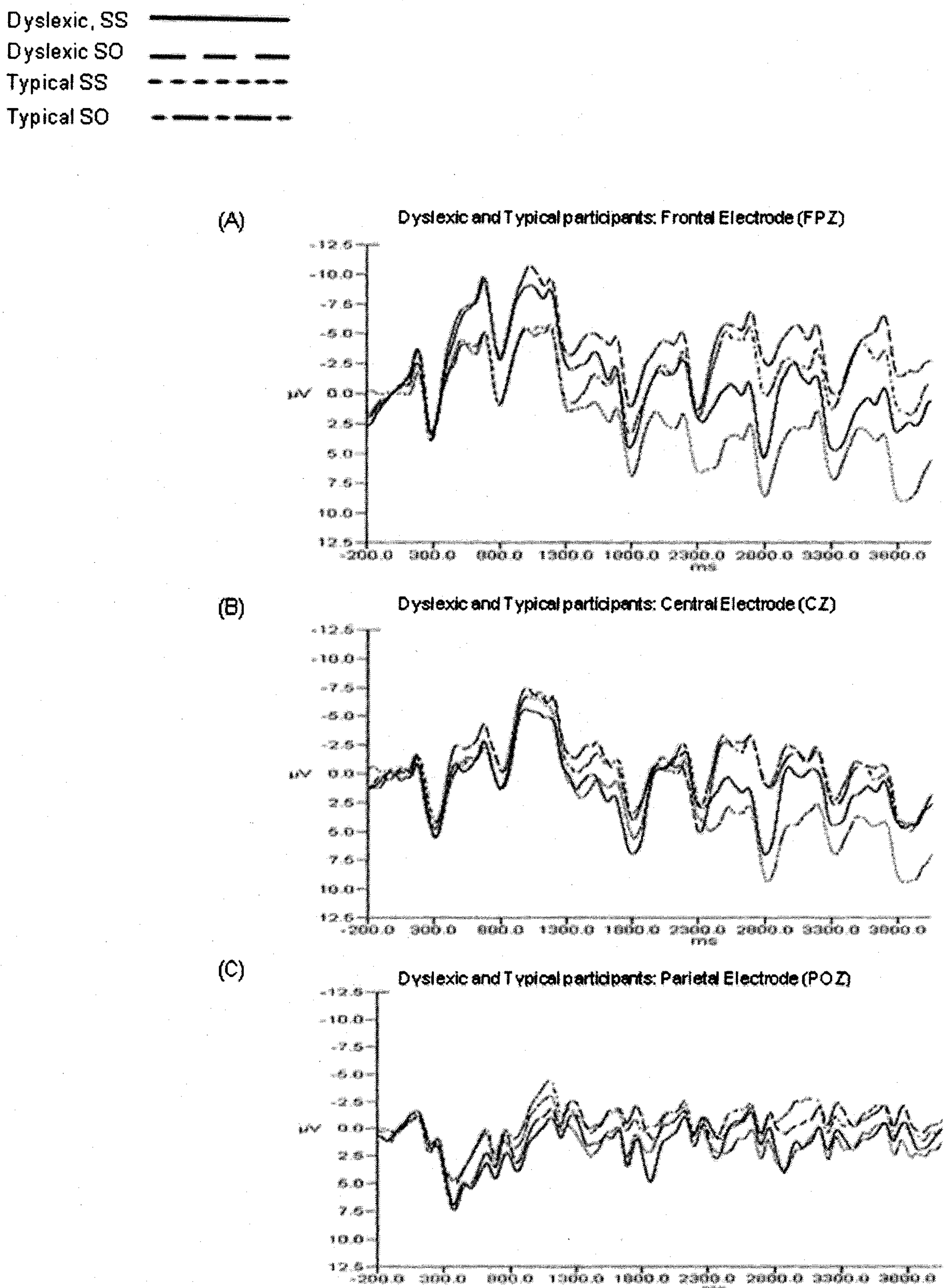

Dyslexic, SS
Dyslexic SO
Typical SS
Typical SO
(A)
Dyslexic and Typical participants: Frontal Electrode (FPZ)
μV
ms
(B)
Dyslexic and Typical participants: Central Electrode (CZ)
μV
ms
(C)
Dyslexic and Typical participants: Parietal Electrode (POZ)
μV
ms

Figure 7

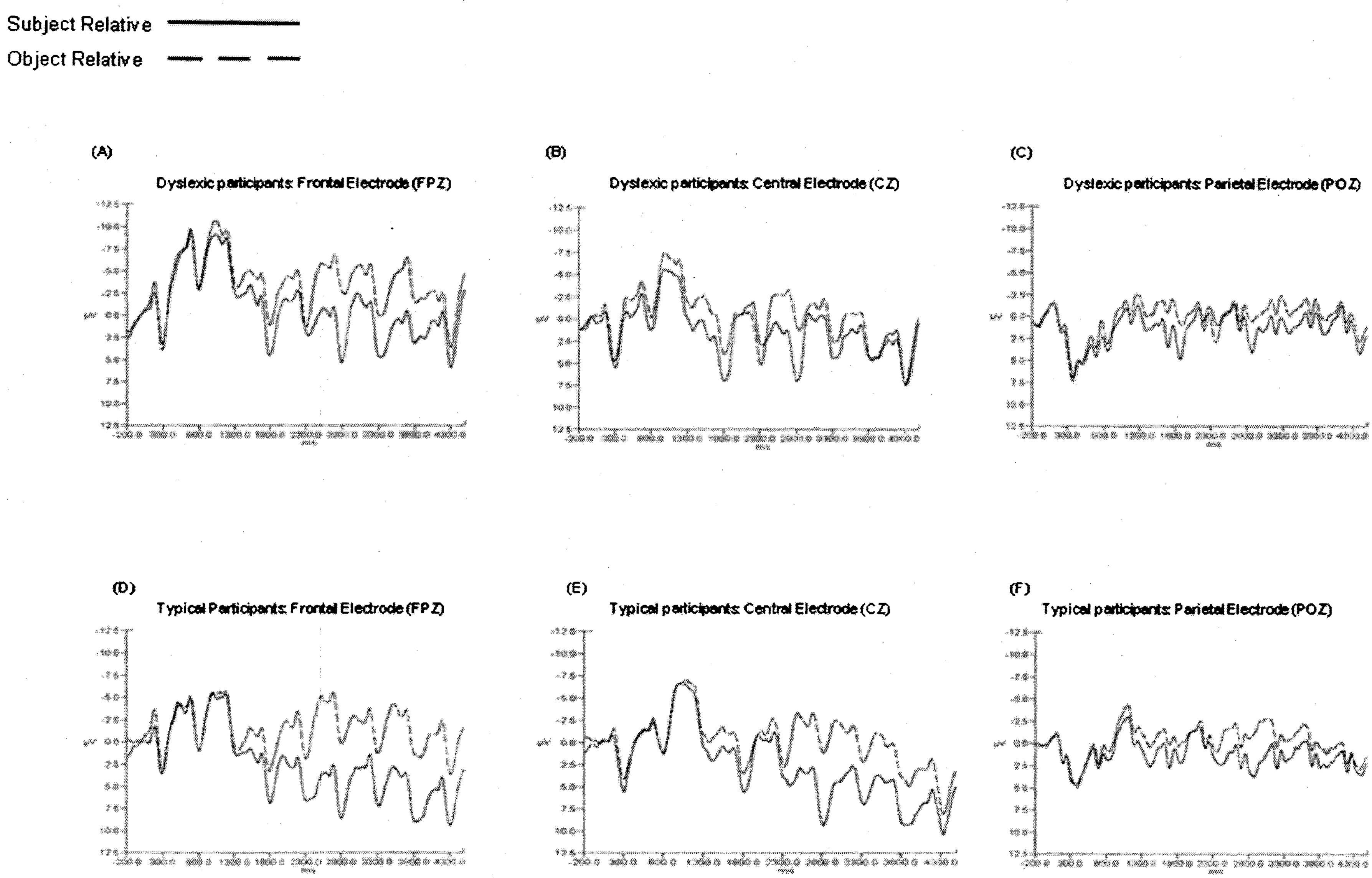
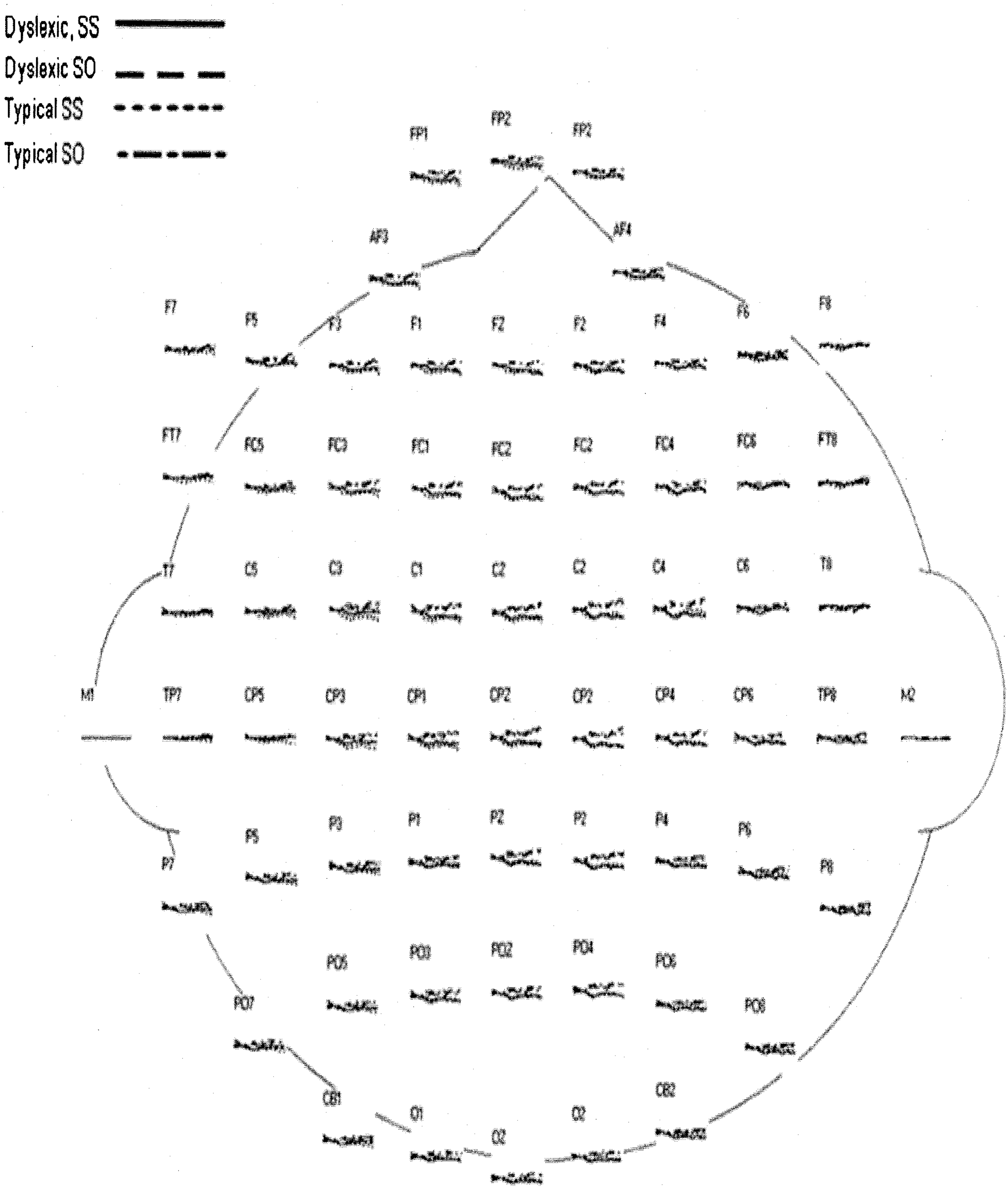

Subject Relative
Object Relative
(A)
Dyslexic participants: Frontal Electrode (FPZ)
(B)
Dyslexic participants: Central Electrode (CZ)
(C)
Dyslexic participants: Parietal Electrode (POZ)
(D)
Typical Participants: Frontal Electrode (FPZ)
(E)
Typical participants: Central Electrode (CZ)
(F)
Typical participants: Parietal Electrode (POZ)

Figure 8


Dyslexic, SS
Dyslexic SO
Typical SS
Typical SO
FP1
FPZ
FP2
AF3
AF4
F7
F5
F3
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FZ
F2
F4
F6
F8
FT7
FC5
FC3
FC1
FCZ
FC2
FC4
FC6
FT8
T7
C5
C3
C1
CZ
C2
C4
C6
T8
M1
TP7
CP5
CP3
CP1
CPZ
CP2
CP4
CP6
TP8
M2
P7
P5
P3
P1
PZ
P2
P4
P6
P8
PO7
PO5
PO3
POZ
PO4
PO6
PO8
CB1
O1
OZ
O2
CB2

Figure 9

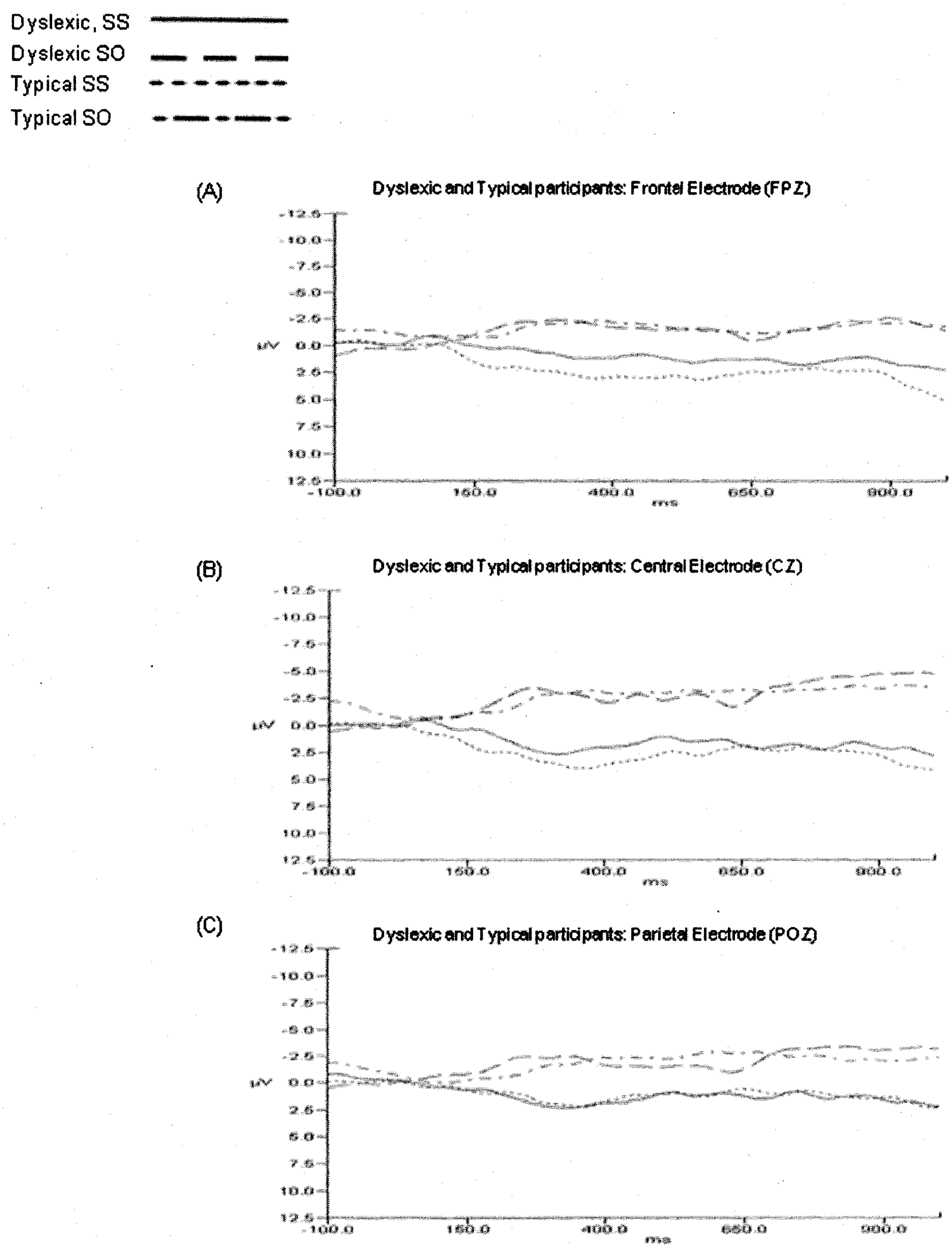

Dyslexic, SS
Dyslexic SO
Typical SS
Typical SO
(A)
Dyslexic and Typical participants: Frontal Electrode (FPZ)
µV
ms
(B)
Dyslexic and Typical participants: Central Electrode (CZ)
µV
ms
(C)
Dyslexic and Typical participants: Parietal Electrode (POZ)
µV
ms

Figure 10

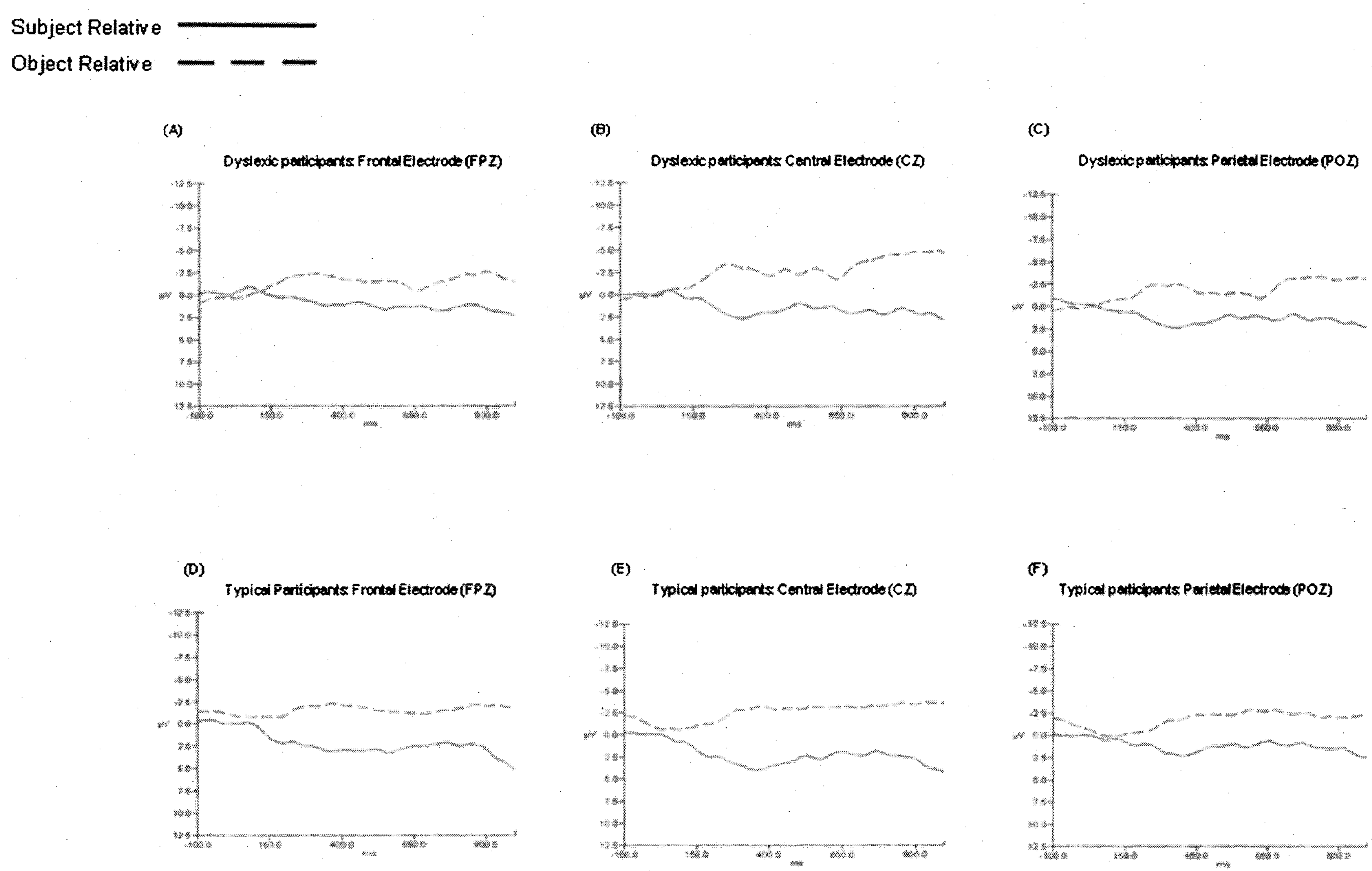

Subject Relative
Object Relative
(A)
Dyslexic participants: Frontal Electrode (FPZ)
(B)
Dyslexic participants: Central Electrode (CZ)
(C)
Dyslexic participants: Parietal Electrode (POZ)
(D)
Typical Participants: Frontal Electrode (FPZ)
(E)
Typical participants: Central Electrode (CZ)
(F)
Typical participants: Parietal Electrode (POZ)

Figure 11

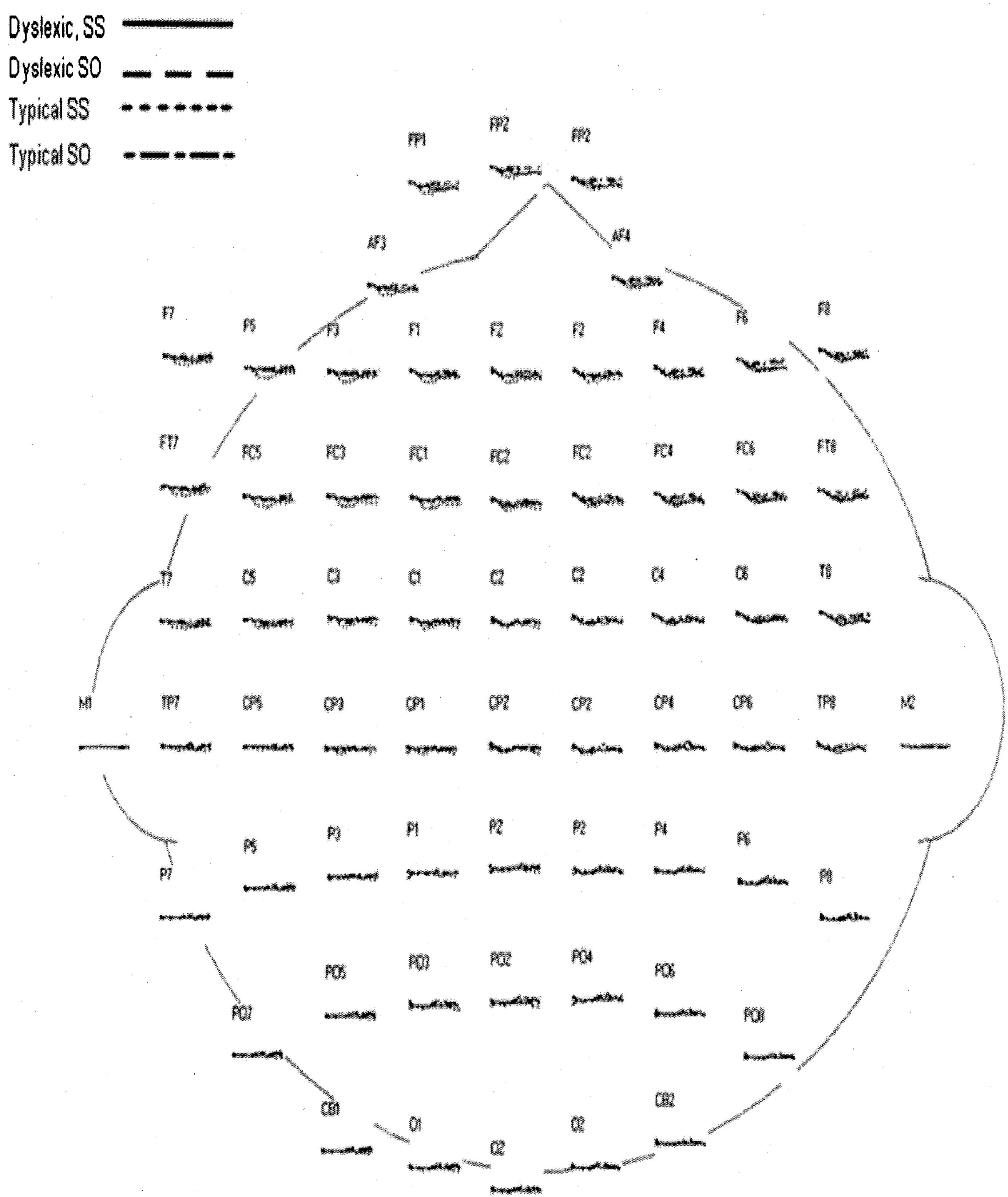


Figure 12

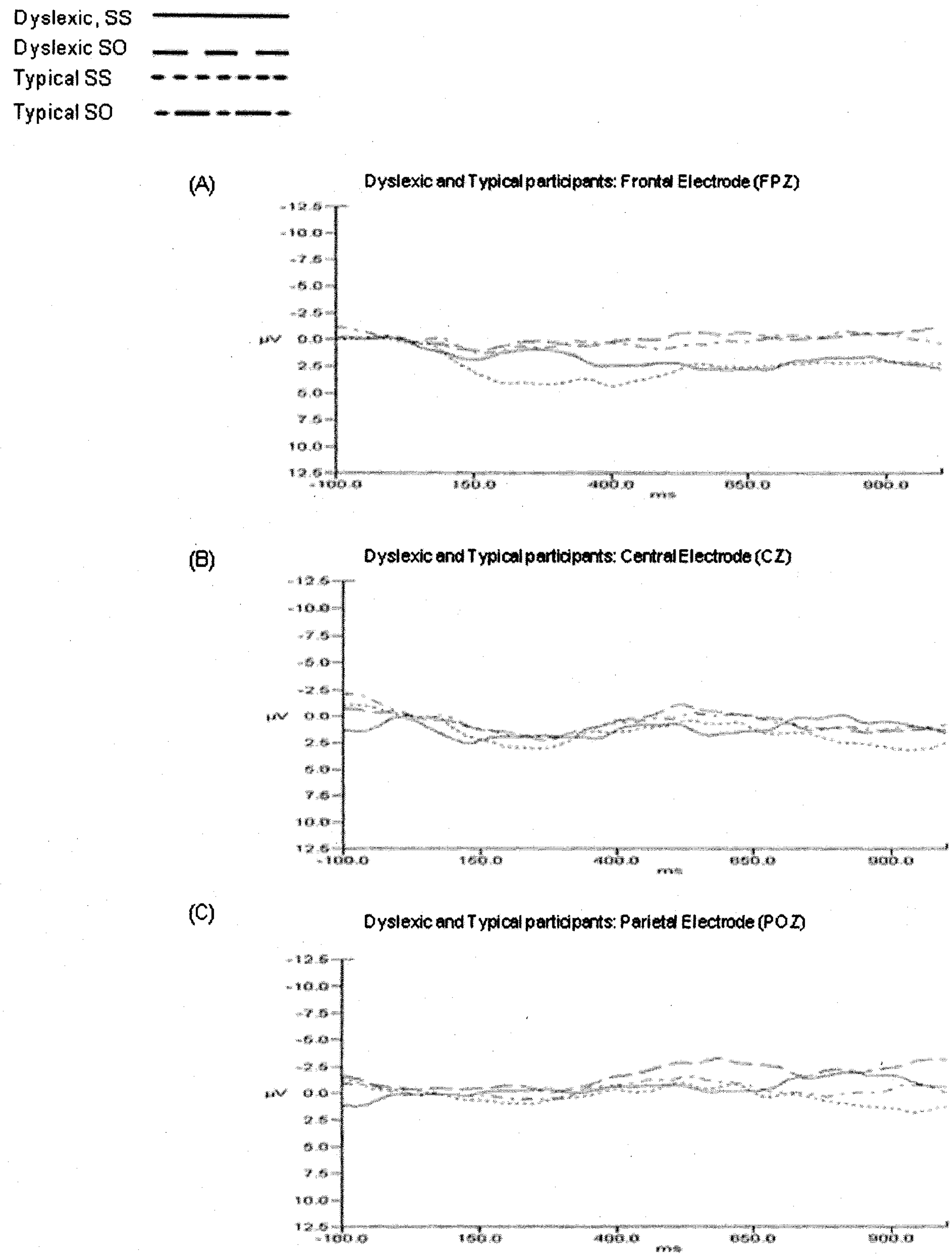

Dyslexic, SS
Dyslexic SO
Typical SS
Typical SO
(A)
Dyslexic and Typical participants: Frontal Electrode (FPZ)
(B)
Dyslexic and Typical participants: Central Electrode (CZ)
(C)
Dyslexic and Typical participants: Parietal Electrode (POZ)

Figure 13

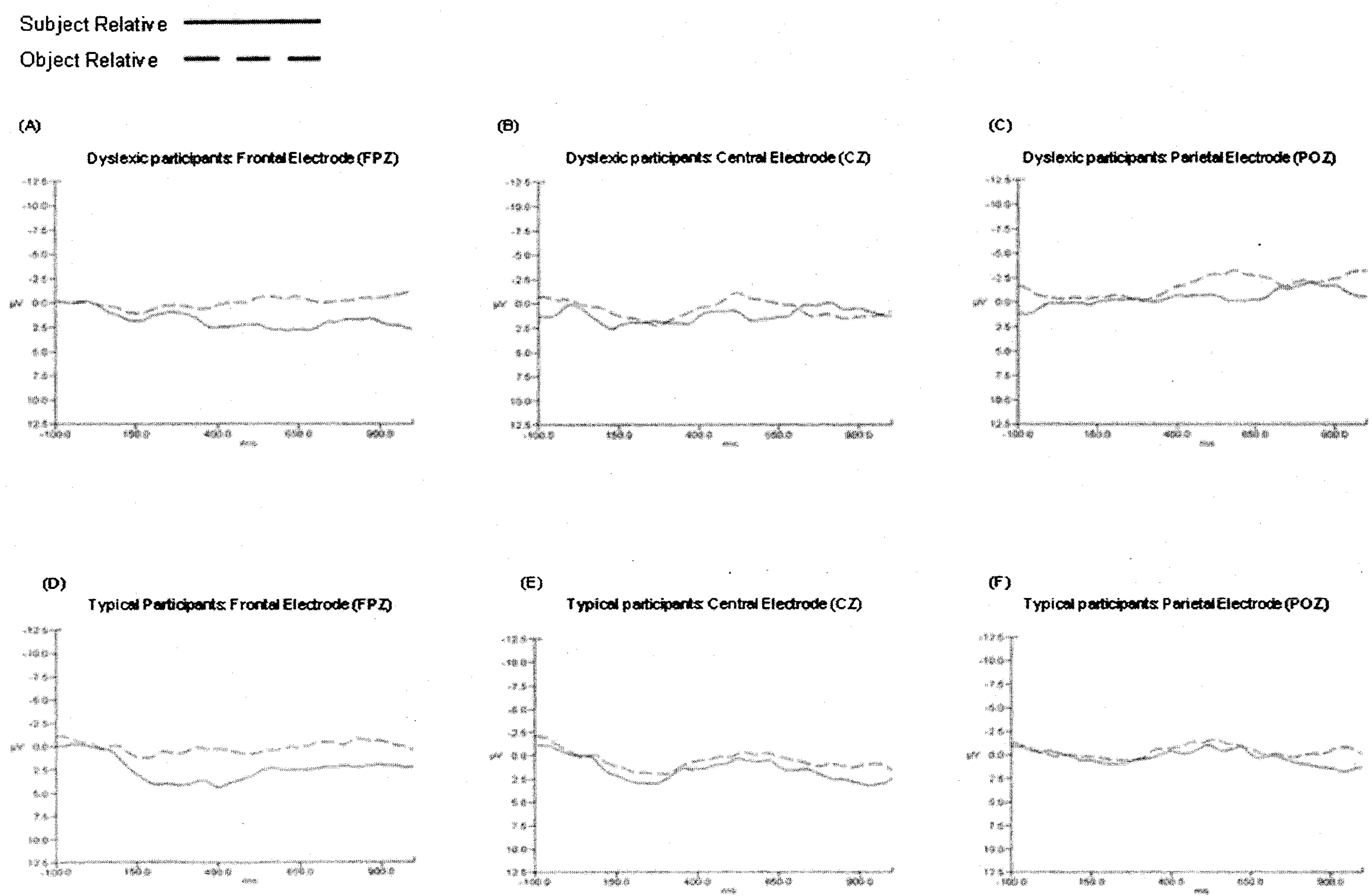
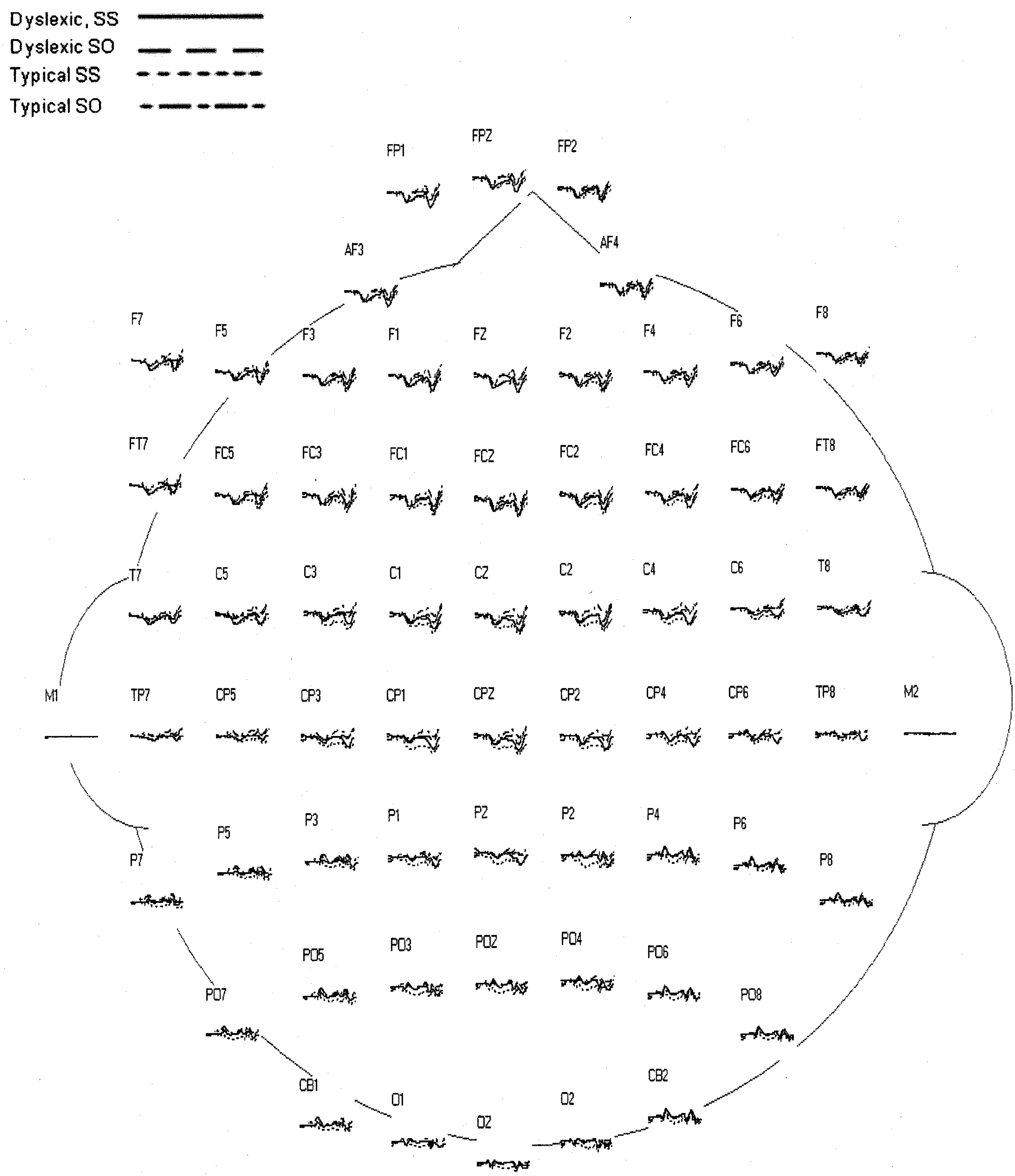

Subject Relative
Object Relative
(A)
Dyslexic participants: Frontal Electrode (FPZ)
(B)
Dyslexic participants: Central Electrode (CZ)
(C)
Dyslexic participants: Parietal Electrode (POZ)
(D)
Typical Participants: Frontal Electrode (FPZ)
(E)
Typical participants: Central Electrode (CZ)
(F)
Typical participants: Parietal Electrode (POZ)

Figure 14


Dyslexic, SS
Dyslexic SO
Typical SS
Typical SO
FP1
FPZ
FP2
AF3
AF4
F7
F5
F3
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FZ
F2
F4
F6
F8
FT7
FC5
FC3
FC1
FCZ
FC2
FC4
FC6
FT8
T7
C5
C3
C1
CZ
C2
C4
C6
T8
M1
TP7
CP5
CP3
CP1
CPZ
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CP6
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P1
PZ
P2
P4
P6
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PO5
PO3
POZ
PO4
PO6
PO8
CB1
O1
OZ
O2
CB2

Figure 15

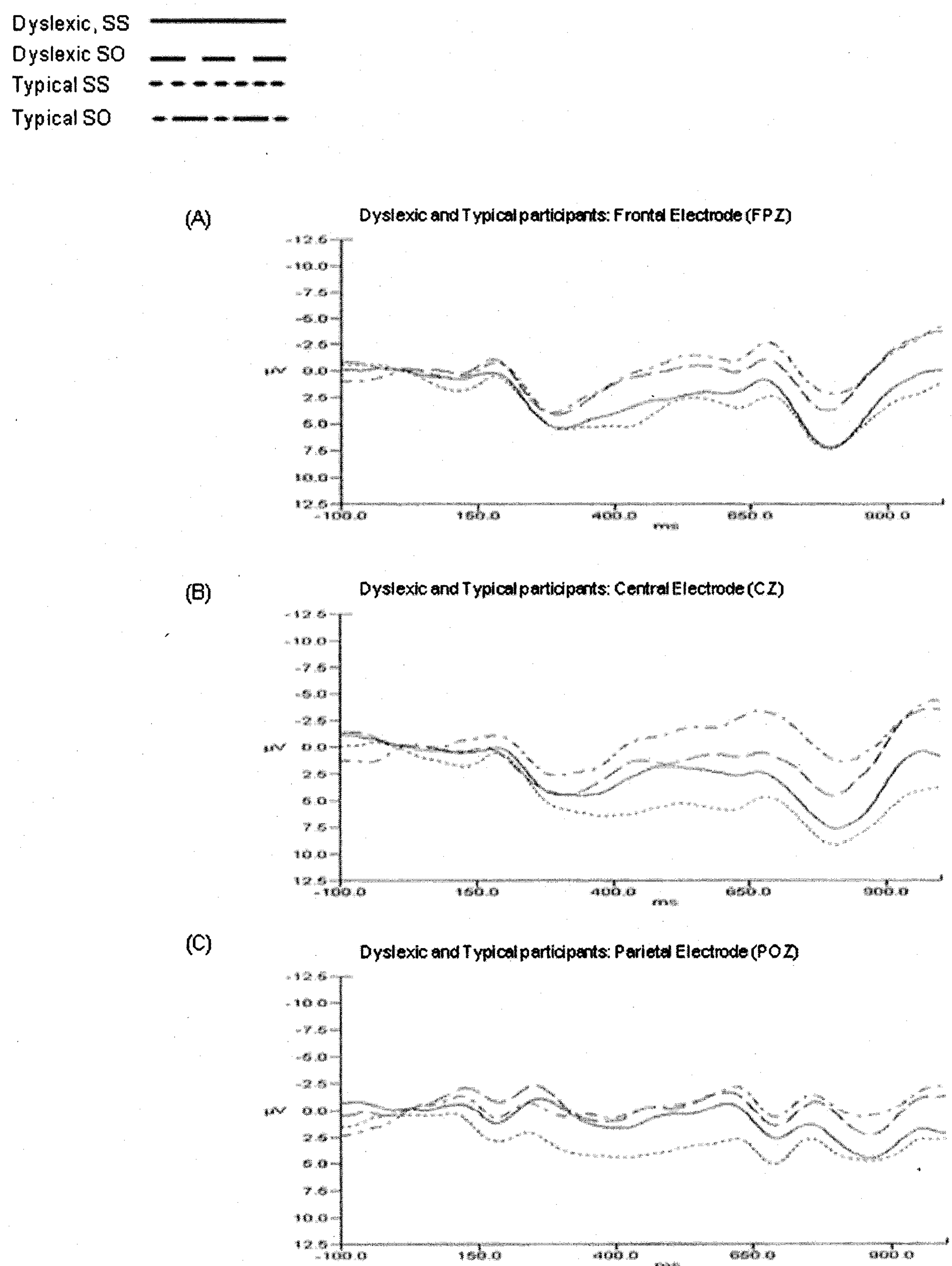

Dyslexic, SS
Dyslexic SO
Typical SS
Typical SO
(A)
Dyslexic and Typical participants: Frontal Electrode (FPZ)
(B)
Dyslexic and Typical participants: Central Electrode (CZ)
(C)
Dyslexic and Typical participants: Parietal Electrode (POZ)
µV
ms
-100.0
150.0
400.0
650.0
900.0

Figure 16

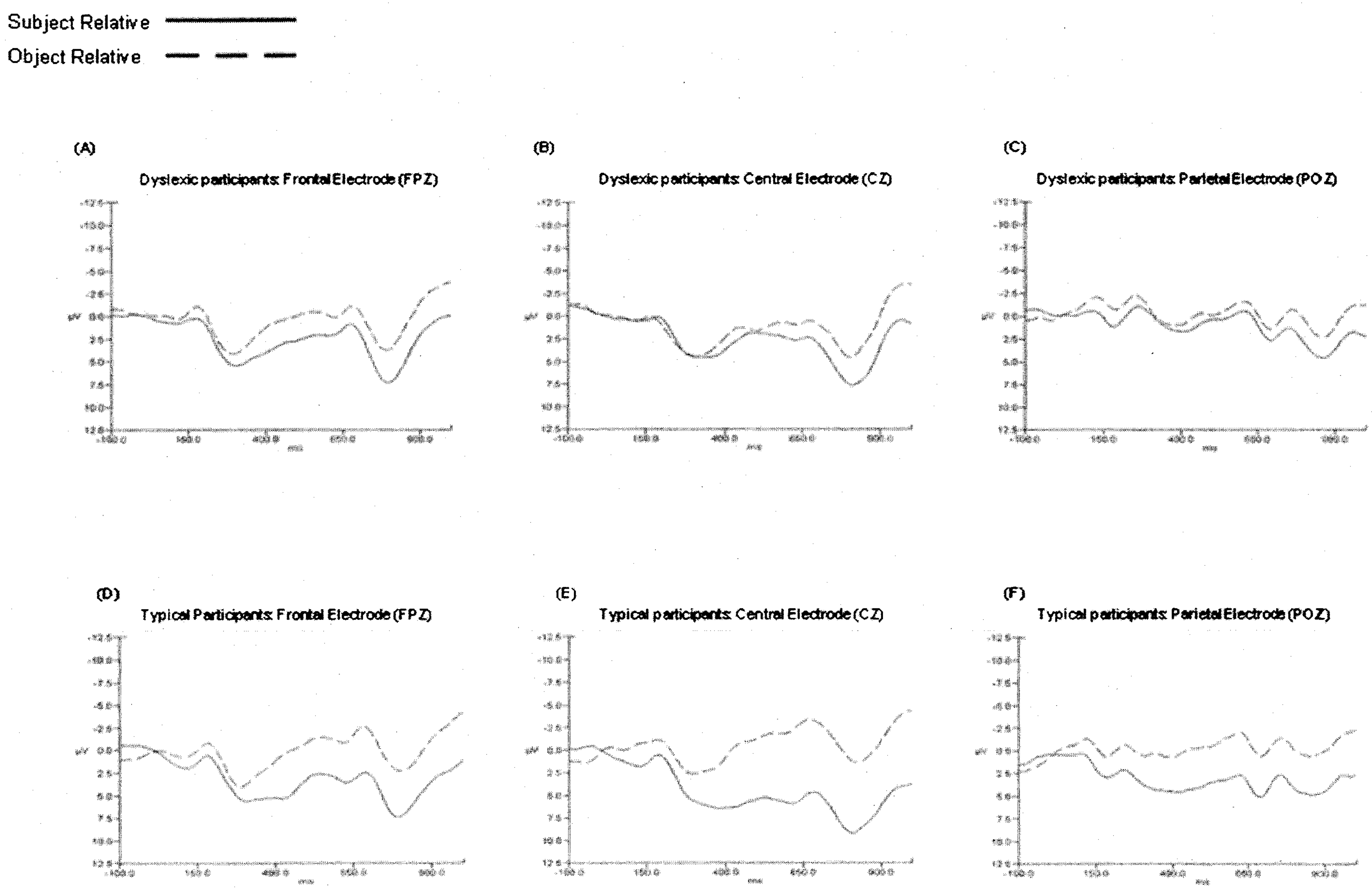

Subject Relative
Object Relative
(A)
Dyslexic participants: Frontal Electrode (FPZ)
(B)
Dyslexic participants: Central Electrode (CZ)
(C)
Dyslexic participants: Parietal Electrode (POZ)
(D)
Typical Participants: Frontal Electrode (FPZ)
(E)
Typical participants: Central Electrode (CZ)
(F)
Typical participants: Parietal Electrode (POZ)

Figure 17

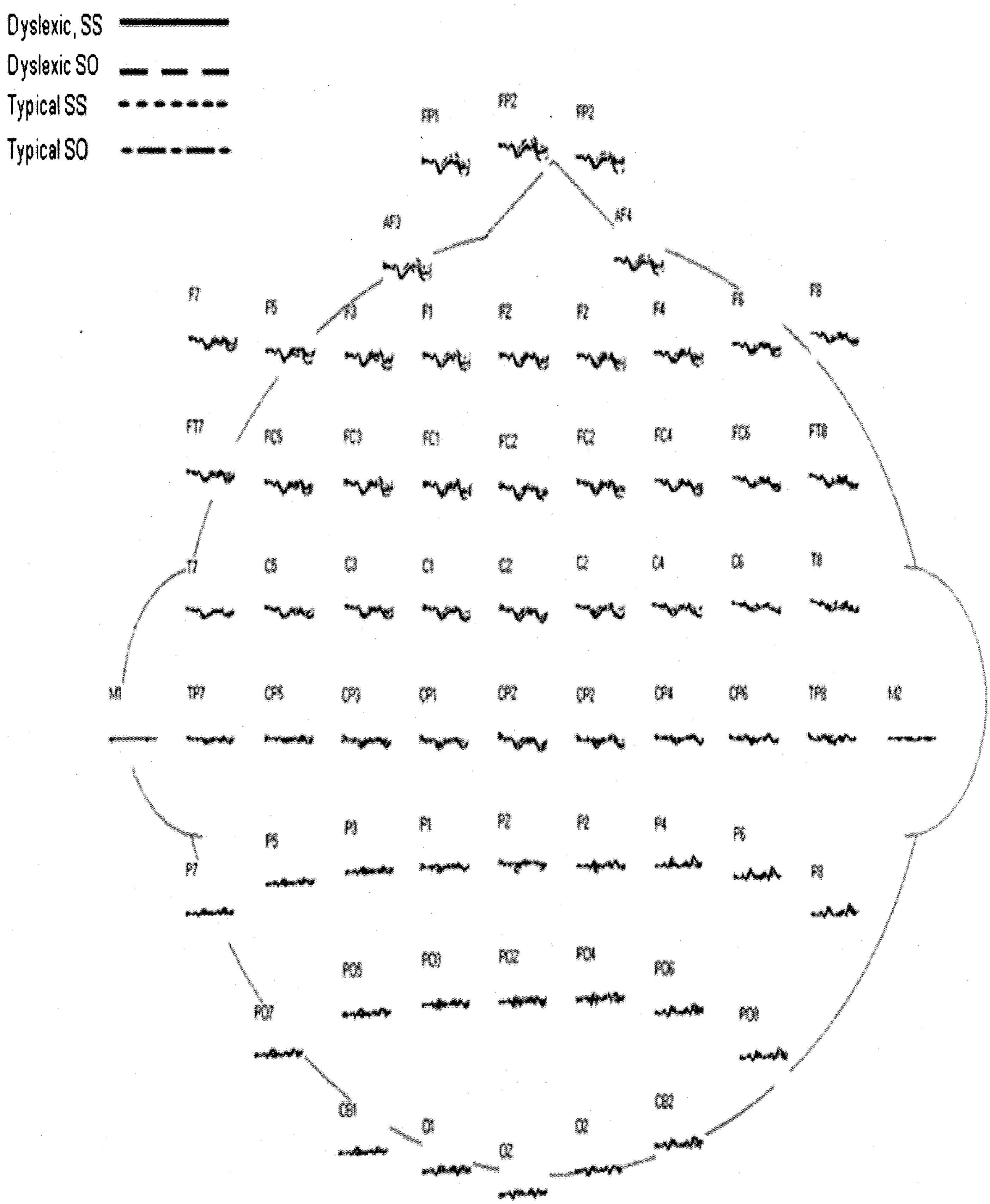


Figure 18

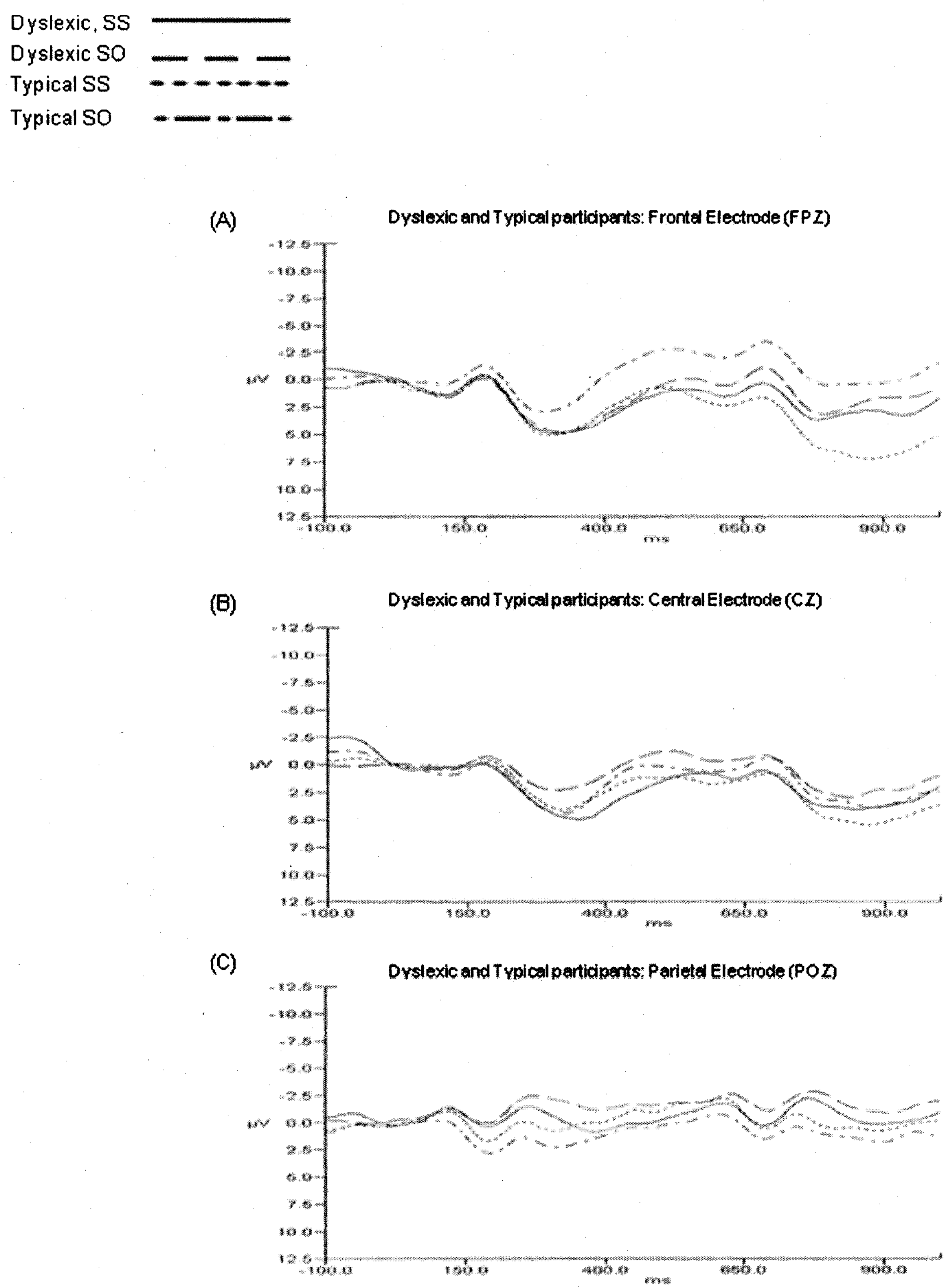
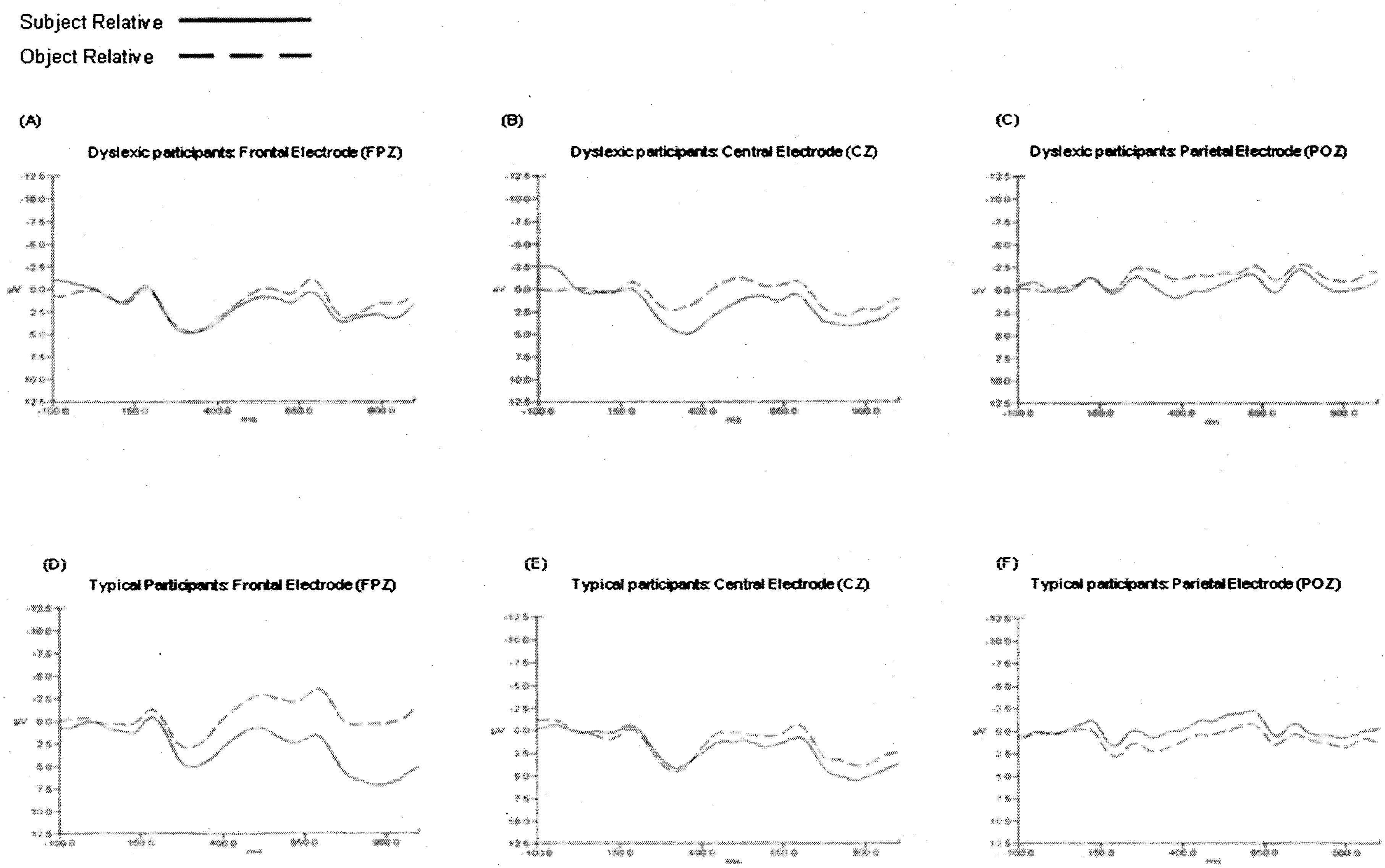

Dyslexic, SS
Dyslexic SO
Typical SS
Typical SO
(A)
Dyslexic and Typical participants: Frontal Electrode (FPZ)
µV
-12.5
-10.0
-7.5
-5.0
-2.5
0.0
2.5
5.0
7.5
10.0
12.5
-100.0
150.0
400.0
650.0
900.0
ms
(B)
Dyslexic and Typical participants: Central Electrode (CZ)
(C)
Dyslexic and Typical participants: Parietal Electrode (POZ)

Figure 19



155