Differences in Low, Average, and Expert Readers as Measured by EEG/ERPs: Preliminary Findings and Challenges of an In-School Psycho-Physiological Research Project

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Abstract

The inability to process sounds is basic to reading deficits. To assess this ability, we used event-related potential (ERP) tasks: oddball tones and phonemes as well as incongruent picture/seen/word heard and picture seen/word seen pairs. Performance data from 112 middle school students from a highly diverse population ethnically, culturally and socio-economically revealed similar patterns when responding to tones. There were also significant differences across low, average and expert readers when responding to phonemes, words heard and words seen. Methodological and procedural challenges encountered when conducting EEG/ERP research within a public school setting are highlighted.

Introduction

The theory that reading disorders result from specific auditory processing deficits has a long, controversial history (Breznitz, 2002; Breznitz & Misra, 2003; Myklebust, 1954). For example, in the early 1970s, Tallal and Piercy (1973, 1974, 1975) found that children with language deficits needed longer (over 300 ms) interstimulus intervals (ISI) between tones to identify them as separate, whereas children without language deficits could process the tones with as little as 8 ms ISI. This team also found that extended tone duration to 250 ms was required rather than the 75 ms of normal responders. However, others (Tomblin, Abbas, Records & Brenneman, 1995), using event-related potentials (ERPs), showed that language-impaired children discriminated adequately under specific experimental conditions.

After Bishop, Carlyon, Deeks, and Bishop (1999) observed that some children in their twin study showed auditory deficits but normal language development, they concluded that language impairment may result from "multiple factors that act synergistically" rather than solely being caused by an auditory temporal processing deficit (p. 1308). In support of this observation Bailey and Snowling (2002) write that "Current evidence is inconsistent, but suggests that not all children with language difficulties have non-verbal auditory processing impairments, and for those that do, the impact on language development is poorly understood" (p. 135). Meanwhile, Studdert-Kennedy (2002) asserts that difficulties in speech perception rather than difficulties in general auditory processing are at the root of reading disorders. Mody (2003) also states that "dyslexia may be traced to a weakness in the phonological component of language. It is," she states, "characterized by a deficit in printed word recognition" (p. 21).

Phonological processing can be observed with ERPs in terms of amplitude and latency of neural waveforms of individuals with language, communication and reading difficulties (Byrne, Connolly, MacLean, et al., 1999; Byrne, Dywan, & Connolly, 1995; Neville, Mills, & Lawson, 1992; Ors, Lindgren & Berglund, 2001). Several studies of language comprehension have used ERP measures in a semantic anomaly paradigm first described by Kutas and Hillyard (1980). Violations in semantic expectation elicit a broadly distributed negativity that peaks at about 400ms post stimulus (N400) and is thought to index the word's 'activation level' in memory and the meaning integration process

(Holcomb, Coffey & Neville, 1992; Kutas & Hillyard, 1980; Neville, Mills & Lawson, 1992). Byrne and his colleagues (1995) demonstrated the use of ERPs to assess the receptive vocabulary in a cerebral palsied patient and normal controls. The researchers presented congruent and incongruent picture word pairs to their study population and observed that when the picture word pairs were within the individual's vocabulary level, an N400 was prominent for the incongruent words. However when the vocabulary was above or beyond the individual's level, the N400 was not evident. Their results demonstrated that an ERP paradigm could be constructed to evaluate the progress of neurologically impaired individuals whose conditions prevent administration of traditional methods of evaluation.

Thus, ERPs have been used with tones, phonemes, single picture/word pairs, and language comprehension tasks to study language and reading disorders. However, to our knowledge, no study exists that investigated tones, phonemes, and incongruence between pictures seen and either words heard or words seen within the same adolescent population. Therefore, we investigated low, average, and expert adolescent readers' reactions to these tasks. We wanted to see if a difference across groups was evident at all four levels as suggested by the general auditory deficit theory or if significant differences occurred only on tasks pertaining to phonemes and read words.

While theoretical controversy about the role of auditory processing in reading deficits continues, researchers have consistently identified phonemic awareness and phonological processing abilities as foundational to reading success. Setting the controversy aside, our research focuses on phonemic awareness and phonological coding as they apply to reading.

Phonemic awareness

Phonemic awareness and phonological coding are considered the most important fundamental skills necessary for language development and reading (National Reading Panel 2000; Troia, 1999; Shaywitz, 2003; Vellutino, et al., 2004), and deficits in these areas are present in virtually every poor reader (Studdert-Kennedy, 2002). *Phonemic awareness* is the underlying ability to discriminate differences among phonemic sounds and is required to understand the phoneme sequences heard in spoken language. Developmentally, sound discrimination is followed by *phonological coding* which is the ability to combine speech sounds and phonemes into words or word parts (Vellutino, et al., 2004; Vellutino & Scanlon, 1987).

Sensitivity to phoneme similarities and differences is basic to language development, reading and spelling. Developmentally, a child moves from comprehension of receptive language and exploration of expressive or spoken language to reading and spelling, and the latter two require knowledge of the a*lphabetic code* or sound/symbol associations. Generally, the alphabetic code or application of phonemes to printed symbols develops when children are taught to read and write; then, it becomes a strong predictor of reading achievement (Goswami, 2002, 2003; Goswami & Bryant, 1990).

Phoneme discrimination and speech are naturally occurring language perception and production aspects of the human condition that require no conscious cognitive effort for most individuals (Jackendoff, 1994; Liberman & Whalen, 2000; Tallal, Stark, & Mellits, 1985). However, many children fail to differentiate between similar sounds (/b/ /d/ /p/ /t/, etc.). Such children have difficulty with language acquisition and often mispronounce common words. For example, children with phonemic awareness deficits may fail to hear differences between /dad/ /pad/ /tab/ /tap/ /bat/ when the word is spoken alone or within a conversation. For them, language may lack sound stability; therefore naming, labeling and word pronunciation difficulties may become apparent during the preschool years or surface only when children begin to read. The cause(s) of these language deficits may be genetic or environmental or a combination of nature and nurture (Shaywitz, 2003). While growth in phonemic skills is developmental, without specific remediation, deficits can continue into middle and high school years, even into adulthood (Knight, 2002).

Phoneme awareness and alphabetic coding are especially important at the upper elementary and middle school levels when children are asked to apply speech sounds to letter patterns. Since the English language lacks a one-to-one sound-letter correspondence as found in Italian and Spanish, multiple letter patterns (1120 graphemes) must be learned for the 40-45 English phonemes they represent (Lishman, 2003; Wagner, Torgesen, Rashotte, et al., 1997). Briefly consider the many spellings for the sound of /a/: *apron, game, raise, straight, gauge, say, blasé, break, where, matinee, vein, eight, bouquet, they, and heir*. Now consider the various pronunciations for the grapheme 'a': apron, above, sat, any, father, senate, quay. It is easy to see why application of sounds heard to the printed page at the middle school level can be quite taxing for struggling readers – especially those who missed onset (initial consonant phonemes; *pl* – ant) and rime (vowel and following phonemes; pl – *ant)* and the segmental nature of speech referred to as phonemic awareness. The onset-rime awareness skill applies to syllable pronunciation as well as one-syllable words and is another strong predictor of reading (Goswami, 2003; Simos, Fletcher, Bergman, et al., 2002). As may be expected, the prevalence of phonological-based reading difficulties varies according to the orthography of a particular language (Kujala & Näätänen, 2001).

Event Related Potentials

Electroencephalograms (EEGs) measure the brain's electrical activity via electrodes that are placed at specific locations on the scalp. Event related potentials (ERPs) are a diagnostic technique used with EEG technology that measure brain waves during different cognitive tasks or stages of information processing Waveforms are expressed in measures of amplitude (intensity) and latency (timing) variations. The components are represented as positive or negative (P, N) in terms of polarity of waveforms. EEGs are valuable in clinical testing because they allow measurement of various stages in information processing in response to sensory stimuli without behavioral observations. They also help establish a language processing timeline within milliseconds that behavioral data alone cannot provide (Brandeis & Lehman, 1986).

The history of EEG technology applied to reading dates back to the 1960s, when a majority (60%) of subjects with learning disabilities were revealed to have waveform abnormalities (Muehl, Knott, & Benton, 1965). Since that time, a number of studies have shown EEG/ERP technology to be an accurate measure of reading and reading-related tasks. For example, decreased accuracy in auditory processing, as measured by tonal and phonemic discrimination tasks, was shown to correlate with weaker phonological skills required for reading regular words and non-words (äää, 2001). Discrimination is often measured by oddball tasks whereby participants actively discriminate between two stimuli such as a high pitch and low pitch or aba/ada. The stimulus is generally presented in a ratio of 4 (standard) to 1 (target). Responses to the standard and the target are averaged separately. Average responses to the standard measures the attentional components while the average responses to the target measures information processing. Difference between the two waveforms (response to standard and response to target) measures the mismatch negativity, an index of the particular factor being studied (auditory memory, working memory, etc.).

After conducting oddball ERP tasks with tones (low, standard; high, target) and then /ba/ (standard) and /da/ (target) syllables, Schulte-Korne, Deimel, Bartling, and Remschmidt (1998) found no MMN during a non-speech oddball tones task, but they did find it in an oddball speech task using the phoneme /da/ as the standard stimulus and /ba/ as the deviant stimulus. They concluded that dyslexia reflected a deficit in phonological processing, not a general auditory processing deficit.

In another MMN study designed to answer criticism that confounding effects such as attention or cognitive capacity caused reading impairment rather than phonemic awareness, Baldeweg, Richardson, Watkins, et al., (1999) structured a task that measured auditory processing free from these effects. They asked participants to gaze at a fixed symbol on the computer monitor –a visual distracter task—while tones were presented binaurally. They found that dyslexics showed impairment in auditory frequency discrimination but not to changes in tone duration.

Csepe (2003) reported on smaller MMNs in dyslexic children in speech and non-speech sounds using consonant, vowel and tone changes, with differences being the most pronounced with consonants. Her research confirms other studies (Farmer & Klein, 1995; Paulesu, Demonet, & Fazio, 2001; Tallal, 1980) showing that dyslexics have difficulty discriminating speech and non-speech sounds that contain rapid transitions.

Several studies focused on other ERP tasks to determine if they measure reading prowess in dyslexic and good readers. In a study of auditory and visual processing of children with language impairment and reading disability, the N140 component showed a lower amplitude and longer latency in dyslexic versus normal readers during a visual recognition task (Neville, Coffey, Holcomb, & Tallal, 1993). The children who performed abnormally on an auditory temporal discrimination task showed abnormal processing in the superior temporal gyrus.

In another study using ERPs with dyslexic and normal children (Taylor & Keenan, 1990), the N200 and P300 latencies were elicited later and the P300 was lower in amplitude during lexical decision tasks among dyslexic children. ERPs were recorded during three visual related tasks: a non-alphabetic, an alphabetic, and a lexical decision task. P300 latency measures the processing time before a response is generated and is a sensitive measure of the brain activity that underlies attention allocation and immediate memory (Polich, 2000). Shorter latencies indicate superior cognitive performance while P300 amplitude measures the brain activity of working memory and the amount of attentional resources applied to a given task (Polich, 2000). According to Polich (1998), the task used most often to elicit the P300 is the two-stimulus discrimination or “oddball” paradigm.

In other studies on reading using evidence from ERPs, McPherson, Ackerman, Holcomb, and Dykman (1998) observed adolescent dyslexics and normal readers during visual and auditory rhyming tasks. By doing so, they identified two different abnormalities in reading disabled individuals: a phonological processing deficit and a processing speed deficit. Their findings support the previous behavioral studies of Ackerman and Dykman (1993) by highlighting phonological processing as a major deficit.

Breznitz (2002) proposes that an underlying cause of dyslexia is an asynchrony between processing rates of the visual and auditory systems. Comparing elementary school children with dyslexia and normal readers, she used ERP waveform components most relevant to reading: N100, P200, N200, P300. The first three are related to attention, visual perception and auditory discrimination, while P300 is associated with working memory. Breznitz found that dyslexic readers were slower than normal readers on most nonlinguistic and linguistic auditory and visual low-level tasks and higher-level orthographic and phonological tasks.

Connolly, Bryne, and Dywan (1995) investigated the relationship between ERPs and performance on the *Peabody Picture Vocabulary Test* (Dunn & Dunn, 1997), a measure of receptive vocabulary. They used a total of 90 pictures from preschool, child and adult levels of difficulty with each stimulus-spoken word presented twice, once with a congruent picture and once with an incongruent picture. They found that two ERP components (phonological mismatched negativity—PMN and N400) were reliably larger in response to incongruent words and not so in response to congruent picture/spoken word pairs. Again, differences between waveform responses were noted only at or below participants’ vocabulary level as determined by psychometric measures. As participant confidence levels lessened regarding the congruity of picture/word pairs, negative ERP components became evident.

From this study, Connolly et al. (1995) demonstrated that the *Peabody Picture Vocabulary Test* (Dunn & Dunn, 1997) could be presented as an ERP task when measuring receptive vocabulary in aphasic/cerebral palsied patients as well as normal participants. The purpose of their study was to bridge the gap between neurolinguistic processing studies and studies using clinical assessments of receptive language. According to Polich (1998) both the single stimulus paradigm used by Connolly et al.

(1995) and the oddball paradigm produce almost the same scalp topographies in response to both auditory and visual stimuli in terms of mismatch negativity; however, for the P300 the oddball task is recommended and is the most commonly used (Polich 2000).

Research Questions

We hypothesize that waveform patterns of low readers produced by specific ERP tasks will show significant differences between the brain's responses to standard stimuli in relation to waveforms produced by target stimuli when compared to average and expert readers. We believe that the MisMatch Negativity (MMN) differences will be seen in all four tasks, thus indicating a general auditory deficit, a phonological deficit, and deficits in receptive language and reading vocabulary of low readers. Therefore, research questions addressed in this paper are:

1. Are there significant MMN differences between low, average and expert readers when processing:
    - tones,
    - phonemes,
    - pictures seen/words heard, and/or
    - pictures seen/words seen?

2. What challenges emerge when conducting a psycho-physiological study within a public school setting that may compromise research results, and how are the challenges diminished?

Methods

This EEG/ERP study took place in a highly ethnically/racially diverse urban/suburban middle school in a northeastern United States' metropolitan area. The racial mix across the 390 sixth-graders included Hispanic (45%), Caucasian (28%). Asian (15%), African American, and other Black students (11%). Less than 2% identified themselves as multiracial or chose not to indicate their race. It's important to note, that 20% of those identified as Caucasian immigrated from the middle-East or North Africa.

Students lived in a variety of housing from extensive low-income complexes to exclusive, multimillion-dollar homes of high salaried executives. Of the 236 sixth graders, 45% were enrolled in English as a second language classes, 22% were identified for special education services, 18% were in general education, 9% were in gifted and talented center-based programs, and 6% participated in school-based gifted and talented classes. Of the sixth grade population, 11% received learning disabilities resource support, 7% were in self-contained classes for students with learning disabilities, 2% received speech and language assistance, and one was identified as being emotionally disturbed. At least 64 different languages are spoken in the homes. A large percentage of students receive free or reduced lunches as seen in Table 1. The annual attrition rate ranges from 24% to 27%.

Table 1. Free and Reduced Lunches

	Grades 6, 7, 8 Total Population (%)	Grade 6 Total Population (%)
Free lunches	554 (44%)	183 (47%)
Reduced Lunches	152 (12%)	53 (13%)
Total	706 (56%)	236 (60%)

Procedures

Classroom reading teachers administered the *Gates MacGinitie Reading Tests* (MacGinitie, MacGinitie, Maria & Dreyer, 2000) in a classroom setting, while the math teachers administered the *Naglieri Nonverbal Ability Test* (NNAT), *Level E* (Naglieri, 1997) after first using *Level C* as warm-up exercises for two weeks to ensure that all children had an opportunity to grasp the idea of matrix reasoning.

Table 2. Psychometric Battery with Listed Subtests Used

Area of Interest	**Test**	**Forms**	**Author(s)/Publisher**
Verbal and Performance IQ	*Wechsler Abbreviated Scale of Intelligence.* Vocabulary, Block Design, Similarities, Matrix Reasoning		The Psychological Corporation, 1999
Nonverbal Ability	*Naglieri NonVerbal Ability Test* (NNAT)	Level E	Naglieri
Receptive Language	*Clinical Evaluation of Language Fundamentals-3rd Ed.* (CELF-3) Receptive Language: Concepts and Directions, Word Classes, Semantic Relationships.		Semel, Wiig, & Secord, 1995
Phonological Processing	*Comprehensive Test of Phonological Awareness (CTOPP).* Elision, Blending Words, Memory for Digits, Rapid Digit Naming, Nonword Repetition, Rapid Letter Naming		Wagner, Torgeson, & Rashotte, 1999
Vocabulary	*Peabody Picture Vocabulary Test-Third Edition (PPVT-III)*	IIIA & IIIB	Dunn & Dunn, 1997
Basic Reading Skills	*Woodcock Reading Mastery Test-Revised (WRMT).* Word Identification, Word Attack.	G & H	Woodcock, 1998
Reading Comprehension	*Gates-MacGinitie Reading Tests*	Level 4-6 Forms S & T	MacGinitie, MacGinitie, Maria, & Dreyer, 2000
Executive Function	*Wisconsin Card Sort Test (WCST)*	Computer Version 3 Research Edition	Heaton & PAR Staff, 1999

Parents of all sixth graders were invited to give permission for student participation in this study. Positive responses were received from 168 families (71%). Students exhibiting ability scores at or above 85 standard score on the *Naglieri Nonverbal Ability Test* and above the 80th percentile on the Gates MacGinitie reading scores were eligible for the expert reader group (n = 24). Students at or below the 29th percentile (n = 88) were eligible for the low reader group, while students with scores between the 30th and 79th percentiles (n = 56) on the *Gates MacGinitie* were dropped from the study.

Once permissions arrived and students were selected, well-prepared psychometricians implemented an extensive test battery as shown on Table 2 to individually evaluate each student. Parents and a teacher for each child completed a *Child Behavior Checklist/4-18,* the *Parent* or *Teacher's Report Form* (Achenbach, 1991) and the *Behavior Rating Inventory of Executive Function* (BRIEF) (Gioia, Isquith, Steven, & Kenworthy, 2000). Parents or guardians also completed a questionnaire of demographic and educational history of the child. One evaluator used a hand-held Snellen chart to screen for visual acuity problems and the school nurse used a pure tone audiometer to check for auditory acuity deficits. When deficits were identified, students were referred for individual visual and/or auditory evaluations or for further evaluation by the school counselor. When a child scored high on the NNAT he or she was referred to the Child Study Committee for possible inclusion in a gifted and talented program.

EEG/ERP Recordings

An EEG/ERP lab was set up in a newly installed teachers lounge with running water and ample space for the NeuroScan EEG system and a LazyBoy recliner. Windows were covered with black paper and electrical noise was shielded with aluminum foil or copper shielding screen.

An elasticized cap with silver-silver chloride electrodes was fitted according to the international 10-20 system (Jasper, 1958), and each electrode was filled with conductive gel. Thirty scalp derivations were referenced to linked earlobes. The ground electrode was built into the cap and was positioned anterior to site Fz. Bipolar vertical and horizontal EEG signals were recorded.

Mastoids were used as reference if the earlobes could not be used due to non-removable earrings. A set of four electrodes was placed around the eyes to measure both vertical and horizontal eye movements.

The equipment was recalibrated each time the NeuroScan software package was reloaded. Students were introduced or re-introduced to laboratory procedures at the beginning of each recording session. The electrode array was fitted and impedances less that 5 k ohms were considered appropriate to proceed; however, in some cases the impedances were in the 5-10 k ohms range. The input impedance of the amplifiers was 1 G-Ohm. The impedances were rechecked when the subject stood during the course of the experiment.

In all cases, the signals were digitized at 1000 Hz using a 16-bit digitizer in continuous acquisition mode. The high pass filter setting was .15 Hz and the low pass setting was 200 Hz. A notch filter at 60 Hz was enabled. Gain was set at 500 Hz. The range was 11 mV and the accuracy was 0.168μV/LSB (least significant bit).

A cursory hearing test was conducted at two frequencies, 500 and 1000 Hz. Initially, the stimulus intensity was 40 dB. Intensity was decreased until the perception threshold was determined. All auditory stimuli were administered at 70 dB peak intensity. Children with a hearing loss were dropped from the study. Earphones were used throughout the ERP tasks.

The participant sat in a recliner at eye level with the mid point of the monitor approximately 17 inches in front at a visual angle of approximately 7 degrees. While the cap was being fitted the student worked on homework or played electronic games on a Game Boy or Play Station. Once all impedances were within acceptable limits, an artifact demonstration followed to show the student how the waveform pattern is destroyed with body movement, eye blinks, and mouth movements.

Students were given a demonstration of each task immediately prior to its implementation. They were asked to push the first button on a four-button keypad with the index finger of the right hand whenever the target tone or word occurred. Mid way through each task (100 items), the pad was moved for accessibility to the left hand and the procedures continued for an additional 100 items.

Each of the four tasks included four sample items. Between tasks, the student was permitted to go to the bathroom, but few students required this interruption. Snacks and drinks were provided while fitting the cap and between tasks to maintain motivation and reduce fatigue. Students were given the choice of gift certificates or age-appropriate games and toys as rewards for their participation.

ERP Tasks

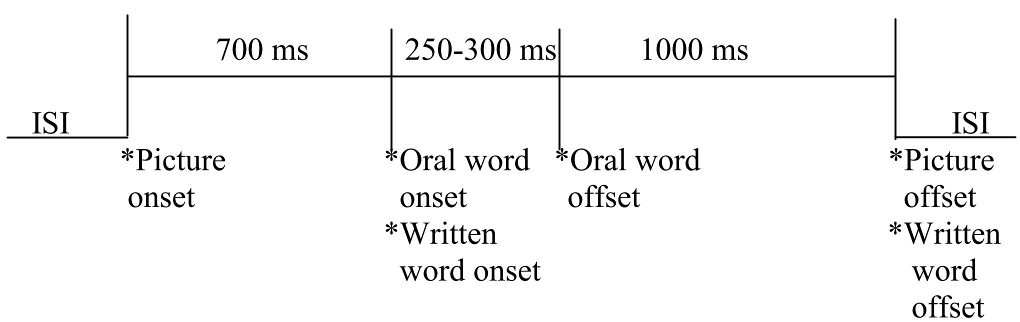
A tonal oddball experiment with a high pitch target tone of 800 Hz and a low pitch non-target tone of 400 Hz was employed. The stimulus duration was 300 ms with a 20 ms rise and a 20 ms fall as consistent with the duration of phonemic stimuli used in subsequent experiments. The subject's eyes were closed during this experiment.

In total for each task, two hundred stimuli were presented, forty target stimuli and one hundred-sixty standard stimuli. A constrained randomization determined the stimulus presentation sequence. Two target presentations were separated by at least two non-target stimuli. The stimulus presentation was dichotic with a peak stimulus intensity of 70 dB. A brief pause after the first one hundred presentations allowed students to change response hands. The inter-stimulus interval varied randomly between 1.8 and 2.2 seconds. Generically specified equipment and recording protocols (electrode montage, filter settings, gain settings, digitizer frequency) were employed.

A phonemic oddball experiment with two phonemes was presented in a random sequence with either /aba/ or /ada/ as the target stimulus. The Scientific Learning Corporation provided the computer-generated phonemes. Each had a duration of 300 ms, with a 20 ms rise and fall time, and a peak intensity of 70 dB. In this experiment, each element of the /aba/ and /ada/ triplets had roughly equal duration (100 ms). The pitch oddball procedures as described above were repeated for this experiment. Again, the students' eyes were closed.

For the congruent/incongruity single word tasks, stimulus pictures from the *Picture-Peabody Vocabulary Test* (Dunn & Dunn, 1997**)** were paired with single words from a graded word list for both the words heard (ERP task #3) and words seen (ERP task #4). Each of these tasks consisted of 200 picture/word pairs of which 160 picture pairs were congruent (80%) and 40 word pairs were incongruent (20% deviant). The presentation included two blocks of 200 words each. In the first block (ERP task #3), the picture was paired with a spoken word and in the second block (ERP task #4) the picture was paired with a printed word.

ERP recordings were time locked to the onset of the spoken word. The onset of words seen was consistent with that of words heard; however, the offset of words seen matched the offset of the picture. Generically specified equipment and recording protocols constructed for the oddball tonal task were used for tasks 3 and 4. The figure below represents the time course of stimulus presentation.



Correct vs incorrect responses to individual items were scored to determine the relationship between average number of items correct and waveform averages at N400 and P300. In keeping with the Connolly et al. (1990, 1992, 1995) procedures, PMN, N400, and P300 amplitude and latency were calculated from word onset to the most negative (N400) peak between 350 and 600 ms or positive (P300) peak between 300 and 600 ms.

Data Analysis

All data were stored in an Intel based Pentium IV desktop computer and transferred to a secure external hard drive for preliminary analysis and averaging. To account for any ocular artifacts, an eye movement reduction algorithm was applied. The EEG and

Electro-oculogram (EOG) data were amplified and epoched for 1000ms with a band pass of 0.01 to 70 Hz and baseline corrected for pre-stimulus interval.

The following ERP components were analyzed in this experiment: N100, N400 and MisMatch Negativity (MMN). Peak amplitudes and latencies for specific components were identified. That is, the N100 was scored as the most negative peak occurring in the interval of 80 to 215 ms, the N400 was scored as the most negative peak between 350 and 600 ms. MMN was measured in the difference waveforms. The peak amplitude and latency at the FZ site (where the amplitude is maximal for N100 and MMN) was subject to ANOVA to compare differences across groups.

Results

Tonal Oddball

With regard to the tonal oddball, there was no significant difference among the groups for the latency of the N100 component as seen in Figure 1. While the average readers evidenced smaller amplitude, the amplitudes for the low and expert readers were similar and higher than those of the average readers, however, differences in amplitude across groups failed to reach significance.

The group mean average waveforms for the standard and target tonal stimuli are represented in Figure 1 for the three groups. MMN is defined as the difference between the response to the target and standard. All three groups evidenced large MMN waves to the tonal stimulus. The low readers displayed decreased amplitude and delayed latency of the MMN in comparison to the average and expert readers, but this finding was not significant. In addition the MMN for the low readers was reduced in comparison to the average and expert readers; again, these differences were not statistically significant.

Phonemic Oddball

Group mean comparisons across the three groups for the standard phonemic response (/aba/) is represented in Figure 1. The N1 amplitudes and latencies of the three groups did not differ significantly indicating that the expert, average and the low readers did not differ in their ability to initiate attention.

With regard to the MMN, as can be seen from Figure 1, significant differences were observed across the groups in terms of the area of the MMN. The low readers evidenced decreased MMN, while the expert readers evidenced enhanced MMN, indicating that the low readers have difficulty in discrimination of phonemes when compared to both the average and the expert readers.

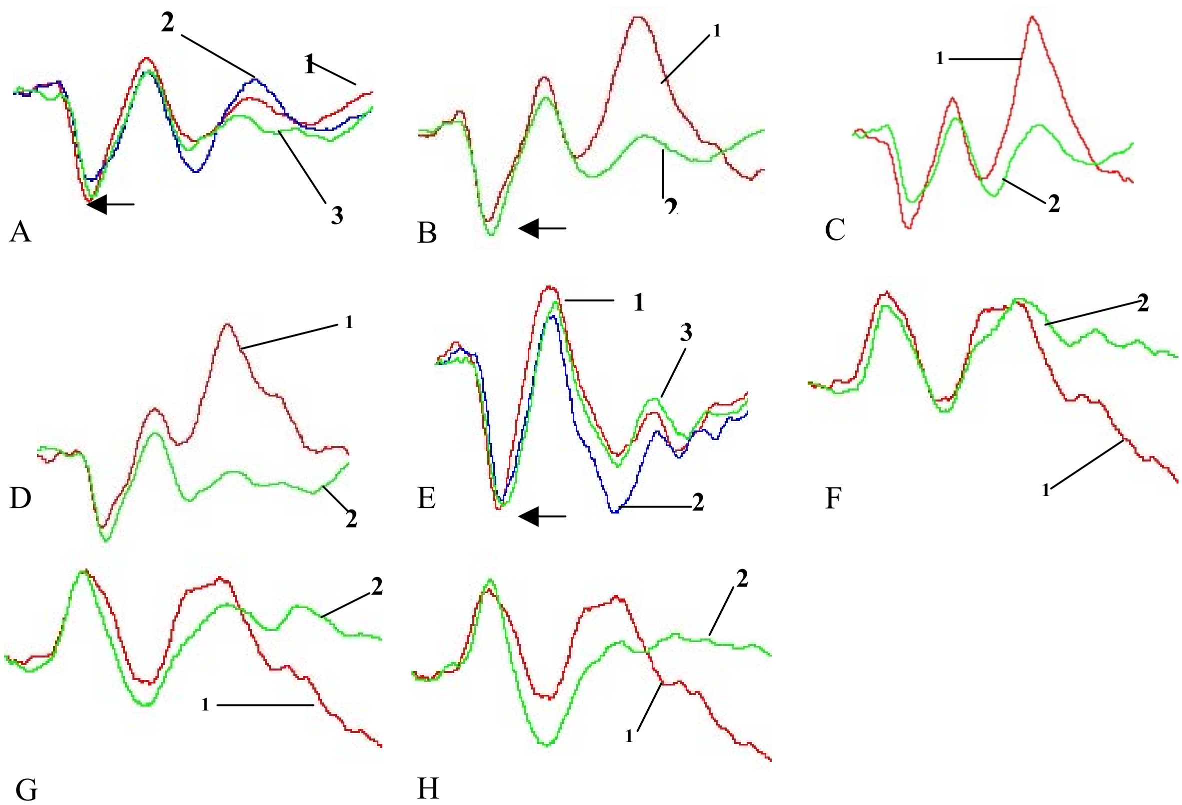
Picture/Word Incongruity Tasks

With regard to the pictures seen/words heard task, the N1 amplitude and latency for the three groups were similar as seen from waveform patterns in Figure 2. While there were no significant differences in amplitude between the expert and average readers on N100, significant differences were observed between the expert and the low readers on N400 with the expert readers showing a much larger amplitude than the low readers. These findings of smaller amplitudes and longer latencies of low readers are similar to those reported by other investigators who found slower information processing of the low readers in comparison to normal readers (Duncan et al., 1994, Taylor & Keenan, 1990).

Picture/Word Incongruity Tasks

As can be observed in Figure 2, the three groups differed in terms of the phonological mismatch negativity. While the expert readers showed a much clearer separation (the MMN area represented by the arrow) for the response to the target words, low and

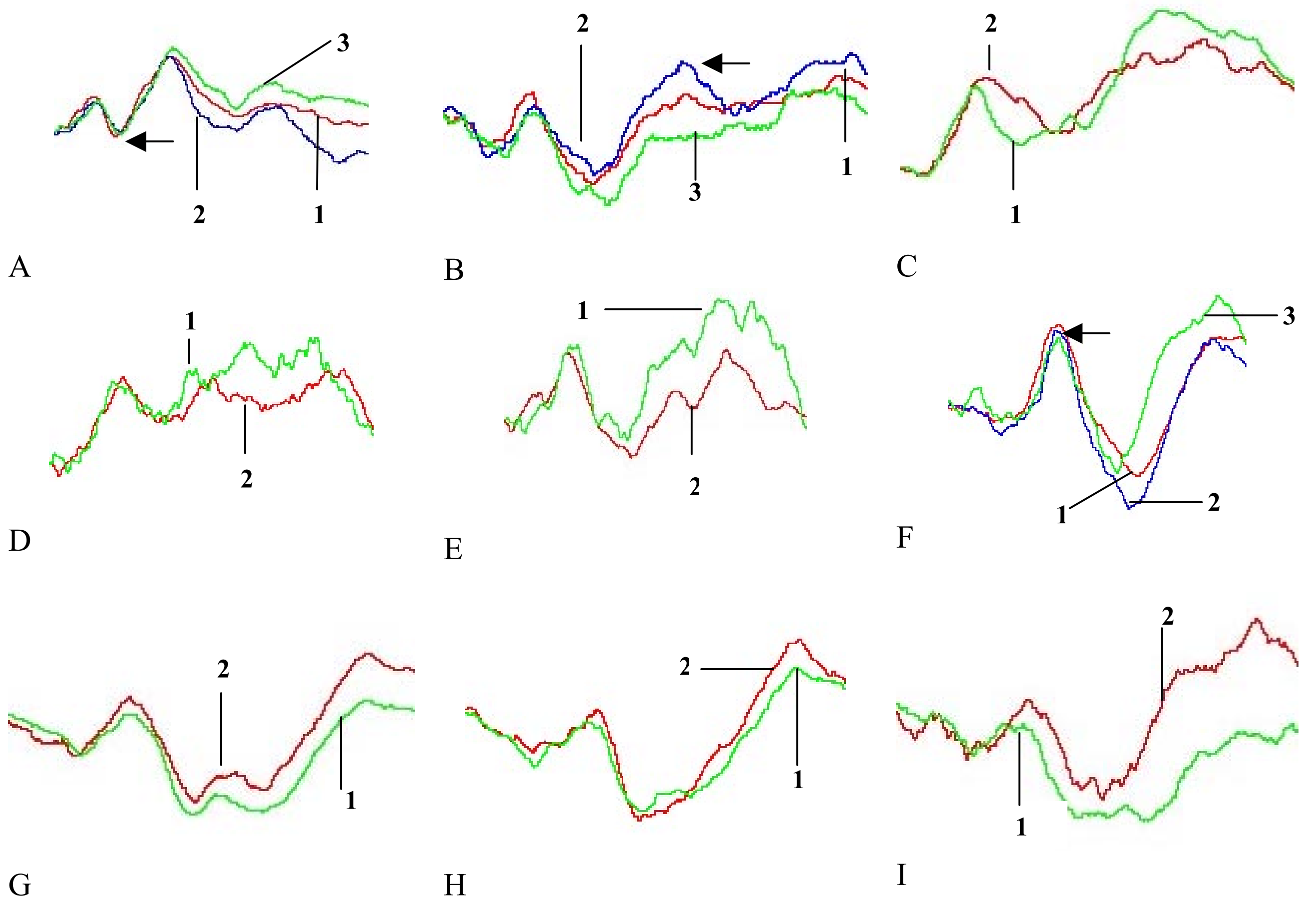
Figure 1. Tonal and Phonemic Oddball Response comparisons of Low, Average and Expert Readers



A: Tonal Oddball, N100 at arrow. 1 = low readers; 2 = average readers; 3 = expert readers.
B: Tonal MMN of low readers. 1 = response to target; 2 = response to standard.
C: Tonal MMN of average readers. 1 = response to target; 2 = response to standard.
D. Tonal MMN of expert readers. 1 = response to target; 2 = response to standard.
E. Phonemic Oddball, N100 at arrow. 1 = low readers; 2 = average readers; 3 = expert readers.
F: Phonemic MMN of low readers. 1 = response to target; 2 = response to standard.
G: Phonemic MMN of average readers. 1 = response to target; 2 = response to standard.
H: Phonemic MMN of expert readers. 1 = response to target; 2 = response to standard.

average readers evidenced smaller separations, indicating difficulty in discriminating the target stimuli (mismatched picture/word). The fact that the groups did not differ in the N100 but showed significant difference both on the N400 latency and the MMN area, implies that the low readers difficulty in reading is not related to difficulties in attention

Figure 2. N100, N400, and Mismatched Negativity Comparisons of Low, Average and Expert Readers.



A: Picture Seen/Word Heard Comparison of N100 at arrow. 1 = low readers; 2 = average readers; 3 = expert readers.
B: Picture Seen/Word Heard Comparison of N400 at arrow. 1 = low readers; 2 = average readers; 3 = expert readers.
C: Picture Seen/Word Heard MMN of Low Readers. 1 = response to target; 2 = response to standard.
D: Picture Seen/Word Heard MMN of Average Readers. 1 = response to target; 2 = response to standard.
E: Picture Seen/Word Heard MMN of Expert Readers. 1 = low readers; 2 = average readers; 3 = expert readers.
F: Picture Seen/Word Seen of N100 at arrow. 1 = low readers; 2 = average readers; 3 = expert readers.
G: Picture Seen/Word Seen MMN of Low Readers. 1 = response to target; 2 = response to standard.
H: Picture Seen/Word Seen MMN of Average Readers. 1 = response to target; 2 = response to standard.
I: Picture Seen/Word Seen MMN of Expert Readers. 1 = response to target; 2 = response to standard.

but perhaps due to phonological processing as evidenced by lower MMN for the phonemes and delayed N400 for the semantic incongruity tasks.

Similar interesting patterns were observed on the last of the oddball tasks namely, picture presented with the verbal word (read word). While there were no significant differences for the N1 component, differences were observed both for the N400 component and the MMN as displayed in Figure 2. The expert readers had a enhanced N400 as seen by increased amplitude and a distinct phonological mismatch negativity as opposed to the low and the average readers who displayed a smaller N400 amplitude and MMN.

Challenges to data collection

Although a number of methodological challenges were encountered when conducting site-based psychometric and EEG research, they were dealt with in a timely manner to prevent negative impact on reliability or validity. The main methodological challenge involved subject selection. In this highly ethnically diverse setting, a major challenge involved limiting the research to students with English proficiency and rejecting those with low English skills. Further, preliminary research assessment identified several students with auditory acuity difficulties, diagnosed psychiatric disorders, and physical impairments that would prevent them from participating in a meaningful way. Rejecting these students after having received parental permission required utmost diplomacy, since the students wanted to participate.

Among the groups of low and average readers (n = 88), 17 different languages were spoken in the home with Spanish accounting for 44 students. Parents were frequently recent immigrants to the United States, thus wherever appropriate, questionnaires were provided in Spanish. However, it was not feasible to provide questionnaires and surveys in all 17 languages. In some instances, the parents asked the child to complete the parent form. When this was discovered, a Spanish member of the project staff called and led Spanish-speaking parents through the questionnaire item by item. All questionnaires were closely examined to eliminate similar occurrences.

Support from an on-site administrative coordinator was instrumental in enlisting teacher support, scheduling student assessments, and coordinating the research efforts within the reality of a middle school setting. Thus, data acquisition challenges regarding student information and skills were overcome by consistent, sustained support from a key school administrator, however, teachers did not always take adequate time for reflection before completing questionnaires about students. Thus, teachers were asked to reflect on each child’s characteristics when considering their responses. This gentle nudging resulted in more specific responding.

With regard to psychometric and EEG/ERP task completion, time of day, failure to eat breakfast or lunch, and religious fasting tended to have a negative effect on some students’ performance. Further, student uncertainty about walking into the unknown of an EEG lab created some initial student nervousness. Some thought the EEG cap and blunt needles used to squeeze conductive gel on the scalp would be painful. With some students, certain hairstyles-- especially braiding-- made data acquisition challenging, yet to unbraid students' hair was a student decision. If the choice was to leave the hair braided, either rescheduling was necessary or the recordings were attempted with the braids. In some cases most electrodes picked up the brain wave signals, but in other cases, rescheduling was required.

Discussion

In terms of tones, there was no significant difference across low, average, and expert reader groups; however, too few electrode sites have been analyzed to question the presence of a general auditory processing deficit.

With regard to phonemes, significant differences were observed for the mismatched negativity that were smaller for low readers than those of expert and average readers. No significant differences were observed on the N100 component, thus indicating that the low readers do not differ from average or expert readers in terms of their attention to the task. However, when required to discriminate between phonemes /aba/ and /ada/, difficulty arose suggesting a phoneme discrimination deficit. Since grouping was determined based on phonemic behavioral data, it is noteworthy that both the psychometric measures and the waveform patterns revealed identical results.

Results of the words heard and words seen when paired with congruent and incongruent pictures revealed a change in the pattern whereby the low and average readers differed significantly from the expert readers on phonological mismatched negativity. The area of the MMN was smaller for the low and average readers than they were for expert readers suggesting a limited receptive vocabulary and a limited reading vocabulary. In addition, the expert readers evidenced a significantly higher N400 amplitude when compared to the other two groups on both heard and seen words. That is, low readers took longer to make an initial brain wave response to stimuli when that stimuli pertained to language whether pictures seen paired with congruent or incongruent words spoken or when paired with written words.

For the heard words, significant differences were observed on the N400 latency and the MMN area. The N400 latency was significantly shorter for expert readers than for the other two groups, while the phonological MMN area was significantly larger as seen in Figure 2. That is, it took longer time for low reader brains to notice incongruence and when they did, there was less certainty about the decisions made. Also the MMN area was smaller for low readers in comparison to the average readers, but this finding was not statistically significant. When words were read, however, low and average readers displayed similar waveforms that differed significantly from those of expert readers. Once again, expert readers displayed an enhanced N400 as seen by increased amplitude and a distinct phonological MMN as opposed to low and average readers who displayed a smaller N400 amplitude and a significantly smaller MMN.

In summary, results of this study indicate that tonal discrimination appears similar across groups, the discrimination of phonemes, receptive vocabulary, and reading of single words were areas of deficit for low readers. There was a progression or gradation of these findings whereby differences between low and expert readers were significant across language oriented tasks, while differences between average and expert readers were obvious on receptive and reading vocabulary tasks there was no such difference on the phonemic oddball task. Waveform patterns produced by adolescents in this study replicate those found in similar studies with dyslexic participants (Connolly, et al., 1995; Näätänen, 2001; Shulte-Körne et al., 1998).

Conclusions

It must be noted that the level of reading proficiency demonstrated on the Gates MacGinitie Reading Tests (MacGinitie, MacGinitie, Maria & Dreyer 2000) that grouped students into expert and low groups failed to maintain when individual testing was considered. Therefore, although including an average group was unintended, individual measurement scores created one. Had the initial screening groups been implemented , the significance differences between the low and expert groups may have remained but with less strength of difference as seen when the average and low readers were treated as separate groups. Thus, when determining reading proficiency, it may be necessary to base level of skill development upon individually administered rather than on group administered measures.

The relationship between phonological awareness and reading was pronounced in this study, as with other studies. The fact that almost half of the students in the "low" reader group actually read within the average range when individually tested, necessitated regrouping the students based upon alternate criteria. Thus, their performance on the Comprehensive Test of Phonological Processing (CTOPP) Phonological Awareness subtest and the Woodcock Reading Mastery Tests (WRMT) Basic Skills subtests served as the grouping criteria. This procedure may have enhanced the differences seen across the three groups in terms of the ERP data, since expert readers were strong in phoneme discrimination and reading while average readers were less so, and low readers were distinctly different in their abilities to discriminate phonemes and to read.

This study gives preliminary findings regarding specific components (N100, N400 and MMN) in only the FZ electrode. Additional analyses regarding the P300 and N200 along with correlations of psychometric measures across groups of electrodes are expected to shed more light on topographical differences and similarities across low, average and expert readers.

Additionally, in keeping with previous research (Hook et al., 2001; Rumsey et al. 1992; Shaywitz et al. 2002; Shaywitz et al., 2003; Simos et al. 2002; Temple et al. 2003) there is need to determine if phoneme, congruent and incongruent word waveforms of low readers become more like those of expert readers after specific interventions or if they remain resistant to specific phonemic training during the adolescent years. Based on intervention research with younger age groups, the hypothesis is that the waveforms will change toward those of expert readers. If so, recommendations for phonemic training and reading skill development at the middle school level can be made.

References

Achenbach, T. M. (1991) *Manual for the Child Behavior Checklist/4-18.* Burlington, VT: University of Vermont

Achenbach, T. M. (1991) *Manual for the Teacher's Report Form.* Burlington, VT: University of Vermont

Bradley, L., & Bryant, P. E. (1983). Categorizing sounds and learning to read—A causal connection. Nature, 301, 419–421.

Ackerman, P. T. & Dykman, R. A. (1993). Phonological processes, confrontational naming, and immediate memory in dyslexia. *Journal of Learning Disability, 26*(9), 597-609.

Bailey, P. J. & Snowling, M. J. (2002). Auditory processing and the development of language and literacy. *British Medical Bulletin, 63*, 135-146.

Baldeweg, T., Richardson, A., Watkins, S., Foale, C. & Gruzelier, J. (1999) Impaired auditory Frequency discrimination in dyslexia detected with mismatch event potentials. *Annals Neurology,* Vol. 45, No. 4: 495-503.

Bishop, D. V. M., Carlyon, R. P., Deeks, J. M., Bishop, S. J. (1999). Auditory temporal processing impairment: Neither necessary nor sufficient for causing language impairment in children. *Journal of speech, Language, and Hearing Research, 42*, 1295-1310.

Brandeis, D. & Lehman, D. (1986) Event-related potentials of the brain and cognitive processes: Approaches and applications. *Neuropsychologia,* Vol. 24, No. 1: 151-168.

Bradley, L. & Bryant, P.E. (1983) Categorizing sounds and learning to read - A causal connection. *Nature,* 301, 419-421.

Breznitz, Z. (2002) Asynchrony of visual-orthographic and auditory-phonological word recognition processes: An underlying factor in dyslexia. *Reading and Writing: An Interdisciplinary Journal,* Vol. 15:15-42.

Breznitz, Z. & Misra, M. (2003) Speed of processing of the visual-orthographic and auditory-phonological systems in adult dyslexics: The contribution of "asynchrony" to word recognition deficits. *Brain and Language,* Vol. 85, No. 3: 486-502.

Bryne,J. M., Connolly, J. F.,MacLean,S. F., Dooley, J. M., Gordon, K. E., & Beattie, T. L. (1999). Brain activity and language assessment using event related potentials: Development of a clinical protocol. Developmental Medicine and Child Neurology, 41, 740-747.

Bryne, J. M., Dywan, C., & Connolly, J. F. (1995). An innovative method to assess the receptive vocabulary of children with cerebral palsy using event-related brain potentials. *Journal of Experimental and Clinical Neuropsychology, 17*, 9-19.

Connolly, J. F., Byrne, J. M., Dywan, C. A. (1995) Assessing adult receptive vocabulary with event-related potentials: An investigation of cross-modal and cross-form priming. *Journal of Clinical and Experimental Neuropsychology,* Vol. 17, No. 4, pp. 548-565.

Connolly, J. F., Stewart, S. H., & Phillips, N. A. (1990). The effects of processing requirements on neurophysiological responses to spoken sentences. *Brain Language, 2,* 302-318.

Connolly, J. F., Phillips, N. A., Stewart, S. H., & Brake, W. G. (1992). Event-related potential sensitivity to acoustic and semantic properties of terminal words in sentences. *Brain and Language, 43*, 1-18.

Csepe, V. (2003). Auditory event-related potentials in studying developmental dyslexia. In Valeria Csepe, *Dyslexia: Different brain, different behavior.* New York: Kluwer Academic/Plenum Publishers.

Duncan, C. C., Fumsey, J. M., Wilkniss, S. M., Denckla, M. B., Hamburger, S. D., & Odou-Potkin, M. (1994). Developmental dyslexia and attention dysfunction in adults: Brain potential indices of information processing. *Laboratory of Psychology and Psychopathology.* Bethesda, MD: National Institute of Mental Health.

Dunn, L. M. & Dunn, L. M. (1997). *Peabody Picture Vocabulary Test (3rd ed.)* Circle Pines, MN: American Guidance Service.

Farmer, M. E. & Klein, R. M. (1995) The evidence for a temporal processing deficit linked to dyslexia: a review. *Psychon. Bulletin* Rev. 2, 460-493.

MacGinitie, W. H., MacGinitie, R. K., Maria, K. & Dreyer, L.G. (2000). Gates-MacGinitie Reading Test, (4th ed.) Houghton Mifflin Co: Riverside Publishing, Itasca, IL

Gioia, G., Isquith, P., Steven, G. & Kenworthy, L. (2000). *Behavior Rating Inventory of Executive Function*. Odessa, FL: PAR Inc.

Goswami, U. (2002). In the beginning was the rhyme? A reflection on Hulme, Hatcher Nation, Brown, Adams, and Stuart. *Journal of Experimental Child Psychology,* 82, 47-47.

Goswami, U. (2003). Phonology, learning to read and dyslexia: A cross-linguistic analysis. In Csépe, V. (Ed.), *Dyslexia: Different brain, different behavior.* New York: Kluwer Academic/Plenum Publishers, pp. 1-40.

Goswami, U. & Bryant, P.E. (1990). *Phonological Skills and Learning to Read.* Hillsdale, NJ: Lawrence Erlbaum.

Heaton, R. K., & PAR Staff (1999). *Wisconsin Card Sorting Test: Computer Version 3 for Windows, Research Edition.* Odessa, FL: Psychological Assessment Resources, Inc.

Holcomb, P. J., Coffey, S. A., & Neville, H. J. (1992). Visual and auditory sentence processing: A developmental analysis using event-related brain potentials. *Developmental Neuropsychology, 8*, 203-241.

Hook, P. E., Macaruso, P. & Jones, S. (2001). Efficacy of Fast ForWord training on facilitating acquisition of reading skills by children with reading difficulties—A longitudinal study. *Annals of Dyslexia, 51*, 75-96.

Jackendoff, R. (1994). *Patterns in the mind: Language and human nature.* New York: Basic Books.

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology, 10*, 371-375.

Knight, J. R. (2002). Adults with dyslexia: Legislation, remediation, therapy, and work. *Perspectives 28*(4), 1 & 4.

Kujala, T. & Näätänen, R., (2001) The mismatch negativity in evaluating central auditory dysfunction in dyslexia. *Neuroscience and Behavioral Review* 25: 535-543.

Kutas, M., & Hillyard, S.A (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science, 207*, 203-205.

Liberman, A. M. & Whalen, D. H. (2000). On the relation of speech to language. *Trends in Cognitive Sciences*, 4(5), 187-196.

Lishman, W.A. (2003). Developmental dyslexia. *Journal of Neurology, Neurosurgery & Psychiatry 74*(12), 1603-1605.

MacGinitie, W. H, MacGinitie, R. K., Maria, K. & Dreyer, L. G. (2000). *Gates MacGinitie Reading Tests.* Itasca, IL:The Riverside Publushing Company.

McPherson, W.B., Ackerman, P.T., Holcomb, P.J., Dykman, R.A. (1998) Event-related brain potentials elicited during phonological processing differentiate subgroups of reading disabledadolescents. *Brain and Language,* Vol. 62, 163-185.

Mody, M. (2003). Phonological basis in reading disability: A review and analysis of the evidence. *Reading and Writing: An Interdisciplinary Journal, 16*, 21-39.

Muehl, S., Knott, J. R., & Benton, A. F. (1965) EEG Abnormality and psychological test performance in reading disability. *Cortex,* Vol. 1:434-39.

Myklebust, H. R. (1954) Auditory disorders in children; a manual for differential diagnosis. New York, Grune & Stratton

Naglieri, J. A. (1997). *Naglieri Nonverbal Ability Test*. San Antonio, TX: Harcourt Brace.

Näätänen, R. (2001) The perception of speech sounds by the human brain as reflected by the mismatch negativity (MMN) and its magnetic equivalent (MMNm). *Psychophysiology, 38,* 1-21.

Näätänen, R. (2003). Mismatch negativity (MMN): Clinical research and possible applications. *International Journal of Psychophysiology, 48,* 179-188.

National Reading Panel (2000). *Teaching children to read: An evidence-based assessment of the scientific research literature on reading and its implications for reading instruction*. Washington, D.C.: National Institute for Literacy, U.S. Department of Health and Human Services.

Neville, H. J., Coffey, S. A., Holcomb, P. J., Tallal, P. (1993) The neurobiology of sensory and language processing in language-impaired children. *Journal of Cognitive Neuroscience, 5:2, 235-253.*

Neville, H. J., Mills, D. L., & Lawson, D. S (1992). Fractionating language: Different neural subsystems with different sensitive periods. *Cerebral Cortex, 2*(3), 244-258.

Ors, M., Lindgren, M., Berglund, C., Hagglund, K., Rosen, I., & Blennow, G. (2001). The N400 component in parents of children with specific language impairment. *Brain and Language, 77*, 60-71.

Paulesu, E., Demonet, J. F., Fazio, F. (2001). Dyslexia: cultural diversity and biological unity. *Science*, 291, 2165-2167

Polich, J. (1998). P300 clinical utility and control of variability. *Clinical Neuropsychology* Vol. 15(1), 14-33

Polich, J. (2000). P300 as a clinical assay: rationale, evaluation, and findings. *International Journal of Psychophysiology* Vol. 38, No. 1:3-19.

Semel,E., Wiig, E. H. & Secord, W. A. (1995). *Clinical Evaluation of Language Fundamentals-3rd Ed.* (CELF-3). Boston: The Psychological Corporation; Harcourt Brace & Company.

Shaywitz, S. (2003). *Overcoming dyslexia: A new and complete science-based program for reading problems at any level.* New York: Alfred A. Knopf.

Shaywitz, B., Shaywitz, S. E., Pugh, K. R., Mencl, W. E., Fulbright, R. K., Skudlarski, P., Constable, R. T., Marchione, K. E., Fletcher, J. M., Lyon, R., & Gore, J. C. (2002). Disruption of posterior bfain systems for reading in children with developmental dyslexia. *Biological Psychiatry, 52*(2), 101-110.

Shaywitz, S. E., Shaywitz, B. A., Fulbright, R. K., Skudlarski, P. S., Mencl, W. E., Constable, R. T., Pugh, K. R., Holahan, J. M., Marchione, K. E., Fletcher, J. M., Lyon, G. R., & Gore, J. C. (2003). Neural systems for compensation and persistence: Young adult outcome of childhood reading disability. *Biological Psychiatry,54*(1), 25-33.

Schulte-Körne, G., Deimel, W., Bartling, J., & Remschmidt, H.(1998). Auditory processing and dyslexia: evidence for a speech processing deficit. *Neuroreport, 9,* 337-340

Simos, P. G., Fletcher, J. M., Bergman, E., Breier, J. I., Foorman, B. R., Castillo, E. M.et al. (2002). Dyslexia-specific brain activation profile becomes normal following successful remedial training. *Neurology,* 58(8), 1203-1213.

Studdert-Kennedy, M. (2002). Deficits in phoneme awareness do not arise from failures in rapid auditory processing. *Reading and Writing: An Interdisciplinary Journal,* 15, 5-14.

Tallal, P. & Piercy, M. (1993). Defects of non-verbal auditory perception in children with developmental aphasia. *Nature, 241,* 468-469.

Tallal, P. & Piercy, M. (1974). Developemental aphasia: Rate of auditory processing and selective impairment of consonant perception. *Neuropsychologia,* 12(1), 83-93.

Tallal, P. & Piercy, M. (1975). Developmental aphasia: The perception of brief vowels and extended stop consonants. *Neuropsychologia,* 13(1), 69-74.

Tallal, P. (1980) Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language* 9, 182-198.

Tallal, P., Stark, R. E., & Mellits, E. D. (1985). Identification of language-impaired children on the basis of rapid perception and production skills. *Brain and Language,* 25, 314-322.

Tallal, P., Miller, S. & Fitch, R. H. (1993). Neurobiological basis of speech: A case for the preeminence of temporal processing. *Annals of the New York Academy of Sciences,* 683, 27-47.

Taylor, M.J., Keenan, N.K. (1990) Event-related potentials to visual and language stimuli in normal and dyslexic children. *Journal of Psychophysiology* 27(3):318-27.

Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenich, M. M., & Gabrieli, D. E. (2003). Neural deficits in children with dyslexia ameliorated by behavioral remediation: Evidence from functional MRI. *PNAS, 100*(5), 2860-2865.

The Psychological Corporation (1999). *Wechsler Abbreviated Scale of Intelligence.* San Antonio, TX: Psychological Corporation

Tomblin, J. B., Abbas, P. J., Records, N. L., & Brenneman, L. M. (1995). Auditory event responses to frequency-modulated tones in children with specific language impairment. *Journal of speech and Hearing Research, 38,* 387-392.

Torgeson, J. K; Mathes, P. (1999) What every teacher should know about phonological awareness. [Chapter] *Consortium On Reading Excellence (CORE). Reading research: Anthology: The why of reading instruction. (pp. 54-61). Novato, CA, US: Arena Press.*

Troia, G. A. (1999). Phonological awareness intervention research: critical review of the experimental methodology. *Reading Research quarterly, 34*(1), 28-52.

Vellutino, F.R., Fletcher, J.M., Snowling, M.J., Scanlon, D.M. (2004) Specific reading disability (dyslexia): what we have learned in the past four decades. *Journal of Child Psychology and Psychiatry 45 (1): 2-40.*

Vellutino**,** F., & Scanlon, D. (1987). Phonological coding, phonological awareness and reading ability: Evidence from a longitudinal and experimental study. Merrill-Palmer Quarterly, 33, 321-363.

Wagner, R. K., Torgesen, J. K., Rashotte, C. A., Hecht, S. A., Barker, T. A., Burgess, S. R. et al. (1997). Changing relations between phonological processing abilities and word-level reading as children develop from beginning to skilled readers: A 5-year longitudinal study. *Developmental Psychology* 33(3), 468-479.

Wolf, M. & Obregón, M. (1992). Early naming deficits, developmental dyslexia, and a specific deficit hypothesis. *Brain and Language, 42*, 219-247.

Woodcock, R. W. (1998). *Woodcock Reading Mastery Test-Revised (WRMT), Forms G and H., Examiner's Manual.* Circle Pines, MN: American Guidance Service.