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Central Auditory Processing and the Link to Reading Ability in Adults

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1 Introduction

What makes someone a good reader? What makes someone a poor reader? The root biological marker of reading ability has yet to be determined. Many scientists agree that phonological awareness, the understanding of speech sounds, and phonological decoding are key components of reading ability (Melby-Lervag, Lyster, & Hulme, 2012). In addition to this, new research suggests that the auditory system, specifically the timing of auditory processing in the brain, provides a crucial platform that supports the development of reading ability (Banai et al., 2009). This thesis provides empirical data to support the link between reading skill level and auditory processing in adults using auditory brainstem responses (ABRs) as an index. ABRs, as will be discussed further, are electrical signals measured from the scalp that reflect activity from subcortical auditory structures. Data was collected as part of an ongoing collaboration between the labs of Dr. Erika Skoe and Dr. Rachel Theodore.

This thesis delivers a review of the existing evidence of the connection between auditory processing and reading ability in various populations (Sections 2 and 3), beginning first with an overview of the ABR (Section 1.2). Based on this literature, the thesis develops a set of testable hypotheses (Section 4), which were explored in an empirical study performed over the last year (Section 5). Lastly, results are presented (Section 6) and discussed with an eye towards future directions (Section 7).

1.1 Study Aims

This study draws from previous work showing that auditory brainstem function is related to reading ability in children (Banai et al. 2009). Specifically, Banai et al. reported that children who performed below average on phonological tasks had a delayed representation of auditory input, as measured by ABRs, compared to those categorized as “good readers”. The relationships observed in the Banai et al. (2009) study fell along a continuum, meaning that as phonological decoding performance increased, so too did the speed of auditory brainstem responses (Banai et al. 2009). These findings fit generally with the notion that reading ability is linked to temporal processing in the auditory domain (Goswami, 2002; Tallal, 1980). We extend this study by testing whether the link between reading ability and auditory brainstem function is unique to childhood or whether auditory brainstem responses serve as an indicator of reading ability in adulthood as well. Additionally, we expand on the Banai et al. (2009) study to test more directly the relationship between reading ability and temporal processing by systematically changing the temporal rate at which the auditory stimulus is presented.

1.2 What is an ABR?

The core methodological tool used for this study is the Auditory Brainstem Response (ABR). The brainstem is a structure within the central auditory system. Sound first enters the peripheral auditory system (outer, middle, and inner ear) and then travels via cranial nerve VIII to the central auditory system, which encompasses the auditory brainstem, thalamus, and cortex. Binaural sounds are integrated in the auditory brainstem where preliminary processing occurs before the neural activity is sent to higher centers of the brain.

An ABR is a recording of the electrophysiological activity of the subcortical auditory system (Skoe, Krizman, Anderson, & Kraus, 2013). Jewett et al. first discovered the ability to use measurements collected at the scalp to demonstrate auditory activity in the brainstem (Jewett, Romano, & Williston, 1970). Auditory brainstem responses are now commonly used clinically to evaluate the health of the auditory system as there is a predictable, stereotyped pattern for a normal response (Krizman, Skoe, & Kraus, 2010). ABRs have become an instrumental clinical tool for evaluating a child's auditory system at birth to help flag any possible warning signs of peripheral or central abnormalities. Their widespread use in these newborn hearing screenings illustrates how non-invasive and easy ABRs are to obtain (Hall, 2007).

1.2.1 ABR Collection

An ABR is collected by repeatedly presenting a sound to a subject and using electrodes placed at specific points on their head to capture and then transmit the electrical signal to a collection device that then amplifies and averages the signal. In clinical contexts, ABRs are stimulated by the presentation of a very brief sound, such as a click (100 microsecond square wave). Manipulation of stimulus intensity and/or rate can alter the ABR latency and amplitude (this study specifically looks at the manipulation of rate while keeping intensity constant). Clicks have been the chief stimulus used for ABRs in the majority of clinics and research studies since the 1970s. Despite the routine use of simple clicks, complex, longer duration stimuli are becoming increasingly popular, as they seem to give a more accurate representation of the system's functionality due to their natural properties (Skoe, Krizman, Spitzer, & Kraus, 2013). In our daily auditory environment, we do not hear clicks or tone bursts, rather we are more likely to hear speech sounds. Thus, it has been argued that it is more informative to use a complex sound to evaluate tasks such as speech processing and hearing in background noise compared to using clicks to evoke the ABR (Banai et al., 2009). Using naturalistic stimuli, such as speech, evokes a longer, more complex ABR (cABR) (Skoe, Krizman, Anderson, et al., 2013).

1.2.2 The Structure of an ABR

There are five primary peaks to a typical click-evoked ABR wave (marked by roman numerals) that correspond to activity from various structures along the central auditory pathway

(Figure 1). Wave I marks the distal portion of the eighth cranial nerve (the auditory nerve) as it leaves the cochlea and enters the brainstem through the internal auditory canal (IAC) (Hall, 2007). Wave II also likely originates from cranial nerve VIII, but the more distal portion that is closer to the brainstem, compared to the site of wave I. Wave III marks the neural activity of the ipsilateral second order neuron of the cochlear nucleus up to the contralateral superior olivary complex (SOC). The presence of waves II and IV are quite heterogeneous within an adult population, and for this reason they are not widely used as biological markers of the auditory system (Hall, 2007). In many adults, wave IV is seen as merging into wave V. This phenomenon is commonly known as the wave IV/V complex, a topic we will discuss further later on in Section 7.2. Wave V, generated by the contralateral path of the lateral lemniscus up to the inferior collicus, is the most robust of the five peaks, which has contributed to its wide-scale use in clinical settings (Hall, 2007).

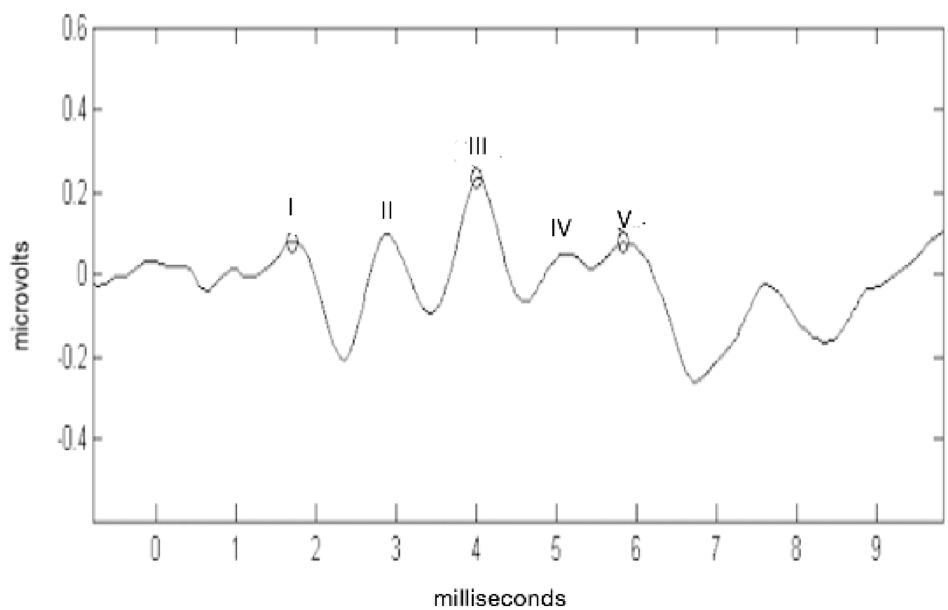


Figure 1. Representative ABR waveform from a study participant

For a given intensity and rate of stimulus presentation, each wave falls within a narrow latency range. Latency refers to the speed of transmission of the signal along the auditory system referenced to when the sound is presented (Hall, 2007). At 70 dB nHL for adults with normal hearing, wave I should occur between 1.5-2 milliseconds (ms), wave II at 2.5-3ms, wave III at 3.5-4ms, and wave IV/V at 5.5-6ms. A wave that occurs at an "abnormal" latency could be a predictor of an auditory dysfunction, such as sensorineural hearing loss, a demyelinating disease, or some kind of brain pathology (Hall, 2007).

1.2.3 The cABR

Stimuli other than clicks are gaining popularity, as they produce a waveform that reflects the specific acoustic properties of the stimulus (Banai, Abrams, & Kraus, 2007). In this study, in addition to a click, we use a speech syllable (“da”) as our complex stimulus. cABRs (complex ABRs) to this stimulus can be divided into two components: an initial onset response, which is analogous to the click-ABR, followed by the frequency following response (FFR) (Banai et al., 2007). FFRs arise in response to periodicities in the stimulus and are generated by the neural activity of the rostral brainstem (Hall, 2007). In the case of the /da/ stimulus, the onset response reflects the spectrotemporal properties of the stop-burst, and the FFR reflects the formant transitions as the articulators move from the alveolar place of articulation for the stop-burst to the back of the mouth for the vowel /a/. Compared to the vowel, the stop-burst of the “da” is lower in intensity, making it more challenging to encode (Banai et al., 2009). This stimulus has been used in a number of studies to examine how speech is processed in the brain (Banai et al., 2009; Skoe, Krizman, Anderson, et al., 2013).

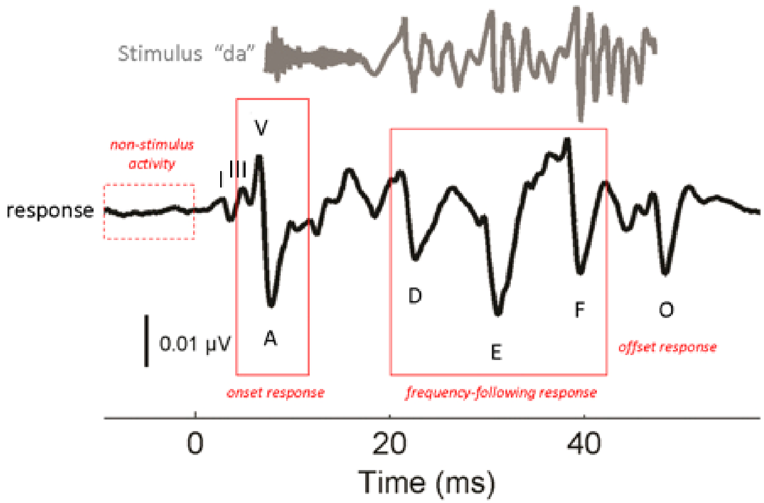


Figure 2. Auditory brainstem responses were recorded to a 40-ms speech syllable. This stimulus produces a form (above) with 6 large peaks (V,A,D,E,F,O).
Modified from Skoe and Kraus, 2013.

As seen in Figure 2, the cABR to the stimulus /da/ we use in this study contains several peaks and troughs. Waves I-V (peaks) are analogous to waves I-V that emerge in a click ABR, and reflect the same neural generators. In addition to these, waves A, D, E, F, and O (troughs) are also labeled for the evaluation of a speech-evoked ABR (Banai et al., 2009). Typical latencies are observed for these waves, with wave A occurring around 8ms, wave D at 23ms, wave E at 30ms, wave F at 43ms, and wave O typically at 48ms. Waves D-E-F represent the primary waves of the FFR, with wave O reflecting the response to the offset of sound. Identifying each wave is a skill that comes with practice and experience.

1.2.4 ABR Development

The ABR waveform varies across the lifespan over the course of development from infant to child to adult. Similar to many other developmental processes in the body, ABRs go through extensive changes within the first few years of life, and become increasingly stable with age. Skoe et al. (2013) collected ABR (click stimulus) and cABR (/da/ stimulus) data on 586 normal hearing and typically developing participants divided into 12 age groups (Skoe, Krizman, Anderson, et al., 2013). Data analysis showed that wave V latency for the click evoked ABR and the speech evoked ABR changed as a function of age. Additionally, the following was noted for the cABR:

> The same general pattern is observed across the 6 peaks: latencies become progressively earlier between infancy and 3-5 years of age, with the nadir occurring across the 5-8 and 8-11 year-old window. Beginning around age 11, latencies then progressively elongate into adulthood after which they stabilize for a period followed by a gradual slowing in the later decades (Skoe, Krizman, Anderson, et al., 2013, p. 3).

Skoe and colleagues reported that the latency data for the 21-30 year age group is the same as that for the 3-5 year age group. This backs up the previously noted idea that 2 year olds have an "adult like" ABR (Hall, 2007; Skoe, Krizman, Anderson, et al., 2013). However, this study revealed a new aspect of ABR development, namely that latencies continue to decrease after age 2, meaning that the response continues to mature after age 2 (Johnson, Nicol, Zecker, & Kraus, 2008; Skoe, Krizman, Anderson, et al., 2013; Spitzer, White-Schwoch, Carr, Skoe, & Kraus, 2015). The data implies that an ABR for those 5-11 years of age is different than responses in adults. Maturation and stabilization of the latencies are then observed to occur after 11 years of age.

Skoe and colleagues argue that the time window between ages 5-11 is reflective of a sensitive period in auditory brainstem development. This 5-11 year old window is theorized to reflect a developmental time window when the brain has an overproduction of myelination coupled with neurogenesis, leading to increased white matter and grey matter within the subcortical auditory system. This manifests as earlier latencies at this point in life compared to any other ages. After this period is over, synaptic pruning and neuron destruction are thought to occur to eliminate unused, excess neural matter, resulting in the delaying of ABR peak latencies (Skoe, Krizman, Anderson, et al., 2013).

Once full maturation is achieved, the average ABR for an individual adult stays consistent across trials and test dates (Song, Skoe, Banai, & Kraus, 2011). Responses do, however, differ from person to person, similar to a finger print (Hall, 2007). Each person's ABR is individual to them, and should be extremely replicable despite the testing environment. Abnormal ABRs and inconsistencies across trials will be discussed further as the relationship between ABRs and an individual's reading ability is investigated.

2 Reading and the Auditory System

Reading is a complex task that requires multiple brain functions to work in concert. Development of reading acquisition relies on auditory linguistic input at an early age (Banai et al., 2009; Boets et al., 2011; Goswami, 2002; Richardson, Thomson, Scott, & Goswami, 2004; Wright & Zecker, 2004). Within the general population, there is a wide spectrum of reading abilities, ranging from those who can read fluently to those who struggle to identify a single syllable. Thus, even within an unimpaired population, reading level is heterogeneous. The cause and biological correlates of reading difficulties, and similar language-based learning disabilities, is a topic of much debate. Many have argued that phonological impairments underlie reading difficulties given evidence that high quality phonological representations are essential to the later accumulation of literacy skills (Richardson et al., 2004). Phonological processing impairments involve the inability to represent phonemes, syllables, and sound patterns mentally (Richardson et al., 2004). An increasing body of research is showing that auditory perception and processing are strongly correlated with the phonological decoding involved with reading. This is known as the "auditory deficit hypothesis of dyslexia", implying auditory processing insufficiencies are associated with reading impairments, such as dyslexia (Banai et al., 2009). The literature review provided in this section summarizes key publications that have helped to establish a connection between auditory processing and reading ability. Given the overlap between dyslexia and other language-based learning disorders, such as specific language impairment (SLI), this section will broadly consider literature from populations with language-based disorders (Boets et al., 2011; Sharma, Purdy, & Kelly, 2009; Wright et al., 1997)

2.1 Auditory Processing and Language Outcomes

Auditory processing can be measured psychophysically using behavioral tests or electrophysiologically using auditory evoked potentials. Auditory discrimination thresholds are a psychophysical (behavioral) index of how well an individual can distinguish one sound from another, a key component of phonological awareness (Wright et al., 1997).

Wright and colleagues compared detection thresholds between children with SLI (mean age=8.1 years) and a control group (mean age=8 years). A low intensity tone was presented before, during, and after masking noises, to determine the acoustic conditions under which the SLI group had the most difficulty hearing the tone. Analysis showed that the SLI group had a pronounced difficulty discriminating the tones presented before the masking noise, a condition referred to as backward masking, but they were matched to the control group when the tone and masker were concurrently presented (Wright et al., 1997). The backward masking condition mimics the acoustic profile of a speech cluster in which a low-intensity, short, stop consonant is followed by a characteristically longer and higher volume vowel (e.g., /da/). The inability to process low intensity sounds that immediately precede (i.e., are temporally close to) high intensity ones may therefore underlie the SLI children's impairments in speech sound processing.

Another necessary skill in learning language is the ability to discriminate between rapidly presented auditory stimuli that have similar acoustic profiles. To test if a diminished discriminatory ability is a predictor of later language impairment, Benasich and Tallal longitudinally tracked 43 normal hearing infants (from English speaking families) who were separated into two groups. The groups consisted of those with a family history of specific language impairment (FH+) and those without a family history of SLI (FH-) (Benasich & Tallal, 2002). Infants were assessed on cognitive measures to monitor their development as well as language measures later on, with standardized scores of language used for data analysis. Rapid auditory processing measures were recorded at the beginning of the study and again at 12, 16, 24, and 36 months of age. Rapid auditory processing was tested using a preferential looking paradigm tailored to infants, instead of the typical psychophysical testing procedures used commonly with older children. Illuminated boxes, motorized toys, and video recording equipment were all utilized to collect auditory discrimination data for this young population. For each trial, two-tone pairs were presented to the infant, who was trained to look in the direction of the speaker presenting the tone-pair that contained two different frequencies. The silent interval between the two tones was shortened (varying from 500ms to 8ms) to find the smallest temporal interval at which the infant was still able to discriminate that there were two sounds (Benasich &

Tallal, 2002). Regardless of which group the infants were initially placed in (family history of SLI or not), those with poorer rapid auditory processing thresholds (150 ms or above) had poorer standardized language scores when evaluated in pre-school (Benasich & Tallal, 2002).

The results of this study by Benaisch and Tallal suggest that temporal processing impairments pre-date when a child learns to speak and read. A similar longitudinal study conducted by Boets and colleagues in Belgium provides further evidence that children diagnosed with dyslexia have impaired auditory processing and perception earlier in development, as well as lower literacy achievement (Boets et al., 2011). This study found that performance for participants in third grade was correlated to measurements taken in kindergarten, implying that the deficits existed prior to diagnosis and persisted throughout development rather than manifesting at the same time, or only once, the child is learning to read.

In summary, there is currently no consensus in the field as to whether temporal processing impairments are a cause or a symptom of poor phonological knowledge. However, given that temporal processing can be tested at an early age, prior to when behavioral tests of reading ability are possible (cf. Benaisch & Tallal, 2002), such tests may prove useful in identifying children at risk for later language impairments.

2.2 Phonological Discrimination and Reading Development: *A proposal for how they might be causally linked*

Very young infants, as young as a few weeks old, have shown the ability to discriminate between phonemes in any language (such as /ba/ and /pa/) (Benasich & Tallal, 2002). Later on, as a child develops and absorbs the linguistic stimuli in their native environment, they are only able to discriminate between sounds present in their own language, a process known as native language neural commitment (Kuhl, 2004). This phenomenon is observed in infants as young as

6-8 months old, and it is considered a necessary event in the development of native-language phonetic learning (Kuhl et al., 2006). Once the child "commits" to the phonemes of his/her native language, phonological skills within the native language can then improve with age and experience resulting in adult level language processing (Benasich & Tallal, 2002).

The argument has been made that being able to discriminate sounds as an infant provides a building block for acquiring phonological skills, and thus normal language development. Learning how to read requires one to first identify and discriminate general phonemes (speech sounds) in one's native language, and then combine these phonemes into morphemes (speech sounds that convey meaning), then morphemes into syllables followed by syllables combining into words. Once all of these steps are mastered, one can then learn how to read full words. If this building block of phonological discrimination is impaired, the development of proper language acquisition, and in turn reading development, is at risk (Richardson et al., 2004).

2.3 Auditory Processing in the Brainstem: The Abnormal ABR

The studies reviewed in the previous section employed behavioral measures to link auditory processing and reading ability. In this next section, the neural indices of reading ability are delved into, with specific focus on temporal processing in the auditory brainstem. As argued by Banai and colleagues, auditory processing deficiencies at the level of the brainstem could obstruct accurate speech perception thus hindering an adequate development of phonological representations (Banai, Nicol, Zecker, & Kraus, 2005). Thus, abnormal brainstem responses suggest that representations of sounds are not being encoded properly in the brain at a basic level within the auditory system.

King and colleagues examined auditory function across two groups of children, one control group, and one group of "learning impaired" children. The child participants were identified as having a learning impairment based on a battery of literacy and verbal processing tasks administered by the experimenter (King, Warrier, Hayes, & Kraus, 2002).

To test the hypothesis that children with language-based disorders have abnormal neural encoding of complex speech sounds, auditory stimuli were played into the right ear of each volunteer participant while a quiet movie played in the left ear. Complex ABRs were collected to a /da/ stimulus to determine how the participants coded the speech-like signal. Analysis of the evoked potentials analyzed the average of 6,000 stimuli. Wave V and wave A were looked at specifically for evaluation, as these waves had been found previously to be delayed in children with learning disabilities (King et al., 2002; Wible, Nicol, & Kraus, 2004). The results of the ABR analysis showed that 40% of the learning disabled children had "abnormal" brainstem timing compared to those who did not have a learning disability (King et al., 2002).

Roughly a decade ago, researchers at Northwestern University set out to answer a proposition that "difficulties in higher level language processes may have roots in the basic representation of sound as low as the brainstem" in children (mean age=10 years) (Banai et al., 2005, p. 9850). They focused on the processing of complex sounds, namely speech. Speech is a multifaceted stimulus comprised of numerous frequencies that can change at a rapid rate (King et al., 2002).

In 2005, Banai and colleagues studied a group of children identified as being learning disabled and further divided the large group into two subgroups. Those identified as having a learning disability but had "normal" ABRs (i.e., matched to the control group) were labeled as LD+ and the learning disabled children with abnormal ABRs were labeled as LD- (Banai et al., 2005). It is important to note is that the LD- group (those with abnormal brainstem responses) had the lowest literacy, verbal processing, visual processing, and cognitive performance scores of all three groups (Banai et al., 2005). These measurements further separated the two learning disabled groups, highlighting the connection between abnormal brainstem responses and low scores on other standardized reading ability tasks.

To further investigate differences among groups in auditory discrimination tasks, mismatch negativity (MMN) responses were recorded and evaluated. MMNs are cortically recorded evoked response potentials that measure an individual's sensitivity to acoustic changes in a repetitive sound sequence (Banai et al., 2005; Näätänen, 1995). An oddball paradigm comprised of two stimuli, /da/ and /ga/, was used to collect MMN responses. The /da/ stimulus was used as the deviant sound to test auditory discrimination. Results show that the LD- group was more likely to have missing MMNs than the other two groups, but the LD+ group was more likely to have a small MMN compared to the control group, implying that, "individuals with abnormal brainstem timing were more likely to show reduced cortical sensitivity to acoustic change compared with individuals with normal brainstem timing" (Banai et al., 2005, p. 9854). This study provides evidence that not all persons with a learning disability have abnormal brainstem responses, but a significant amount do. In addition, it suggests that abnormal brainstem processing timing in children could be a *risk* factor of learning disabilities and reading difficulties.

To address more specifically the link between cABRs and reading ability, a follow-up study in 2009 evaluated 63 children, ages 7-15 (mean age=10 years), with a wide range of reading skills (Banai et al., 2009). A psychoeducational assessment battery was used to evaluate each child's reading level and separate them into two groups (good readers and poor readers).

The following tasks were included in the psychoeducational assessment: elision, blending words, rapid letter naming, rapid number naming, digit repetition, and nonword repetition. The authors hypothesized that there is a direct relationship between literacy skills (as measured by single word reading tests), phonological processing (as measured by elision, blending words and rapid naming tasks), and the speech-evoked ABR (Banai et al., 2009).

Data analysis showed a significant correlation between the reading of nonwords (word attack scores) and the latencies of cABR waves. Group analysis further revealed that good readers had shorter cABR average latencies than the poor readers (Banai et al., 2009). Results suggest a relationship between auditory processing in the brainstem and a child's level of reading and phonological skill. The children who read poorly exhibited abnormal (delayed) timing of auditory stimuli at the level of the brainstem, leading to an impoverished representation the signal (Banai et al., 2009). In contrast, those who had good reading abilities were measured to have shorter peak latencies in their cABRs, so their auditory systems seem to be processing sound precisely, which may facilitate the process of coding rapid phonological changes within speech and on the written page. The poor readers had more delayed latencies, indicating there was more of a lag time for auditory encodings. This in turn leads to a conclusion that those who are poor readers have poor subcortical auditory process timing (Banai et al., 2009).

Another plausible interpretation is that the delayed response that is measured at the scalp reflects inconsistent neural activity in the brain, otherwise known as is impaired neural synchrony. It may not be just that the neurons are firing too slowly, but that they do not fire as a cohesive unit, which manifests as a delayed response in the waveform collected from the scalp (Banai et al., 2009). The implications of this are that if an auditory signal is not being accurately or consistently processed in the brainstem, later phonological processing in the cortex will be at a disadvantage, setting up a domino effect that may eventually affect literacy development.

To summarize the Banai et al., 2005 and 2009 studies: having a learning disability does not necessarily mean that one's ABRs are abnormal. Instead, abnormal ABRs serve as a risk factor that may compromise the development of normal reading skills. Because they are so simple to collect even during infancy, ABRs may serve as a tool for identifying possible warning signs of auditory dysfunction associated with literacy development.

2.4 Auditory Processing in Adults with Reading Impairments

The focus of the current study is on adults. Research conducted on adults with dyslexia provides evidence that deficits in the area of temporal auditory processing persist into adulthood (Thomson, Fryer, Maltby, & Goswami, 2006). To illustrate this, Thomson et al. conducted a study in which ten dyslexic subjects, diagnosed by an educational psychologist, were compared to a control group of normal readers. Participants underwent phonological processing tasks of phoneme deletion, rapid picture naming, and rapid digit naming. Auditory processing tasks were also administered and included intensity discrimination, duration discrimination and rise time discrimination. They used an envelope onset task previously used by Richardson et al. (2004) to assess temporal processing associated with this last test. Stimuli with varying rise times (varied logarithmically from 15ms to 300ms) were presented to the participant who was asked to identify which sound had a "sharper beat" (Thomson et al., 2006).

Significant differences were found for the phonological tasks, with the dyslexic group showing poorer performance than the control group. Additionally, significant differences were present on auditory processing tasks. The dyslexic adults were found to have delayed perception of the slow temporal qualities of syllables (the basic foundation of speech). It has been theorized that listeners use perceptual centers of syllables to understand the rhythm of speech, and that focussing on these kinds of stimuli is therefore beneficial to understanding reading ability in adults (Goswami, 2002).

Previous literature notes that children with dyslexia show a deficit in processing specific stimulus rise times, while normal reading children do not perform as poorly (Goswami, 2002; Richardson et al., 2004). Thus, the Thompson et al. study suggests that the trend observed in dyslexic children does in fact continue into adulthood (Banai et al., 2009). A proposed theory for the persistance of perceptual impairements is that those with reading difficulty have a halted development of auditory processing and perceptual skills such that they they fail to develop beyond adolescence (Wright & Zecker, 2004). Wright and Zecker claim that those whose development is arrested may never achieve the processing skills of a normal adult, resulting in the proccesing skills of a child. This halting is hypothesized to be caused by neurobiological changes associated with puberty (Wright & Zecker, 2004).

While the link between ABRs and reading ability has been explored in children, less attention has been paid to adults. Thus, while behavioral-indices of auditory processing deficits have shown to continue from childhood to adulthood, it is not clear whether the ABR-correlates of reading ability are the same in children and adults. The current study aims to fill this gap.

2.5 Two Theories of Temporal Processing in Reading Impaired Populations

As reviewed above, temporal processing has been implicated in reading disabilities. However, there are two competing theories regarding the nature of the temporal processing disorder proposed by Tallal and Goswami, respectively.

2.5.1 Fast Temporal Hypothesis

Tallal found that when children were given tasks involving discrimination and temporal processing, the reading impaired children made more perceptual errors than the control group at faster rates (stimuli with shorter ISIs) of presentation (Tallal, 1980). This has become known as the "fast temporal hypothesis". This hypothesis claims those with reading impairments struggle to process fast stimuli within speech, such as formant transitions, compared to their normal reading peers, as their system is more taxed by these fast rates. Tallal administered a set of stimuli with varying ISIs (8ms, 15ms, 30ms, 60ms, 150ms, and 305ms) to measure rapid perception. Tallal found no significant differences between groups when presented with slower rates (stimuli with longer ISIs) of presentation, unlike the significant differences seen when the groups were presented with faster rates (Tallal, 1980).

2.5.2 Slow Temporal Hypothesis

In contrast, Goswami has proposed the "slow temporal hypothesis" of dyslexia, which theorizes that reading impaired individuals struggle more with processing auditory information presented at a slow rate (Goswami, 2002). This theory implies that reading impairments could be caused by a deficit in separating syllables within a stream of sound, the basis of speech perception (Goswami, 2002). Goswami notes that dyslexic children have shown a deficit in processing sounds in the range of 2-10 Hz, with average speech prosody falling within this range at 4-7 Hz (Goswami, 2002). It is worth noting that these rates are much slower than the usual rates used in clinical ABR testing. A further discussion and comparison of the slow versus fast temporal processing theories is described below as part of the sections on study design and study hypotheses. This study aims to deliver further substantiation of theories of auditory processing in reading impaired individuals by eliciting ABRs at different rates of presentation (“Rate Study”).

3 Rate of Sound Presentation and the ABR

While the primary purpose of our study was to extend the Banai et al. (2009) study to an adult population, the rate study component of our project was additionally added to dissociate between the slow and fast temporal theories of reading ability. It is important to note that, historically, speech and click stimuli have not been presented at comparable rates when collecting ABRs. Speech is, by its very nature, longer than the average click stimuli and therefore presented in ABR paradigms at slower rates. The Banai et al. studies reviewed above found no differences between click stimuli ABR measurements for groups who differed on tests of literacy; instead the differences were limited to speech stimuli (Banai et al., 2009(Banai et al., 2005; Krizman et al., 2010). Our aim was to determine whether or not this lack of differentiation for the click stimulus was due to the differences in the rate of presentation between the click and speech stimulus, or due to the differences in the real-world prevalence and acoustics of the stimulus, such as frequency and amplitude envelope, as previously claimed.

3.1 Clinical Uses of Increased Rates

Increasing the rate of sound presentation is commonly used in clinical settings to examine the functional integrity of the auditory brainstem by taxing the auditory system with faster and faster rates of stimulation. Using different rates with various interstimulus intervals for ABR collection can be used clinically to evaluate neural conduction in the auditory brainstem, that is the speed and accuracy of signal processing within the auditory system. One population where this stimulus manipulation has been used is patients with Multiple Sclerosis, a demyelinating disease known to have neurological symptoms. Jacobson, Murray, and Deppe conducted a study where clicks were presented at rates of 10, 33, 67, and 80 Hz to a population of patients with

Multiple Sclerosis and their ABRs were evaluated. At all rates, both slow and fast, abnormalities and latency differences in the MS patients were present. However, while the abnormalities were present at slow rates, they became easier to detect at the faster rates (Jacobson, Murray, & Deppe, 1987). The Jacobson et al. study focused solely on patients with Multiple Sclerosis but highlights the importance of using rate variation and resulting ABR measures to distinguish populations.

3.2 Varying Rates and the ABR in a Normal Population

In a population of adults with no history of neurological impairment, Krizman, Skoe, and Kraus (2010) investigated how the auditory brainstem responds when stimuli are presented at varying rates. Normal hearing adults were used in the study, and both click and speech-evoked ABRs were collected. Three different rates were used: 15.4 Hz, 10.9 Hz, and 6.9 Hz. These rates were chosen based on common rates used in ABR literature for the /da/ stimulus (Krizman et al., 2010). Both the click and /da/ ABR were presented at all three rates and then the latency of the waves were analyzed and compared. Data analysis revealed that rate of presentation affected the latency of the /da/ ABR but not the analogous peaks of the click ABR. In other words, the latency was stable for the click ABR at these rates. For the speech-evoked (/da/) ABR, latency of wave V monotonically increased with increasing rates (Krizman et al., 2010). However, wave amplitude was not affected by a change in rate. As predicted from the literature, there were no significant differences among the timing of the click responses across the three rates used in the study compared to the variations observed in the speech-evoked ABR. One possible explanation for this is that the two stimuli have different spectrotemporal profiles. A click contains a wide range of frequencies while speech is more, "spectrally shaped" (Krizman et al., 2010). Compared to the click stimulus, which has a near instantaneous onset, the onset of the /da/ stimulus is gradual, making it more susceptible to backward masking of a large formant transition.

Another explanation is the variation in interstimulus intervals (ISI) between click and speech stimuli for the same rate of presentation. A click is shorter than the /da/ stimulus, so there is a longer ISI associated with this stimulus, meaning a longer silence between successive clicks compared to the ISI between /da/ stimuli presented at the same rate. Longer ISIs for the click lessens the stress of an increased rate, compared to the speech stimuli (Krizman et al., 2010).

3.3 Varying Rates and the ABR in a Reading Impaired Population

Increasing rate of presentation forces the auditory system to work harder to process faster stimuli, thus degrading the system and altering a typical ABR. Even in normal hearing, normal developing individuals with average ABRs, increasing the rates of presentation leads to delayed latencies (Krizman et al., 2010). Now imagine taxing the system of an already impaired auditory system, as found in a large subset of individuals with reading difficulties. Children with SLI show later latencies than normal developing children across a variety of rates of presentation (11.1/sec, 21.1/sec, 51.1/sec, and 71.1/sec), suggesting that even a at slow rates of presentation the auditory system is being inordinately taxed (Basu, Krishnan, & Weber‐Fox, 2010). Poor readers have a higher incidence of abnormal ABRs, more varied responses, and an overall more difficult time processing rapid auditory changes (Banai et al., 2005; Hornickel & Kraus, 2013; Wright et al., 1997). How poor readers respond to various rates of presentation compared to a normal population is a question being addressed for the first time in this study.

4 Hypotheses

4.1 Rate Study Hypotheses

The auditory brainstem, being the most basic level of processing in the central auditory system, is highly sensitive to the temporal features of incoming acoustic stimuli and can be used to explore the temporal precision with which sounds are represented (Krizman et al., 2010). As previously discussed, accurate temporal encoding of speech stimuli is essential to the development of phonological skills necessary for reading (Banai et al., 2009). General observations agree that increasing the rate of stimulation past a certain point increases wave latency and decreases wave amplitude, but how does this vary as a function of reading level? (Hall, 2007)

The Krizman et al. (2010) study was designed to test if varying the rate of presentation of ABR stimuli could elicit distinct patterns across the rates in a group of neurologically-intact adults. It was hypothesized that changing the rate of the click stimulus would have no effect while varying the speech-like stimulus would show a significant variation as a function of rate of presentation. No significant differences were found within the observed group across the three different click-ABR rates, as predicted (Krizman, Skoe, & Kraus, 2010). We take this study one step further by examining if differences emerge as a function of reading level as the click stimulus is presented at a variety of rates. It is hypothesized that differences will in fact emerge between groups of adults distinguished based on reading level (below average readers and above average readers), with the fast and slow temporal hypotheses making distinct predictions for how these group differences will manifest. If the groups differ at faster rates, that data would support the fast temporal theory, which maintains that reading impaired individuals struggle with processing quicker stimuli. The opposite result, i.e., group differences for slow rates, would imply slower stimuli, such as speech sounds, are processed differently as a function of reading level.

4.2 ABR Development Hypotheses

There is evidence that children with reading impairments have abnormal auditory brainstem responses compared to their average reading peers (Banai et al., 2009; Hornickel, Anderson, Skoe, Yi, & Kraus, 2012), but do the same trends occur in adulthood? Based on the literature, multiple different outcomes are predicted.

4.2.1 Arrested Development Theory

Wright and Zecker have proposed that individuals with language-based disorders, such as dyslexia, have an arrested development of auditory-based perceptual skills (Wright & Zecker, 2004). They theorize that auditory development halts around the onset of adolescence in these individuals, never reaching typical adult levels. If this theory holds, ABRs from below-average reading (BAR) adults are predicted to differ from age-matched controls but resemble an immature response due to development stopping prematurely. Consistent with this theory, Moisescu-Yiflach and Pratt found that at the cortical level there are delays in auditory evoked potentials in adults, similar to the delays seen in children (Moisescu-Yiflach & Pratt, 2005). If this theory holds, below average reading adults are predicted to resemble the below average reading children in latency.

4.2.2 Developmental Delay Theory

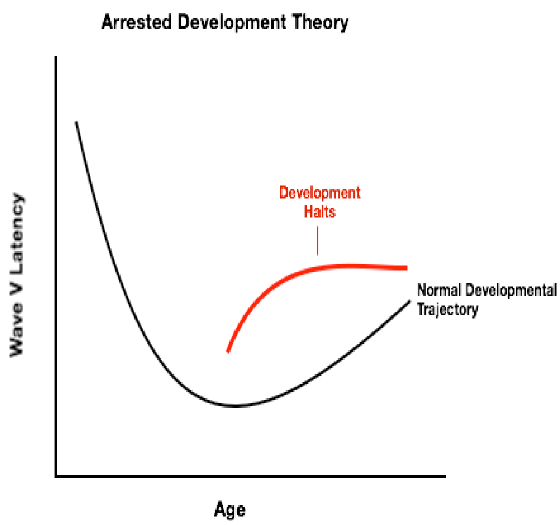
An alternative theory is that individuals with language-based impairments have a developmental delay of their auditory system, but eventually reach the same end state as typically developing adults. In this case, ABRs from BAR adults are not expected to differ from age-matched controls. In line with this possibility, two different studies tested adults with dyslexia and found no differences in latencies relative to age matched control groups (Lauter & Wood, 1993; Mcanally & Stein, 1996); however, neither study specifically tested phonological abilities in their cohort of participants. Under this Developmental Delay Theory, the ABR latency differences observed in poor-reading children is not predicted to be present in poor-reading adults. This outcome would suggest that the latency differences observed in childhood constitute a developmental delay that is ameliorated between childhood and adulthood.

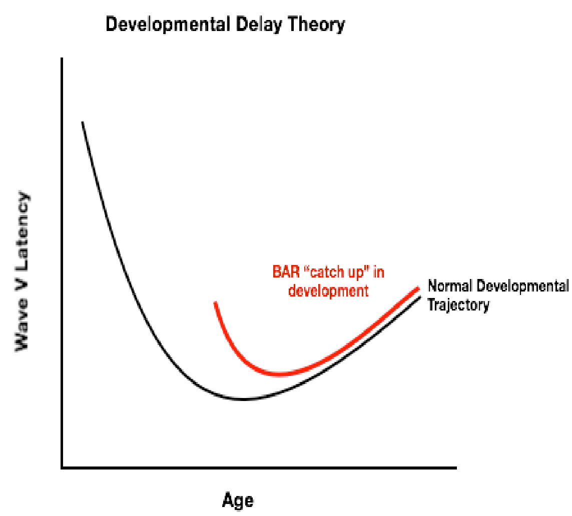
4.2.3 Shifted Development Theory

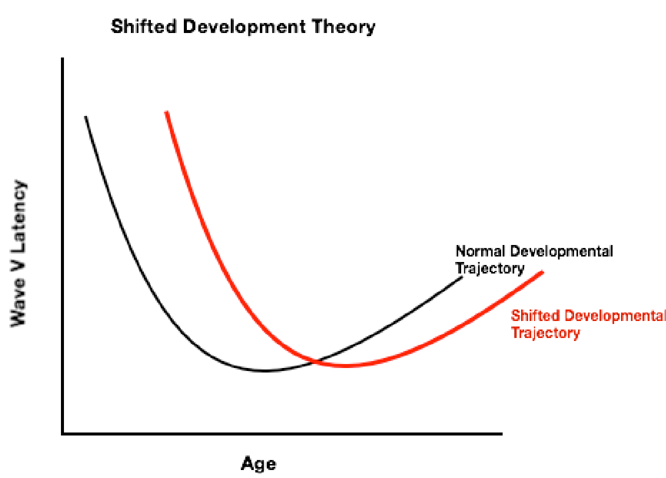
Another alternative outcome is that auditory processing impairments are present in both adults and children with poor reading ability, as the consequence of continued (i.e., prolonged) auditory development in poor reading adults. In other words, milestones in auditory development, such as sensitive periods, may be shifted later. In such case, BAR adults may have ABRs that mimic normally developing children between the ages of 5-11, a group known to have earlier latencies due to the nature of their developing neurological system (Skoe et al., 2013).

In this study, three alternative theories were examined by comparing the neurophysiological results obtained from adults to existing published data on children allowing us to evaluate whether BAR adults have delayed responses similar to poor reading children, early responses similar to normally developing children, or responses similar to their normal reading peers.

A graphical depiction of the three hypotheses is presented below. The nadir in the normal developmental trajectory occurs between ages 5-11 (Skoe et al., 2013):







5 Methods

5.1 Participants

40 adults ranging in age from 18-25 (mean=21.29 yrs, 29 female, 11 male) participated in the study. All are native, monolingual speakers of American English with no history of auditory

or hearing disorders. Participants were required to complete questionnaires prior to testing, which outlined their language and health background. Two bilingual participants were tested but later excluded from data analysis. Bilinguals perform differently on tests of phonological awareness compared to monolinguals, which motivated their exclusion (Canbay, 2011). One participant with a history of a neurological disorder (epilepsy) was also excluded from the study. Another participant was excluded as an outlier for having an unusually late wave V latency at our standard Click 31.25 rate. All participants were given an audiological screening test (pure tone air conduction audiometry) and were ensured to have normal hearing on the day of testing (> 20 dB nHL for 0.5, 1, 2, 4, and 8 kHz). Assurance of normal hearing was important given that that ABR latencies are influenced (i.e. delayed) by hearing loss (Hall, 2007).

5.2 Reading Assessment Battery

Data collection occurred in two sessions, with each session typically performed on different days. In session 1, each participant was given an assessment battery of standardized psychoeducational tests that measure nonverbal intelligence, working memory, reading comprehension, and phonological processing. In session 2, the ABR protocol was administered. The reading battery was administered by either myself or a member of a team of students from Dr. Theodore's Laboratory for Spoken Language Processing who were also trained in the assessment of each individual test. The assessment battery consisted of the following tests (Table 1).

TEST	SUBTEST	DESCRIPTION
TONI-4 *This test acts an exclusion criterion. Participants had to receive standard score≥ 80 to be eligible.*	Test of Nonverbal Intelligence	Untimed non-verbal task; Participant must identify the missing picture of a given pattern from a list of possible symbols without speaking

WRMT-III (Woodcock Reading mastery Tests)	Word ID **Word Attack** *Word Attack served as our main test for group identification* Passage Comprehension	Untimed verbal task; Read groups of words **Untimed verbal task;** **Read groups of non-words (e.g., "pnir")** Untimed verbal task; Read short passage with a blank word, then fill in the blank with a word they feel fits the best
CTOPP (Comprehensive test of Phonological Processing) *While not used as our main test for group distribution, groups did differ on scores for elision, blending words, and non-word repetition*	Elision Blending Words Non-Word Repetition	Untimed verbal task; Participant asked to say part of word after saying whole word (e.g. Say the word 'spider'. Now say 'spider' without saying 'der') Untimed verbal task; Put sounds of a word together to make one word (e.g. 'can'+'dy'='candy') Untimed verbal task; Repeat back a list of non-words they hear as accurately as possible
TOWRE (Test of Word Reading Efficiency)	Sight Word Efficiency Phonemic Decoding	Timed 45 second verbal task Read a list of words as quickly as possible Timed 45 second verbal task; Read a list of non-words as quickly as possible
RAN (Rapid Automatized Naming)	RAN Numbers RAN Letters RAS 2-set	Timed verbal task; Read a list of numbers as quickly as possible Timed verbal task; Read a list of letters as quickly as possible Timed verbal task; Read a list that contains both numbers and letters as quickly as possible

WMS-IV (Wechsler Memory Scale) *This test was included to ensure that any phonological processing deficiencies were not a result of working memory deficiencies. Groups did not differ on WMS-IV measures*	Logical Memory 1	Untimed verbal task; Listen to a story and repeat as much information as they can remember directly after
	Logical Memory 2	Untimed verbal task; Recall as much information from the two stories previously told to them and answer yes or no questions about said stories
	Verbal Paired Associates 1	Untimed verbal task; Listen to a list of word pairs and then answer which word belongs to it's partner word (e.g. 'paint, big'; 'which word goes with paint?)
	Verbal Paired Associates 2	Untimed verbal task; Recall which word goes with the given partner word from lists previously read to them and then answer whether or not a given word pair was read to them
	Designs 1	Timed non-verbal task; Place pictures on a grid in the correct spaces that correspond to pictures on a grid shown to them right before
	Visual Reproduction 1	Timed non-verbal task; Recreate pictures shown to them right before

Table 1: Reading Assessment Battery

The Test of Nonverbal Intelligence (TONI-4) was administered to assess an individual's IQ, and requires participants to fill in blank spots of a pattern sequence without verbal communication. A raw score is taken based on the number of correct responses. The TONI was used as an exclusion criterion if the participant did not have a standard score ≥80. The Word Attack portion of the Woodcock Reading Mastery Test, 3rd Edition served to group the participants into below and above average reading groups. This test was selected because the scores showed a normal distribution across our populations, and also because Word Attack was used to sort participants in the Banai et al. (2009) study. Word Attack phonological assessment is a task that measures how well a participant is able to correctly read aloud a variety of ambiguous non-English words presented to them. The experimenters were trained how to judge whether a pronunciation was correct, and a raw score of how many "correct" responses was converted into a standard score that was then used in the statistical evaluation. Scores on the standardized assessments were then used to assign participants to “above average” and “below average” reading groups, using a standard score of 100 (i.e., 50th percentile as the cutoff). Specifically, those assigned to the above average (AAR) group had a score above the 50th percentile. The below average reading (BAR) group consists of those with a word attack score below the 50th percentile. Group distribution is further discussed in data analysis.

5.3 ABR Collection

Part 1 of the ABR paradigm is a replication of the Banai et al. (2009) study; Part 2, the rate study, is an extension of the Krizman et al. (2010) study. Both parts were administered during the same recording session.

5.3.1 Part 1: Standard Click and the cABR

In part 1, two stimuli were presented: a click stimulus (100 microsecond square wave) and a speech stimulus. Adopting the procedures in Banai et al. (2009) study, the click stimulus was presented at a standard rate of 31.25 stimuli per second (Hz) at 70 dB nHL with 1,000 trials being collected per each of the two runs. This rate was chosen as it has been used as a standard rate in previous studies (Krizman et al., 2010). This stimulus is abbreviated with the name "C31.25" to signify both the stimulus type and range. Auditory brainstem responses were subsequently recorded to a synthesized speech sound /da/ that is 40-ms in duration at 80 dB SPL with 3,000 trials per each of the two runs. This stimulus, which was created by Dr. Skoe and colleagues at Northwestern University, has been used in various studies on auditory brainstem processing in individuals of diverse ages and auditory processing levels, including the Banai et al. (2009) study. The stimulus, abbreviated "da10.9" is composed of five speech formants that change rapidly in frequency over the course of the stimulus. This stimulus was selected in the Banai et al. study because individuals with reading disabilities have been shown to have impaired perception of rapid speech elements (Tallal, 2004).

5.3.2 Part 2: Rate Study

In part 2, the click stimulus was presented at 5 additional rates: 6.9 Hz, 10.9 Hz, 15.4 Hz, 46.5 Hz and 61.5 Hz, respectively, and each protocol used 1,000 trials per each of the two runs. The slowest rates were chosen to allow comparison to the results of the Krizman et al. study (Krizman et al., 2010). The fastest rates were selected in intervals of 15 Hz above the standard click rate of 31.25 Hz to mimic the faster rates that are often used clinically.

5.3.3 Procedure

Scalp electrodes were used to collect ABRs from each participant. Following the hearing screening and assessment battery, three electrodes were sanitized and placed on the forehead, ear lobe, and central vertex (Figure 3) of the participant's head using an electrically conductive paste following a mild scrubbing of the skin. Contact impedance was maintained at ≤5kΩ across electrodes. The electrodes, which are dime-sized sensors, measured neurophysiological responses via the bio-Logic Navigator Pro AEP System by Natus, Inc. Auditory stimuli were presented to the right ear (monaurally) through inner ear headphones. The stimuli were presented in the following order: C31.25, da10.9, C6.9, C10.9, C15.4, C46.5, C61.5. Each stimulus condition was presented twice. During the recordings, participants were seated comfortably in a chair and watched a movie/television show of their choice (on a tablet placed roughly arms-length in front of them on a small table built into the chair) while stimuli were presented. Figure 3 depicts how each participant was positioned during testing. The soundtrack of the movie was turned on, but at low intensity, and subtitles were turned on at the participant's request.

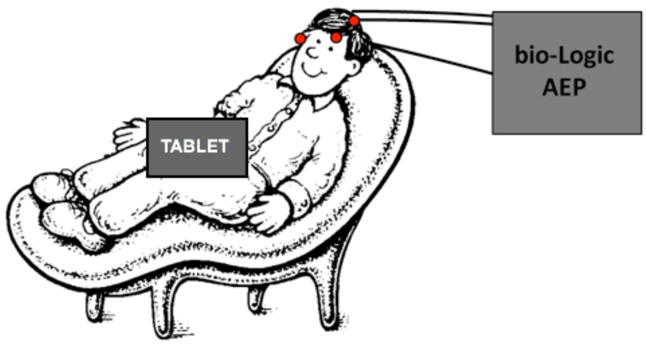


Figure 3. Auditory brainstem responses were measured using small sensors (electrodes) placed on the head while the participant sits comfortably watching a movie.

5.4 Data Analysis

An average neurophysiological response across the two presentations of each condition was used in data analysis. Averages were calculated in the AEP system. After data collection, each average waveform was examined. For the different click ABR conditions, waves I, III, and V were marked for analysis. As previously stated, each wave corresponds to a specific landmark along the central auditory system. ABR waves I, III, and V for click stimuli and waves V, A, D, E, F and O for /da/ stimuli were visually identified and labeled on the bio-Logic Navigator Pro AEP System and subsequently reviewed for accuracy by an experienced peak picker.

The rate data were analyzed in SPSS (IBM, Inc.) using a mixed-model repeated measures analysis of variance (RMANOVA) in which the two reading groups were compared across six dependent measures (latency). Given that males tend to have later latencies than females (Krizman, Skoe, & Kraus, 2012), the effect of sex was also explored as part of this same analysis. The analysis was performed separately for wave V vs. wave I. The RMANOVA was followed by post-hoc comparisons (1-way ANOVAs, covarying for sex and IQ) to further explore main effects and interactions.

For the speech-ABR data, the analysis presented here focuses specifically on wave V. The analysis of the other waves will be the focus of future work. The latency of wave V was compared to a population of typical and reading impaired children, using a dataset collected at Northwestern University.

6 Results

6.1 Group Distribution

As previously stated, our two groups (n=18, each) were divided based on their Word Attack scores obtained from the reading assessment battery. Our above average reading group (AAR), with word attack scores above 50th percentile, consisted of 14 females and 4 males with a mean age of 21.47 years. The below average reading group (word attack score below 50th percentile) represents a continuum of reading abilities ranging from dyslexic to simply poorer readers. This group consisted of 13 females and 5 males with a mean age of 21.11 years.

The two reading groups also performed statistically different across the series of additional reading tasks, including CTOPP-Elision, CTOPP-Blending words, and the TOWRE for Phonemic Decoding and Word Identification (Table 2). The two groups, however, also did differ significantly on the memory and intelligence tests. Consequently, IQ was used as a covariate in the statistical analysis.

Group Statistics

Group 1=Below Average Readers (BAR) 2=Above Average Readers (AAR)		N	Mean	Std. Deviation	Std. Error Mean	P-value
Age	1.0	18	20.94	2.775	.654	.558
	2.0	18	21.50	2.854	.673	
WMSIV AMI	1.0	18	0.00	0.000	0.000	.000
	2.0	17	88.47	43.599	10.574	
WMSIV IMI	1.0	18	105.33	15.617	3.681	.058
	2.0	18	114.94	13.705	3.230	
TONI-4	1.0	18	91.83	7.846	1.849	.022
	2.0	18	100.17	12.486	2.943	
RAN Numbers	1.0	18	111.33	4.563	1.076	.650
	2.0	18	112.11	5.593	1.318	
RAN Letters	1.0	18	109.22	4.052	.955	.788
	2.0	18	108.72	6.693	1.578	
RAS 2-set	1.0	18	113.11	5.870	1.384	.818
	2.0	18	112.56	8.326	1.962	
CTOPP Elision	1.0	18	9.44	2.502	.590	.025
	2.0	18	10.89	.758	.179	
CTOPP Blending Words	1.0	18	11.44	2.175	.513	.339
	2.0	18	12.06	1.552	.366	
CTOPP Nonword Repetition	1.0	18	9.89	2.423	.571	.070
	2.0	18	11.22	1.801	.424	
TOWRE Sight Word Efficiency	1.0	18	108.22	10.581	2.494	.002
	2.0	18	114.17	12.320	2.904	
TOWRE Phonemic Decoding	1.0	18	105.61	9.350	2.204	.007
	2.0	18	115.28	7.568	1.784	
WRMTIII WordID	1.0	18	101.78	11.685	2.754	<0.005
	2.0	18	115.56	8.733	2.058	
WRMTIII Word Attack	1.0	18	92.11	7.395	1.743	grouping measure
	2.0	18	109.83	6.336	1.493	
WRMTIII Passage Comprehension	1.0	18	106.11	15.045	3.546	
	2.0	18	115.06	6.512	1.535	.027

Table 2: Group Statistics Across Reading Assessment Subtests

6.2 ABR Results

The results of the rate study are presented first followed by an analysis of the ABR to /da/.

6.2.1 Rate Study

For wave V (Figure 4), there was a significant main effect of rate (F(5,28) = 6.308, p <0.001), such that as the rate increased so too did the latency. A significant interaction between group and rate (F(5,160) = 3.241, p = 0.03, Greenhouse-Geisser corrected) was also found; however, none of the other main effects (Group, Sex) or interactions (Rate x Sex, Rate x Group x

Sex) were significant. For wave I, which reflects more peripheral auditory generators, the effect of rate was minimized compared to wave V ($F(5,28) = 5.00$, $p = 0.013$). Although the males had delayed waves relative to females ($F(1,32) = 5.45$, $p = 0.031$), none of the interactions with sex were significant (Table 2). This suggests that the differences observed between the groups for wave V reflect differences in central, not peripheral, auditory processing

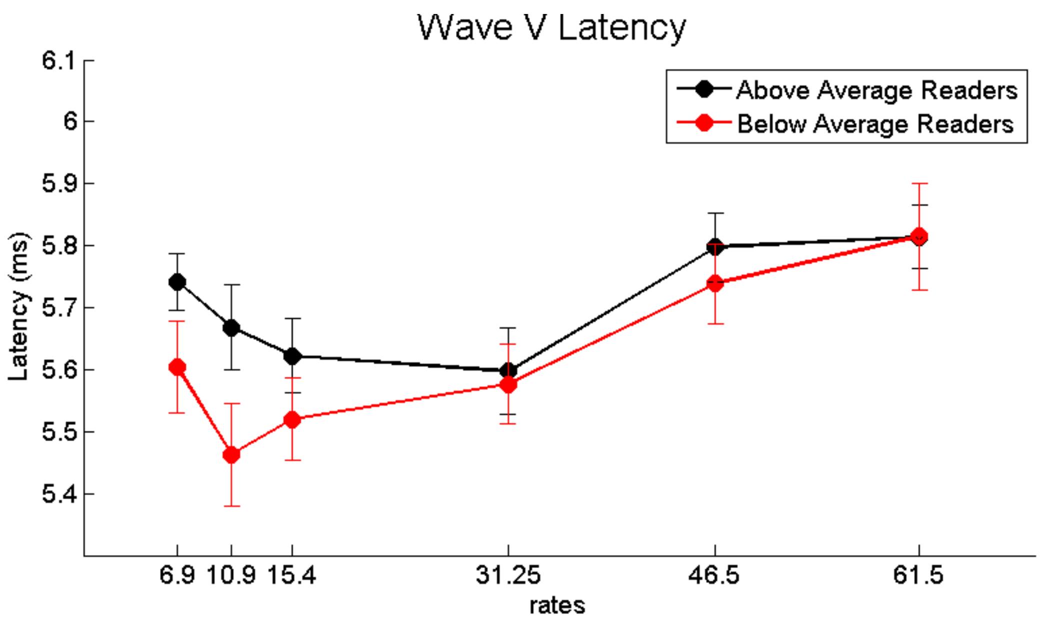


Figure 4. Wave V latency as a function of rate of presentation in the above average reader group (black) and the below average reader group (red)

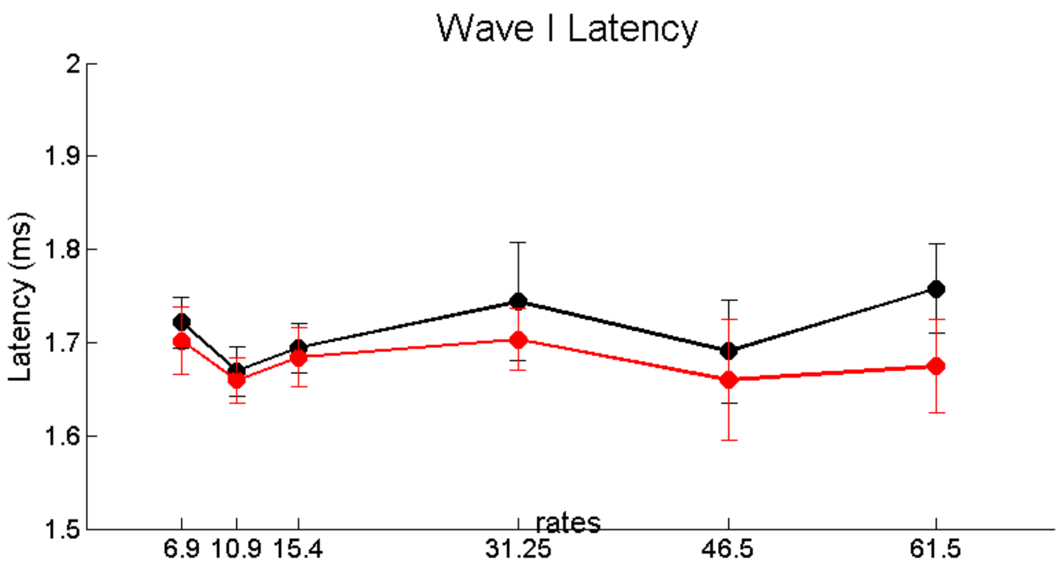


Figure 5. Wave I latency as a function of rate of presentation in the above average reader group (black) and the below average reader group (red)

As can be seen in Figure 4, the latency of wave V becomes longer as the rate of presentation increases for both reading groups. In the BAR, the effect of rate is more pronounced, such that the latencies become relatively more delayed when comparing the slow vs. fast rates. As part of follow-up post-hoc analyses, two composite measures of wave V latency were created, representing the average across the slow rates (6.9, 10.9, 15.4) and fast rates (31.25, 46.5, 61.5), respectively. The ANCOVA revealed that the reading groups differed for the slow presentation rates ($F(1,33) = 5.901$, $p = 0.021$) but not on the fast rates ($F(1,33) = 0.390$, $p = 0.537$). The mean latency for the slow rates was 5.50 ms ($SD = 0.27$) for the BAR group, whereas in the AAR group the latencies were comparatively later (5.69 ms, $SD = 0.256$). It is important to note that the two groups are showing variation at wave V but not at wave I (figure 5). In Figure 6, the group average waveforms are plotted for the two groups across the six rates of presentation.

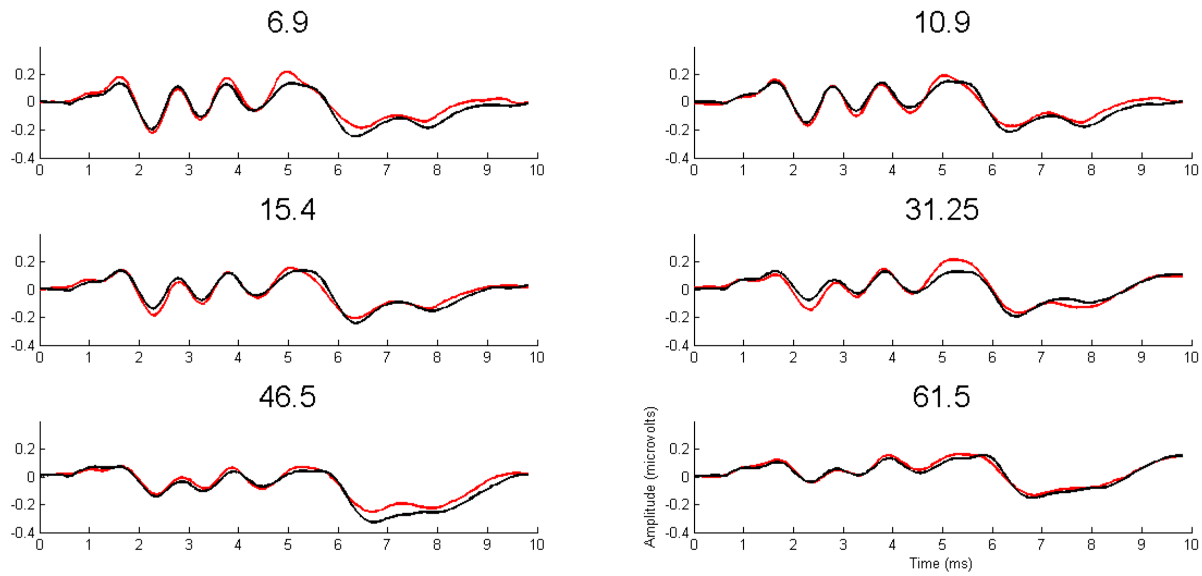


Figure 6. Grand average waveforms across the six rates for the above average readers (black) and below average readers (red).

As a final analysis of the rate study, the latency of wave V (average across the three slow rates) was correlated with performance on the Word Attack test, again co-varying for sex. This revealed a modest correlation ($r = 0.360$, $p = 0.034$), in which earlier responses were indicative of poorer phonological decoding scores.

Overall the results of the rate study indicate that below average adult readers have earlier ABRs than their above average reading counterparts. This is in contrast to the Banai et al. study, which found that poor reading children have delayed ABRs compared to peers. In the next set of analysis, a more direct comparison to the Banai et al. study is made.

6.2.2 Association Between the ABR and Reading Level in Children and Adults

Figure 7 plots average wave V latencies in poor reading children (data from Banai et al., 2009) and BAR adults, relative to the developmental trajectory of the speech-evoked wave V (data from Skoe et al., 2013). As seen in this figure, the poor reading children have delayed ABRs relative to age-matched controls, whereas the BAR group in our study is comparatively earlier than the control group from the Skoe et al. (2013) study. When comparing the two groups in the present study, there is a trend for all of the peaks in the speech-ABR to be earlier; however, the difference does not reach statistical significance. Data analysis for this component of the thesis is still underway.

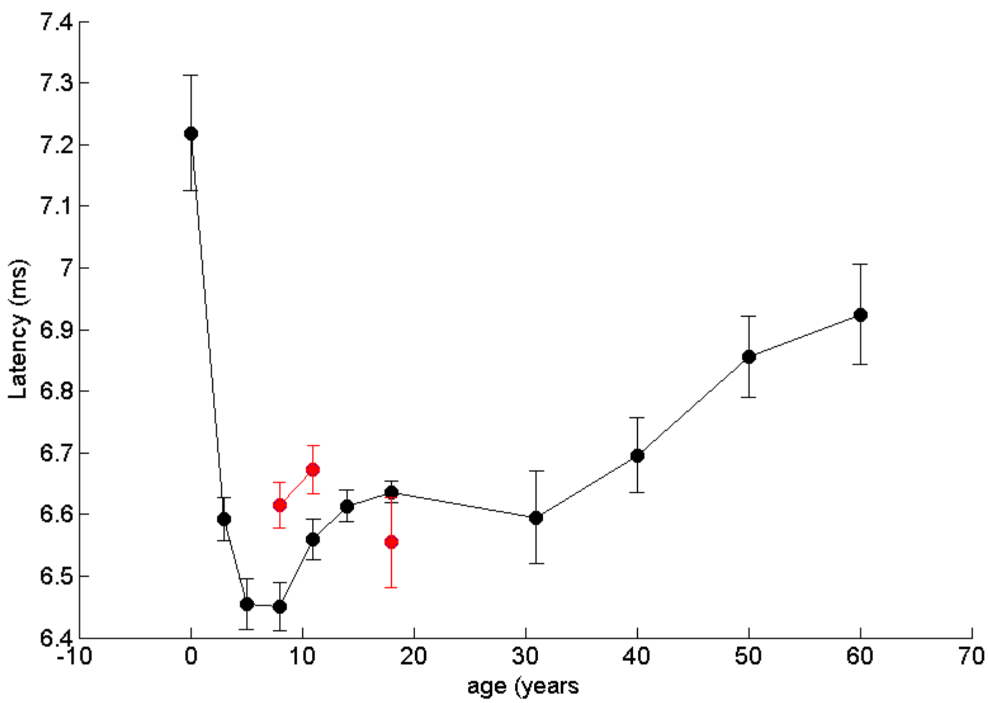


Figure 7. Latency of wave V across the lifespan in controls (black) and poor reading populations (red)

7 Discussion and Implications

7.1 Correlates of Reading Level in the Adult ABR

This study reveals that adults with varying reading level can be distinguished based on the ABR to slow rates of presentation. Specifically, it was found that adults who are below average readers have earlier latencies at slow rates of presentation compared to age-matched adults who are classified as reading above the average level. This finding advances the slow-temporal hypothesis and does not support the fast temporal hypothesis of dyslexia. Moreover, similar to the Banai et al. (2009) study, a correlation was found between reading scores and cABR latency, with the relationship in our study being specific to the slow, not fast, rates. This outcome implies that cABR measurements can be predictive of reading abilities, not only for those who are poor readers, but for all levels of reading ability. However, the findings of this study suggest that the nature of the relationship between ABRs and reading ability changes between childhood and adulthood, transitioning from a negative relationship (earlier latencies mapping onto higher scores in childhood) to a positive relationship (earlier latencies mapping onto lower scores in adulthood). However, it is important to note that our findings might have been slightly different if the focus had been specifically on a dyslexic population rather than a continuum of reading abilities within college students.

This study provides initial evidence that the poorer readers have earlier latencies across the slow click rates, but what about the /da/ measurements? There is an observed trend that responses to the /da/ stimulus are earlier in the below average reading group. However, in the current dataset, this is not shown to be statistically different due to the variability within the wave V cABR measurements in the group of below average readers. For the click stimulus, the greatest group separation is observed at the 10.9 Hz click rate, which is the rate at which the /da/ stimulus is presented. Demonstrating that the reading groups differ on the click stimulus for the slow rates suggests that the deficits observed in previous work for the cABR wave V, but not the click-evoked wave V, is due to the slower rate of presentation for the /da/ compared to the click, not the different acoustic properties of the stimuli. Thus, the results of this study suggest ABR abnormalities in below average readers extend to non-speech stimuli presented at slow rates. Thus, temporal processing abnormalities should occur with any stimulus at the slow rates, a prediction that is very testable.

Future work should assess ABRs at even slower rates than the ones in the current study. Even the slowest rate (6.9 Hz) is faster than the average rate of speech syllables. If phonological processing is the deficit in question, using stimuli at the rate of conversational speech could offer more insight into the nature of the auditory processing differences observed in the present study. However, at this point, it is not possible to dissociate whether these adults have an auditory system that has stopped developing altogether or is just shifted in development.

7.2 Wave IV/V Complex

In looking at individual waveforms, the AAR group was more likely to have a visible wave IV compared to the BAR group. This is an *observed* trend as wave IV was not marked for latency in data analysis. This could imply that the observed wave V in the BAR group is analogous to wave IV in the AAR group. Chiappa et al. found, after collecting ABR data for 50 adults, that there are six observable patterns for the wave IV/V complex that are considered normal in variability. What is now being proposed is that this variability, while still observed in normal populations, could be reflective of something meaningful relating to individual differences in language function. This question will be examined more fully in a follow up study where we examine the degree to which wave IV emerges or disappears with different stimulus manipulations.

7.3 The Implication of Earlier Latencies in Adulthood

Skoe and colleagues demonstrate the typical development of the ABR over the lifespan and show that school aged children (5-11 years of age) have the earliest latencies across all ages (Skoe, Krizman, Anderson, et al., 2013). In this study, below average reading adults were observed to have earlier latencies than the above average reading counterparts. Earlier latencies in the below average reading group may be indicative of an immature auditory system, implying that the responses in our below average readers mimic those of a normal developing school-age child. This would be consistent with this group performing below age level on testing of reading ability. The results of this study favor the shifted developmental theory; however, to get a more accurate depiction of the ABR development as a function of reading level, more data must be collected across all ages. Specifically, adolescents and older adults should be tested to fill the gaps in the current dataset. This would provide a more complete, clear image of how ABR development is or is not different between individuals of different reading levels. Within the current adult population, there is a narrow age range, with most of the participants falling in their early 20s, which limits the ability to look at age-related differences in adults using existing data.

Work is also underway to expand this paradigm to musicians with diverse reading levels. The goal of this research is to understand how auditory training might influence how low reading level manifests in the auditory system. Thus, this study is the start to a series of investigations aimed at understanding the link between ABR development and reading level in diverse populations.

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