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Short communication

Reading ability reflects individual differences in auditory brainstem function, even into adulthood

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ABSTRACT

Research with developmental populations suggests that the maturational state of auditory brainstem encoding is linked to reading ability. Specifically, children with poor reading skills resemble biologically younger children with respect to their auditory brainstem responses (ABRs) to speech stimulation. Because ABR development continues into adolescence, it is possible that the link between ABRs and reading ability changes or resolves as the brainstem matures. To examine these possibilities, ABRs were recorded at varying presentation rates in adults with diverse, yet unimpaired reading levels. We found that reading ability in adulthood related to ABR Wave V latency, with more juvenile response morphology linked to less proficient reading ability, as has been observed for children. These data add to the evidence indicating that auditory brainstem responses serve as an index of the sound-based skills that underlie reading, even into adulthood.

1. Introduction

Individual differences in auditory-system function and development at both cortical and subcortical levels have been widely documented in the literature. Auditory brainstem responses (ABRs), neurophysiological indicators of cochlear and subcortical auditory processing, have been linked to individual variation on a wide variety of behaviors, including working memory capacity (Sorqvist, Stenfelt, & Ronnberg, 2012), selective attention (e.g., Krizman, Marian, Shook, Skoe, & Kraus, 2012; Lehmann & Schonwiesner, 2014), and perceptual learning (Skoe, Krizman, Spitzer, & Kraus, 2013; Song, Skoe, Banai, & Kraus, 2012).

The fidelity of the auditory-brainstem pathway has also been linked to spoken language processing (Bidelman, Villafuerte, Moreno, & Alain, 2014) and language acquisition (e.g., Banai et al., 2009; Basu, Krishnan, & Weber-Fox, 2010). Compared to typically-developing children, children with atypical language development including those with autism spectrum disorder, specific language impairment, and reading impairment have delayed ABR latencies and more variable ABR morphology (Banai et al., 2009; Basu et al., 2010; Purdy, Kelly, & Davies, 2002; Rocha-Muniz, Befi-Lopes, & Schochat, 2012; Russo, Nicol, Trommer, Zecker, & Kraus, 2009), two indicators of an immature central auditory system (Lauter & Loomis, 1986; Skoe, Krizman, Anderson, & Kraus, 2015). In infants, ABR latency has also been found to be predictive of later language outcomes, such that infants with more mature ABRs are more likely to reach higher language outcomes as preschoolers (Amin, Vogler-Elias, Orlando, & Wang, 2014; Chonchaiya et al., 2013). As further support of the link between language development and auditory development, in studies of school-age children with diverse reading levels that spanned from impaired to exceptional, children with the strongest literacy skills presented with more mature ABRs to speech stimuli compared to biologically age-matched peers who had lower performance, even when controlling for differences in the latency of the ABR to a non-speech, click stimulus (Banai et al., 2009; Hornickel & Kraus, 2013).

In children with language disorders, there is evidence to suggest that auditory brainstem impairments are restricted to spectrotemporally complex acoustic signals, such as speech, and that the encoding of (non-speech) broadband click stimuli is intact (Banai et al., 2009; Hornickel & Kraus, 2013; Song, Banai, Russo, & Kraus, 2006). This specificity lead to the proposition that speech-ABRs are more sensitive measures of language ability than

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click-evoked ABRs (Song et al., 2006). However, this proposition is confounded by the fact that the click stimulus was presented at a faster rate (~31 Hz) than the speech stimulus (~11 Hz) in the studies on which this conclusion is based. Stimulus rate is an important consideration because click-ABR latencies are relatively stable for stimulation rates below 20 Hz, (Krizman, Skoe, & Kraus, 2010; Lasky, 1997) yet for faster rates, ABR latencies undergo significant prolongation as the rate increases (Lasky, 1997). This rate-dependent prolongation is likely due to decreased synaptic efficiency resulting from neurotransmitter depletion (Wynne et al., 2013) and/or decreased neural synchronization resulting from incomplete or disrupted myelination that may be too subtle to emerge at slow rates (Fujikawa & Weber, 1977; Jacobson, Murray, & Deppe, 1987; Ken-Dror et al., 1987; Kim, Turkington, Kushmerick, & Kim, 2013; Lasky, 1984).

As reviewed above, the literatures examining individual differences in ABRs and the subsequent link to reading-related behavior have focused primarily on pediatric populations and/or compared pathological versus control populations. Largely absent from the literature is an examination of auditory brainstem function in adults who display a typical range of reading ability. To explicate the relationship between auditory-system maturity and reading ability at a theoretical level, we examined speech- and click-ABRs in young adults with a spectrum of typical reading levels and no history of speech, language, hearing, or neurological impairment. We examined the differential sensitivity of speech vs. non-speech stimuli in assessing the sensorineural correlates of reading ability in adults, by recording ABRs to a speech stimulus (/da/) and click stimulus played at the *same* presentation rate (10.9 Hz). Click-ABRs were measured at five additional rates that spanned from 6.9 to 61.1 Hz, allowing us to examine the relationship between ABRs and reading ability across different timescales. While previous work has elucidated a relationship between auditory processes and reading skills, there is considerable theoretical disagreement over whether the auditory processes associated with reading are specific to temporal processing or reflect more general auditory processes (reviewed in Protopapas, 2014). Among the various temporal theories of reading, there is further contention as to whether reading is most closely associated with the encoding of rapid information at the phoneme level (Benasich & Tallal, 2002; Tallal, 1980) or slower temporal information at the syllable level of speech (Goswami, 2015). To test whether the relationship between ABRs and reading ability generalizes across timescales or has a speech-related time signature, click stimuli were presented at rates that model syllabic (6.9, 10.9, 15.4 Hz) and phonetic (31.25, 46.5, 61.1 Hz) timescales (Poeppel, 2003; Rosen, 1992).

We predicted that the relationship between reading ability and ABRs observed previously in children would persist into the early adult years, with stronger relationships expected for speech vs. non-speech stimuli (Song et al., 2006). To investigate the anatomical and physiological basis of the auditory processes associated with reading ability, we compared the strength of the relationship between ABRs and reading at different presentation rates for the more peripherally vs. centrally generated components of the click-ABR (Wave I vs. Wave V). If a relationship were evident for reading ability and Wave I of the click-ABR, then this would point to the peripheral auditory system as the locus of the sensory-based auditory differences that underlie reading ability, given that Wave I reflects the functional coupling of the cochlea and auditory nerve. Alternatively, if Wave V relates to reading ability, but Wave I does not, then this would implicate the role of the rostral brainstem in auditory-based reading skills. Furthermore, if the relationships become stronger with increased presentation rate, then this would suggest that reading ability is linked to the integrity of auditory processing, including its susceptibility for increased synaptic fatigue, as the auditory system is taxed (Basu et al., 2010). Yet, if the nature of the relationships is not different between syllabic vs. phonetic rates of presentation, then this would be viewed as evidence that reading reflects basic auditory processes not bounded by specific temporal scales. Finally, the absence of a relationship between reading level and any of the ABR conditions in this unimpaired population would suggest that reading ability and auditory brainstem function become uncoupled as the auditory brainstem matures.

2. Results

In our young adult population, reading scores ranged from the 40th to the 85th percentile, as measured by a composite index derived from a battery of standardized reading assessments. For the speech-ABR, response latency (as indexed by a composite index of multiple waves) was significantly correlated with reading scores ($r = 0.399$, $p = 0.026$), with longer latencies associated with better reading scores. To assess the generalizability of this ABR-reading relationship, comparisons were then made to the click-ABR recorded at the same presentation rate as the speech stimulus (10.9 Hz). This set of analyses focused on Wave V latency of the speech-ABR and its analog in the click-ABR (King, Warrier, Hayes, & Kraus, 2002; Song et al., 2006). Due to differences in the acoustic rise time between the speech and broadband click stimuli, Wave I is not reliably present in response to this speech stimulus and Wave V is prolonged in latency compared to the click-ABR (Table 1) (Song, Banai, & Kraus, 2008). When the presentation rate was the same for the click and speech stimuli, the effect size was nominally larger for the speech-evoked Wave V than its click counterpart ($r = 0.433$ vs. 0.336). However, a comparison of the r-values for the rate-matched speech and non-speech stimuli revealed that they are not statistically different ($p = 0.49$, two-tailed) (Lee & Preacher, 2013).

To further explicate the relationship between Wave V and reading ability, the dataset was divided based on the latency of Wave V for the speech stimulus. The 32 participants were evenly split between those who fell above and those than fell below their age-normed latency value for Wave V, using norms published in Skoe et al. (2015). Consistent with the correlations reported in Table 1, participants on the early side of the normative range for Wave V had lower reading scores (63.91 ± 13.82 percentile) compared to those who fell on the later side of the normative range (71.86 ± 9.54 percentile) ($F(2,29) = 3.919$, $p = 0.057$, covarying for IQ).

As the rate of presentation increased for the click stimulus, Wave I and V latencies prolonged in a predictable fashion (Tables 1 and 2, Supplemental materials), as expected for a neurotypical adult population. For both waves, latency increased progressively between the 31.25 Hz and 61.5 Hz conditions (Supplemental materials, Tables 1 and 2) yet the extent of the latency prolongation was not predictive of reading level for either wave (Wave I: $r = 0.109$, $p = 0.558$; Wave V: $r = 0.078$, $p = 0.675$). However, when considering the absolute latencies at the various rates, Waves I and V patterned differently vis-à-vis reading. For Wave I, the effect sizes were generally small (Cohen, 1988) and unlike Wave V, none of the correlations were significant, using even a liberal alpha of 0.05 (Tables 1 and 2). In comparison, medium effect sizes were found for Wave V and reading ability (ranging from 0.325 to 0.468), with the faster rates yielding larger effects than the slower rates. However, we are cautious about drawing strong conclusions from this, given the statistical equivalence of the highest r-value among the fast rates and lowest r-value among the slow rates ($p = 0.531$, two-tailed).

As an illustration of how reading ability is reflected in the ABR, speech- and click-evoked ABR waveforms are plotted in Fig. 1 for two female participants matched in age (both 20-years-old) but who fall on different ends of the reading spectrum.

Table 1
(A). Wave V latency for the speech and click-evoked auditory brainstem responses elicited at different presentation rates. (B). Correlations between reading and Wave V latency covarying for non-verbal intelligence.

	Table 1A				Table 1B: Reading-Wave V Correlation			
	Wave V (ms)				Covarying for IQ		Uncorrected	
Condition	Mean	Min	Max	Std. dev.	*r*	*p*	*r*	*p*
Speech (10.9 Hz)	6.56	6.07	7.16	0.28	0.433	0.015	0.374	0.035
Click (6.9 Hz)	5.57	4.90	6.15	0.28	0.325	0.074	0.313	0.082
Click (10.9 Hz)	5.56	5.03	6.15	0.27	0.336	0.064	0.312	0.083
Click (15.4 Hz)	5.56	5.03	6.07	0.26	0.349	0.055	0.316	0.078
Click (31.25 Hz)	5.69	5.15	6.24	0.26	0.468	0.008	0.446	0.011
Click (46.5 Hz)	5.81	5.24	6.45	0.24	0.380	0.035	0.390	0.027
Click (61.5 Hz)	5.92	5.15	6.36	0.24	0.430	0.016	0.432	0.014

Table 2
(A). Wave I latency for the click-evoked auditory brainstem responses elicited at different presentation rates. (B). Correlations between reading and Wave I latency covarying for non-verbal intelligence.

	Table 2A				Table 2B: Reading-Wave I Correlation			
	Wave I (ms)				Covarying for IQ		Uncorrected	
Condition	Mean	Min	Max	Std. dev.	*r*	*p*	*r*	*p*
Click (6.9 Hz)	1.67	1.45	1.82	0.12	−0.009	0.963	−0.045	0.808
Click (10.9 Hz)	1.68	1.45	1.95	0.12	−0.006	0.973	−0.045	0.809
Click (15.4 Hz)	1.69	1.45	2.07	0.12	0.063	0.735	0.034	0.853
Click (31.25 Hz)	1.70	1.45	2.07	0.13	0.203	0.274	0.166	0.363
Click (46.5 Hz)	1.73	1.45	2.16	0.15	0.145	0.436	0.127	0.490
Click (61.5 Hz)	1.76	1.41	2.16	0.15	0.134	0.471	0.132	0.470

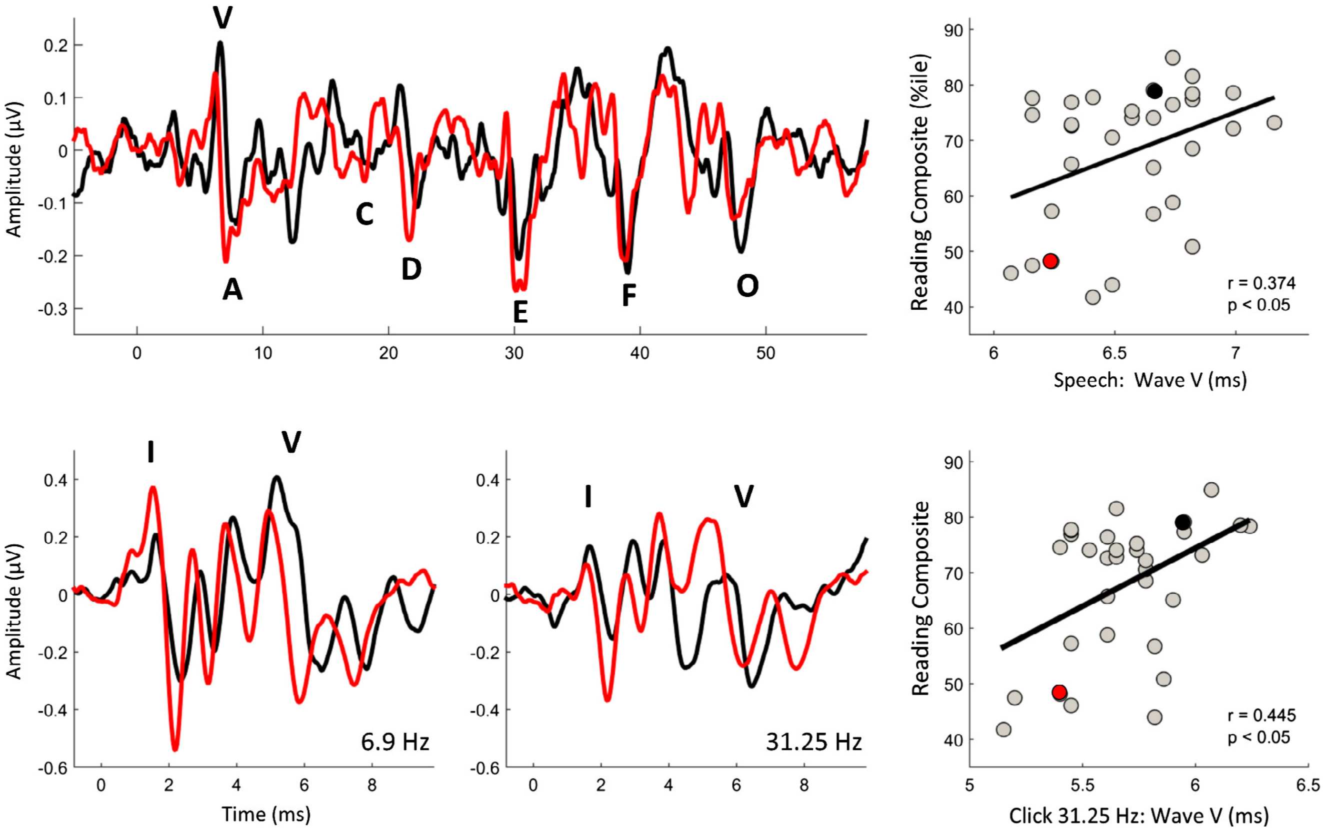

Fig. 1. Representative speech (top) and click-evoked (bottom) auditory brainstem response (ABR) waveforms from two age-matched female participants who differ in their reading ability, as assessed by a battery of standardized tests. The participant plotted in red has an average reading percentile score of 48, and the participant in black has an average percentile score of 79. The scatter plots on the right illustrate the relationship between the reading composite score and the latency of Wave V for the speech (top) and the 31.25 Hz click condition (bottom), with the two representative participants highlighted by red and black circles. To illustrate the effect of stimulus presentation rate, ABR waveforms to the 6.9 Hz condition are plotted to the left of the 31.25 Hz condition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Discussion

We provide evidence from an unimpaired population that reading variability in adults is systematically related to the auditory brainstem response. Similar to findings with children, reading ability correlated with the Wave V latency of the ABR, with the relationship capturing a spectrum of reading ability and ABR function within the normal range (Banai et al., 2009; Skoe et al., 2015). However, we found that the direction of the relationship is different for children versus adults, transitioning from a negative relationship in childhood (Banai et al., 2009) to a positive relationship in adulthood, in which earlier latencies are associated with lower reading scores in adults. As corroborating evidence, this pattern was replicated across both speech and non-speech stimuli.

What are the biological mechanisms underlying these reading-related latency differences? To begin to address this question, we must first take into consideration that ABR wave latencies reflect a multitude of complex mechanisms within cochlear and retrocochlear structures, including cochlear transport time (i.e., shorter latencies for more basal activation sites), auditory filter tuning (i.e., shorter latencies for broader auditory filters), the synaptic delay between inner hair cells and auditory nerve fibers, as well as neural conduction times within the central auditory system (Don & Eggermont, 1978; Don, Ponton, Eggermont, & Kwong, 1998; Strelcyk, Christoforidis, & Dau, 2009). While our current methodological approach does not allow us to pinpoint the specific physiological mechanisms at play, our constellation of findings offer insight into the potential mechanisms underlying the reported effects. By showing that reading ability relates to Wave V latency but not Wave I latency, this lends support to the possibility that reading is linked to physiological differences in the central auditory system, specifically the rostral brainstem (see, however, below). Moreover, the generalizability of the relationships across speech and non-speech conditions at different presentation rates leads us to posit that variations in reading level in this unimpaired adult population reflect physiological variations (neural and/or synaptic) of general, non-verbal auditory processes within the rostral brainstem that are not tied to specific stimulus acoustics or temporal scales (Ahissar, Protopapas, Reid, & Merzenich, 2000). We then take one step further by speculating that the relationship between Wave V latency and reading reflect physiological differences associated with the development of the central auditory system. The auditory brainstem response has long been thought to develop early and reach a developmental end-state around the third year of life (e.g., Eggermont & Don, 1986; Salamy, 1984). However, a recent series of large-scale studies, converge with studies from the 1990s, to delineate a more protracted developmental time course that extends into the second decade of life (Johnson, Nicol, Zecker, & Kraus, 2008; Krizman et al., 2015; Lauter & Oyler, 1992; Lauter, Oyler, & Lord-Maes, 1993; Mochizuki, Go, Ohkubo, Tatara, & Motomura, 1982; Skoe et al., 2015; Spitzer, White-Schwoch, Carr, Skoe, & Kraus, 2015). In a study of 500+ individuals ranging from 3 months to 73 years, Skoe et al., 2015 report that Wave V latency for both click and speech stimuli, decreases during the first three years of life and that Wave V latency is comparable between adults and children ages 3–5 years, similar to what has been observed previously (Gorga, Kaminski, Beauchaine, Jesteadt, & Neely, 1989). The critical new finding from this study, however, was that developmental changes continue beyond age 3, culminating in a brief developmental window during which Wave V is earlier than (i.e., overshoots) the adult value (Skoe et al., 2015). On the group level, this developmental overshoot occurs between ages 5 and 10. Prior to this developmental overshoot phase, Wave V latencies decrease with increasing age, but after this overshoot, latencies tend to increase gradually with age. This change in slope within the developmental trajectory of Wave V is critical to the interpretation of our results because it provides a possible explanation for why the direction of the ABR-reading relationship inverts between childhood and adulthood. When this biphasic trajectory is taken into consideration, a common thread emerges between our findings and previous reports linking ABR and reading level in children: in both children and adults, better reading skills are observed in individuals with more *mature* brainstem response morphology. For children, more mature responses translates to shorter latencies, whereas in young adults more juvenile responses translates to shorter latencies. Within this developmental framework, the least proficient readers in the unimpaired adults tested here would be considered to have central auditory systems that are more juvenile (i.e., less mature). We acknowledge, though, that this maturation-based interpretation of our findings draws on a relatively new discovery of the biphasic developmental trajectory of the ABR that would benefit from future replication, and that other potential accounts of the observed relationship between reading ability and auditory brainstem responses must be mechanistically investigated (see below).

The notion that language development is linked to the developmental state of the central auditory system is, however, not new (Bishop & McArthur, 2004, 2005; Edgar et al., 2015; Johnson et al., 2008; Wright & Zecker, 2004). Wright and Zecker (2004), for example, proposed that individuals with language-based disorders have an atypical development of auditory-based perceptual skills that initially lags behind age-matched peers and then prematurely arrests during adolescence due to biological changes associated with puberty, never reaching typical adult levels in some individuals. In our *unimpaired* young adult population, we speculate that differences in reading level may reflect normal, non-pathological differences in auditory system physiology and we argue for the possibility that earlier latencies in our young adult population may reflect incomplete, or alternatively not yet complete, developmental pruning of the central nervous system (Kral & Sharma, 2012). However, follow-up studies will be critical for testing whether developmental processes for the least proficient readers in our *unimpaired* sample have reached their end-state and have arrested in an immature form, are still on-going, or whether other physiological factors, not specifically related to development or the central auditory system, may be at play. Recent longitudinal evidence suggests that Wave V latency (of the speech ABR) does not undergo significant developmental changes during adolescence (ages 14–17), downplaying the possibility that group-level developmental processes are still on-going in our adult population (Krizman et al., 2015). Nevertheless, either outcome (arrested development or prolonged development) would be consistent with the viewpoint that central auditory system development is not the same for all individuals, even within an unimpaired population (Bishop & McArthur, 2005; Sharma, Dorman, & Kral, 2005; Skoe & Kraus, 2013). Future work should also expand the age of investigation to include adolescent and aging populations, adopting both longitudinal and cross-sectional designs in impaired and unimpaired populations, with the goal of understanding how and whether the ABR is coupled to individual differences in reading ability across the lifespan. We speculate that a functional relationship between reading and ABRs will be observed in both typical and impaired populations across the lifespan, but we leave open the possibility that the nature of the relationships at various stimulus presentation rates, and the neural mechanisms underlying those relationships, may be distinct for adult populations within and without a childhood history of reading difficulties (Ahissar et al., 2000; Kouni, Giannopoulos, Ziavra, & Koutsojannis, 2013).

While there is evidence to suggest that variations in central auditory system development may underlie the relationships between reading and ABR latency we report, we must also consider the possibility that individual differences in hearing thresholds may be contributing to the relationships we report (Don et al., 1998; Gorga, Worthington, Reiland, Beauchaine, & Goldgar, 1985; Jerger, 1978; Strelcyk et al., 2009). The influence of hearing thresholds, however, cannot be directly assessed in our dataset, because although we screened for clinically-normal hearing in our healthy young adult population, audiometric thresholds were not measured. It is well established that behavioral thresholds, especially for hearing in the 2–4 kHz range, can be predicted from ABR thresholds to broadband clicks (Gorga et al., 1985; Jerger, 1978). In the current study, however, the (broadband) ABR stimulus was presented well above threshold and not at threshold. Under such supra-threshold conditions, the relationship between ABR latency (to broadband stimulation) and behavioral thresholds, especially for those individuals with hearing thresholds in the clinically normal to moderate-hearing loss range, is less clear (Bauch & Olsen, 1986; Jerger & Johnson, 1988). Yet, for derived-band ABRs, which reflect more place-specific activation of the cochlea compared to ABRs to broadband clicks, ABR Wave V latencies have been shown to *decrease* as thresholds increase, particularly for more apical sites of cochlear activation (Don et al., 1998; Strelcyk et al., 2009). This decrease in ABR latency as a function of increased thresholds has been attributed to a change in cochlear response time that arises from auditory filters becoming more broadly tuned when cochlear amplification is compromised by outer hair cell loss (Don et al., 1998; Scheidt, Kale, & Heinz, 2010; Strelcyk et al., 2009). In theory, a relationship between ABR latency and cochlear filter bandwidth should be evident for Wave V as well as Wave I (Scheidt et al., 2010), although in the current investigation the relationship with reading was specific to Wave V. However, because the cochlear site of generation is not necessarily the same for Waves I and Wave V when broadband stimulation is used (Don & Eggermont, 1978), this confounds our ability to fully rule out a peripheral explanation for our findings. In other words, although our participants did not show any clinical signs of hearing loss, using the current set of measurements, subclinical hearing losses cannot be excluded. Thus, based on studies of derived-band ABRs, we leave open the possibility that the least proficient readers in our young adult sample have broader auditory tuning curves than the most proficient readers, given that broader tuning curves have been associated with earlier ABR latencies. By this explanation, lower reading scores would be associated with worse auditory acuity, an idea that is supported by evidence of lower literacy levels in children with sensorineural hearing loss (e.g., Briscoe, Bishop, & Norbury, 2001; Halliday & Bishop, 2005). However, we are careful to point out that auditory system immaturities can co-exist with cochlear losses (Sharma et al., 2005), and that our findings could potentially be explained by one or both accounts. This calls for a more mechanistic approach to be adopted in futures investigations of the sensorineural correlates of reading ability. Such studies should expand their methodology beyond a hearing screening to include a comprehensive evaluation of cochlear function in conjunction with other, complementary measurements of the central auditory nervous system (e.g., diffusion magnetic resonance imaging) (e.g., Chang et al., 2004).

Literacy is a complex, multifaceted process, influenced by many interrelated factors, including socioeconomic status, home literacy environment, cognition, and phonological ability, with auditory acuity being just one component (Banai, Abrams, & Kraus, 2007; Briscoe et al., 2001; Evans & Maxwell, 1997; Protopapas, 2014; Wagner, Torgesen, & Rashotte, 1994). In this regard, the relatively modest correlation observed between our composite measure of reading ability and ABRs, is perhaps not surprising. Nevertheless, it is noteworthy that this measure of basic auditory function can account for upwards of 22% of the variability in this unimpaired young adult population. This raises the question of causality. Sensory-based theories of reading posit that basic auditory processes influence the successful mastery of sound-based skills, such as phonological awareness, that underlie reading (Protopapas, 2014). However, we must also consider the possibility that the relationship may instead, or additionally, reflect more global processes associated with neural migration, connectivity and/or pruning or cochlear function that coincidentally affect both reading and auditory processing (Bishop & McArthur, 2005; Protopapas, 2014).

3.1. Conclusion

Our findings suggest that variations in reading ability observed in the general population may be reflective of differences in low-level auditory processing for both children and young adults.

4. Methods

Data collection occurred in two sessions, typically performed on two different days. In session 1, we performed a hearing screen and administered a battery of standardized tests that assessed nonverbal intelligence as well as a host of reading-related measures (e.g., speed of processing, phonological processing, reading comprehension). The ABR protocol occurred in session 2.

4.1. Participants

Thirty-two monolingual, native speakers of American English between the ages of 18 and 30 were recruited for the study (M = 21.0 years, SD = 2.8). All research procedures were approved by the Internal Review Board at the University of Connecticut. Lab-internal questionnaires confirmed that the participants had no history of speech, language, hearing, reading, or neurological disorders. To be included in the study, participants were also required to have clinically normal hearing. This was confirmed using a two-part hearing screening consisting of pure tone air conduction audiometry (20 dB HL for 0.5, 1, 2, and 4 kHz administered using the Earscan 3 Manual Audiometer (Micro Audiometrics) and click-evoked ABR Wave V latency measurements (rarefaction click at an intensity of 70 dB nHL at a rate of 31.25 Hz). The participant would have failed the screening if s/he was unable to detect any of the pure tone test frequencies at 20 dB HL in either ear or if the Wave V latency fell outside of 2.5 standard deviations of the age-normed mean reported in Skoe et al. (2015).

4.2. Reading assessment battery

In session 1, participants completed a standardized assessment battery that included a measure of non-verbal intelligence (*Test of Nonverbal Intelligence, TONI-3*) and measures of reading sub-skills and reading comprehension. The reading measures were composed of the *Woodcock Reading Mastery Tests* (*WRMT-III*) to measure reading comprehension, the *Comprehensive Test of Phonological Processing* (*CTOPP*) to assess phonological awareness, the *Test of Word Reading Efficiency* (*TOWRE*) to measure timed and untimed word and nonword reading, and *Rapid Automatized Naming* (*RAN*) to measure rapid digit and letter naming. Scores on each reading sub-test were converted to age-normed percentile scores following conversion algorithms provided by the test manufacturers. As in Kadam, Orena, Theodore, and Polka (2016), a composite reading score was calculated for each participant, defined as the mean percentile across the reading assessment measures (Kadam et al., 2016). Given that reading ability reflects a wide constellation of abilities, the reading composite score is a more veridical measure of reading ability in this unimpaired population as compared to, for example, performance on any single assessment within the battery.

4.3. ABR collection protocol

To promote comparisons with previous investigations in school-age children, speech-ABR stimulus and recording parameters modeled those used in Banai et al. (2009). In brief, ABRs were recorded to a 40 ms synthesized /da/ stimulus played at 10.9 Hz in alternating polarity to the right ear at 80 dB SPL through insert earphones (Etymotic ER3-14). The responses were differentially recorded in Bio-logic AEP (Natus, Inc.) with a vertical, ipsilateral electrode montage (Cz = non-inverting electrode, A2 = inverting electrode, forehead = ground), with contact impedance maintained $\leqslant 5$ kΩ for all electrodes throughout the recording. The responses were filtered from 100 to 2000 Hz, digitally sampled at 12 kHz over an 85.33 ms time window, artifact-rejected, and averaged online. Once 6000 artifact-free trials were reached, the recording was automatically terminated. Bio-logic AEP's default artifact rejection criterion for ABR was selected, resulting in any activity exceeding ±23.8 μV being rejected from the average.

ABRs were also recorded to 100 microsecond rarefaction clicks played to the right ear at 80 dB SPL at six presentation rates 6.9, 10.9, 15.4, 31.25 Hz, 46.5 and 61.5 Hz. Adopting published procedures, responses were digitally sampled at 24 kHz, filtered online from 100 to 1500 Hz, artifact-rejected (±23.8 μV criteria), and averaged online (Krizman et al., 2010). Once 2000 artifact-free trials were reached, the recording was automatically terminated.

To minimize fatigue and muscle movements during the recordings, participants sat in a quiet room and watched a video of their choice, following published procedures (Skoe & Kraus, 2010). The movie was presented on a tablet (Samsung Galaxy S3) placed arms-length in front of the participant on a small table attached to the chair. The soundtrack of the movie was played at a low volume with subtitles turned on at the participant's request. The left ear was unblocked allowing the participant to hear the movie soundtrack played in English. The ER2-14 ear inserts, which were seated deeply in the ear canal, provided a background sound attenuation of ~30 dB SPL (Frank & Wright, 1990).

4.4. ABR analysis

The broadband click stimulus produces a highly stereotyped response characterized by a series of waves, the first of which (Wave I) originates from activity within the cochlear nerve with a latency of 1–2 ms (for suprathreshold stimulation). Wave V, the most robust ABR Wave, reflects stimulus-evoked activity within the lateral lemniscus and inferior colliculus (Hall, 2007), with an approximate latency of 5–6 ms.

The /da/ speech stimulus employed in this study also elicits a response with a highly stereotyped morphology that includes seven waves, referred to as V, A, C, D, E, F, O (Fig. 1, top) (Banai et al., 2009; Skoe et al., 2015). Waves V and A, of the speech-ABR, comprise the onset response, C comprises the voice onset response, D-E-F comprise the frequency-following response, and Wave O reflects the offset of sound. The latencies of these seven waves implicate the lateral lemniscus and the inferior colliculus as the primary underlying generators (Chandrasekaran & Kraus, 2010; Coffey, Herholz, Chepesiuk, Baillet, & Zatorre, 2016).

Waves I and V of the click-ABR and the seven characteristic waves for the speech-ABR were labeled by the experimenter and then reviewed for accuracy by a second experimenter and the lead author. To ensure accuracy in identifying click-evoked Waves I and V, the intervening peaks (II, III, IV) were also identified by the experimenter but they were not factored into the analysis. All raters were blind to the composite reading score while labeling the ABR waveforms. To control for multiple comparisons, a composite timing score was derived for each participant for the speech-ABR, by converting each latency value to a Z score and then averaging the Z scores across all seven peaks, similar to procedures outlined in Banai et al., 2009.

4.5. Statistical analyses

To examine relationships between basic auditory function and reading skill, ABR latency was compared via Pearson correlation in SPSS (IBM, Inc.) to a composite index of reading, representing the mean percentile across the reading assessment measures. To better isolate the relationship between reading ability and ABR, non-verbal IQ was used as a covariate in the analysis to account for the trending relationship between the *TONI-3* and the composite reading measure ($r = 0.335$, $p = 0.061$). Unless explicated noted the reported results covary for non-verbal IQ.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandl.2016.09.003.

References

Ahissar, M., Protopapas, A., Reid, M., & Merzenich, M. M. (2000). Auditory processing parallels reading abilities in adults. *Proceedings of the National Academy of Sciences USA, 97*(12), 6832–6837.

Amin, S. B., Vogler-Elias, D., Orlando, M., & Wang, H. (2014). Auditory neural myelination is associated with early childhood language development in premature infants. *Early Human Development, 90*(10), 673–678.

Banai, K., Abrams, D., & Kraus, N. (2007). Sensory-based learning disability: Insights from brainstem processing of speech sounds. *International Journal of Audiology, 46*(9), 524–532.

Banai, K., Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Reading and subcortical auditory function. *Cerebral Cortex, 19*(11), 2699–2707.

Basu, M., Krishnan, A., & Weber-Fox, C. (2010). Brainstem correlates of temporal auditory processing in children with specific language impairment. *Developmental Science, 13*(1), 77–91.

Bauch, C. D., & Olsen, W. O. (1986). The effect of 2000–4000 Hz hearing sensitivity on ABR results. *Ear and Hearing, 7*(5), 314–317.

Benasich, A. A., & Tallal, P. (2002). Infant discrimination of rapid auditory cues predicts later language impairment. *Behavioural Brain Research, 136*(1), 31–49.

Bidelman, G. M., Villafuerte, J. W., Moreno, S., & Alain, C. (2014). Age-related changes in the subcortical-cortical encoding and categorical perception of speech. *Neurobiology of Aging, 35*(11), 2526–2540.

Bishop, D. V., & McArthur, G. M. (2004). Immature cortical responses to auditory stimuli in specific language impairment: Evidence from ERPs to rapid tone sequences. *Developmental Science, 7*(4), F11–F18.

Bishop, D. V. M., & McArthur, G. M. (2005). Individual differences in auditory processing in specific language impairment: A follow-up study using event-related potentials and behavioural thresholds. *Cortex, 41*(3), 327–341.

Briscoe, J., Bishop, D. V., & Norbury, C. F. (2001). Phonological processing, language, and literacy: A comparison of children with mild-to-moderate sensorineural hearing loss and those with specific language impairment. *Journal of Child Psychology and Psychiatry, 42*(3), 329–340.

Chandrasekaran, B., & Kraus, N. (2010). The scalp-recorded brainstem response to speech: Neural origins and plasticity. *Psychophysiology, 47*(2), 236–246.

Chang, Y., Lee, S.-H., Lee, Y.-J., Hwang, M.-J., Bae, S.-J., Kim, M.-N., et al. (2004). Auditory neural pathway evaluation on sensorineural hearing loss using diffusion tensor imaging. *NeuroReport, 15*(11), 1699–1703.

Chonchaiya, W., Tardif, T., Mai, X., Xu, L., Li, M., Kaciroti, N., et al. (2013). Developmental trends in auditory processing can provide early predictions of language acquisition in young infants. *Developmental Science, 16*(2), 159–172.

Coffey, E. B., Herholz, S. C., Chepesiuk, A. M., Baillet, S., & Zatorre, R. J. (2016). Cortical contributions to the auditory frequency-following response revealed by MEG. *Nature Communication, 7*, 11070.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Lawrence.

Don, M., & Eggermont, J. J. (1978). Analysis of the click-evoked brainstem potentials in man using high-pass noise masking. *The Journal of the Acoustical Society of America, 63*(4), 1084–1092.

Don, M., Ponton, C. W., Eggermont, J. J., & Kwong, B. (1998). The effects of sensory hearing loss on cochlear filter times estimated from auditory brainstem response latencies. *The Journal of the Acoustical Society of America, 104*(4), 2280–2289.

Edgar, J. C., Fisk Iv, C. L., Berman, J. I., Chudnovskaya, D., Liu, S., Pandey, J., et al. (2015). Auditory encoding abnormalities in children with autism spectrum disorder suggest delayed development of auditory cortex. *Molecular Autism, 6*, 69.

Eggermont, J. J., & Don, M. (1986). Mechanisms of central conduction time prolongation in brain-stem auditory evoked potentials. *Archives of Neurology, 43*(2), 116–120.

Evans, G. W., & Maxwell, L. (1997). Chronic noise exposure and reading deficits the mediating effects of language acquisition. *Environment and Behavior, 29*(5), 638–656.

Frank, T., & Wright, D. C. (1990). Attenuation provided by four different audiometric earphone systems. *Ear and Hearing, 11*(1), 70–78.

Fujikawa, S. M., & Weber, B. A. (1977). Effects of increased stimulus rate on brainstem electric response (BER) audiometry as a function of age. *Journal of the American Audiology Society, 3*(3), 147–150.

Gorga, M. P., Kaminski, J. R., Beauchaine, K. L., Jesteadt, W., & Neely, S. T. (1989). Auditory brainstem responses from children three months to three years of age: Normal patterns of response. II. *Journal of Speech and Hearing Research, 32*(2), 281–288.

Gorga, M. P., Worthington, D. W., Reiland, J. K., Beauchaine, K. A., & Goldgar, D. E. (1985). Some comparisons between auditory brain stem response thresholds, latencies, and the pure-tone audiogram. *Ear and Hearing, 6*(2), 105–112.

Goswami, U. (2015). Sensory theories of developmental dyslexia: Three challenges for research. *Nature Reviews Neuroscience, 16*(1), 43–54.

Hall, J. W. (2007). *New handbook of auditory evoked responses*. Boston: Allyn and Bacon.

Halliday, L., & Bishop, D. (2005). Frequency discrimination and literacy skills in children with mild to moderate sensorineural hearing loss. *Journal of Speech, Language, and Hearing Research, 48*(5), 1187–1203.

Hornickel, J., & Kraus, N. (2013). Unstable representation of sound: A biological marker of dyslexia. *Journal of Neuroscience, 33*(8), 3500–3504.

Jacobson, J. T., Murray, T., & Deppe, U. (1987). The effects of ABR stimulus repetition rate in multiple sclerosis. *Ear and Hearing, 8*(2), 115–120.

Jerger, J. (1978). Prediction of sensorineural hearing level from the brain stem evoked response. *Archives of Otolaryngology, 104*(8), 456–461.

Jerger, J., & Johnson, K. (1988). Interactions of age, gender, and sensorineural hearing loss on ABR latency. *Ear and Hearing, 9*(4), 168–176.

Johnson, K. L., Nicol, T., Zecker, S. G., & Kraus, N. (2008). Developmental plasticity in the human auditory brainstem. *Journal of Neuroscience, 28*(15), 4000–4007.

Kadam, M. A., Orena, A. J., Theodore, R. M., & Polka, L. (2016). Reading ability influences native and non-native voice recognition, even for unimpaired readers. *Journal of the Acoustical Society of America, 139*, EL6–EL12.

Ken-Dror, A., Pratt, H., Zeltzer, M., Sujov, P., Katzir, J., & Benderley, A. (1987). Auditory brain-stem evoked potentials to clicks at different presentation rates: Estimating maturation of pre-term and full-term neonates. *Electroencephalography and Clinical Neurophysiology, 68*(3), 209–218.

Kim, S. E., Turkington, K., Kushmerick, C., & Kim, J. H. (2013). Central dysmyelination reduces the temporal fidelity of synaptic transmission and the reliability of postsynaptic firing during high-frequency stimulation. *Journal of Neurophysiology, 110*(7), 1621–1630.

King, C., Warrier, C. M., Hayes, E., & Kraus, N. (2002). Deficits in auditory brainstem pathway encoding of speech sounds in children with learning problems. *Neuroscience Letters, 319*(2), 111–115.

Kouni, S. N., Giannopoulos, S., Ziavra, N., & Koutsojannis, C. (2013). Brainstem auditory evoked potentials with the use of acoustic clicks and complex verbal sounds in young adults with learning disabilities. *American Journal of Otolaryngology, 34*(6), 646–651.

Kral, A., & Sharma, A. (2012). Developmental neuroplasticity after cochlear implantation. *Trends in Neurosciences, 35*(2), 111–122.

Krizman, J., Marian, V., Shook, A., Skoe, E., & Kraus, N. (2012). Subcortical encoding of sound is enhanced in bilinguals and relates to executive function advantages. *Proceedings of the National Academy of Sciences USA, 109*(20), 7877–7881.

Krizman, J. L., Skoe, E., & Kraus, N. (2010). Stimulus rate and subcortical auditory processing of speech. *Audiology and Neurotology, 15*(5), 332–342.

Krizman, J., Tierney, A., Fitzroy, A. B., Skoe, E., Amar, J., & Kraus, N. (2015). Continued maturation of auditory brainstem function during adolescence: A longitudinal approach. *Clinical Neurophysiology, 26*(12), 2348–2355.

Lasky, R. E. (1984). A developmental study on the effect of stimulus rate on the auditory evoked brain-stem response. *Electroencephalography and Clinical Neurophysiology, 59*(5), 411–419.

Lasky, R. E. (1997). Rate and adaptation effects on the auditory evoked brainstem response in human newborns and adults. *Hearing Research, 111*(1–2), 165–176.

Lauter, J. L., & Loomis, R. L. (1986). Individual differences in auditory electric responses: Comparisons of between-subject and within-subject variability. I. Absolute latencies of brainstem vertex-positive peaks. *Scandinavian Audiology, 15*(3), 167–172.

Lauter, J. L., & Oyler, R. F. (1992). Latency stability of auditory brainstem responses in children aged 10–12 years compared with younger children and adults. *British Journal of Audiology, 26*(4), 245–253.

Lauter, J. L., Oyler, R. F., & Lord-Maes, J. (1993). Amplitude stability of auditory brainstem responses in two groups of children compared with adults. *British Journal of Audiology, 27*(4), 263–271.

Lee, I. A., & Preacher, K. J. (2013). Calculation for the test of the difference between two dependent correlations with one variable in common <http://quantpsy.org>.

Lehmann, A., & Schonwiesner, M. (2014). Selective attention modulates human auditory brainstem responses: Relative contributions of frequency and spatial cues. *PLoS One, 9*(1), e85442.

Mochizuki, Y., Go, T., Ohkubo, H., Tatara, T., & Motomura, T. (1982). Developmental changes of brainstem auditory evoked potentials (BAEPs) in normal human subjects from infants to young adults. *Brain and Development, 4*(2), 127–136.

Poeppel, D. (2003). The analysis of speech in different temporal integration windows: Cerebral lateralization as 'asymmetric sampling in time'. *Speech Communication, 41*(1), 245–255.

Protopapas, A. (2014). From temporal processing to developmental language disorders: Mind the gap. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 369*(1634), 20130090.

Purdy, S. C., Kelly, A. S., & Davies, M. G. (2002). Auditory brainstem response, middle latency response, and late cortical evoked potentials in children with learning disabilities. *Journal of the American Academy of Audiology, 13*(7), 367–382.

Rocha-Muniz, C. N., Befi-Lopes, D. M., & Schochat, E. (2012). Investigation of auditory processing disorder and language impairment using the speech-evoked auditory brainstem response. *Hearing Research, 294*(1–2), 143–152.

Rosen, S. (1992). Temporal information in speech: Acoustic, auditory and linguistic aspects. *Philosophical Transactions of the Royal Society of London, 336*(1278), 367–373.

Russo, N., Nicol, T., Trommer, B., Zecker, S., & Kraus, N. (2009). Brainstem transcription of speech is disrupted in children with autism spectrum disorders. *Developmental Science, 12*(3), 557–567.

Salamy, A. (1984). Maturation of the auditory brainstem response from birth through early childhood. *Journal of Clinical Neurophysiology, 1*(3), 293–329.

Scheidt, R. E., Kale, S., & Heinz, M. G. (2010). Noise-induced hearing loss alters the temporal dynamics of auditory-nerve responses. *Hearing Research, 269*(1–2), 23–33.

Sharma, A., Dorman, M. F., & Kral, A. (2005). The influence of a sensitive period on central auditory development in children with unilateral and bilateral cochlear implants. *Hearing Research, 203*(1–2), 134–143.

Skoe, E., & Kraus, N. (2010). Auditory brain stem response to complex sounds: A tutorial. *Ear and Hearing, 31*(3), 302–324.

Skoe, E., & Kraus, N. (2013). Musical training heightens auditory brainstem function during sensitive periods in development. *Frontiers in Psychology, 4*, 622.

Skoe, E., Krizman, J., Anderson, S., & Kraus, N. (2015). Stability and plasticity of auditory brainstem function across the lifespan. *Cerebral Cortex, 25*(6), 1415–1426.

Skoe, E., Krizman, J., Spitzer, E., & Kraus, N. (2013). The auditory brainstem is a barometer of rapid auditory learning. *Neuroscience, 243*, 104–114.

Song, J. H., Banai, K., & Kraus, N. (2008). Brainstem timing deficits in children with learning impairment may result from corticofugal origins. *Audiology and Neurotology, 13*(5), 335–344.

Song, J. H., Banai, K., Russo, N. M., & Kraus, N. (2006). On the relationship between speech- and nonspeech-evoked auditory brainstem responses. *Audiology and Neurotology, 11*(4), 233–241.

Song, J. H., Skoe, E., Banai, K., & Kraus, N. (2012). Training to improve hearing speech in noise: Biological mechanisms. *Cerebral Cortex, 22*(5), 1180–1190.

Sorqvist, P., Stenfelt, S., & Ronnberg, J. (2012). Working memory capacity and visual-verbal cognitive load modulate auditory-sensory gating in the brainstem: Toward a unified view of attention. *Journal of Cognitive Neuroscience, 24*(11), 2147–2154.

Spitzer, E., White-Schwoch, T., Carr, K. W., Skoe, E., & Kraus, N. (2015). Continued maturation of the click-evoked auditory brainstem response in preschoolers. *Journal of the American Academy of Audiology, 26*(1), 30–35.

Strelcyk, O., Christoforidis, D., & Dau, T. (2009). Relation between derived-band auditory brainstem response latencies and behavioral frequency selectivity. *The Journal of the Acoustical Society of America, 126*(4), 1878–1888.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language, 9*(2), 182–198.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1994). Development of reading-related phonological processing abilities: new evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology, 30*(1), 73.

Wright, B. A., & Zecker, S. G. (2004). Learning problems, delayed development, and puberty. *Proceedings of the National Academy of Sciences USA, 101*(26), 9942–9946.

Wynne, D. P., Zeng, F. G., Bhatt, S., Michalewski, H. J., Dimitrijevic, A., & Starr, A. (2013). Loudness adaptation accompanying ribbon synapse and auditory nerve disorders. *Brain, 136*(Pt 5), 1626–1638.