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Investigating the Cross-Domain Plasticity of Musical Training and Reading Acquisition: A Developmental Perspective

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Abstract

For a child acquiring a spoken language, learning to read is a complex sensory and cognitive process that involves mapping mental representations of discrete speech units (e.g., phonemes, syllables) to representations of their visual forms (e.g., graphemes). This process relies, largely, on knowledge about how discrete speech units can be assembled to create larger structures (e.g., phonological awareness) and accessing sound-symbol knowledge in real-time (e.g., decoding). Several authors have observed that reading and music training share similar task demands (e.g., accessing combinatorial knowledge, decoding) and rely on overlapping neural processing mechanisms for speech and music perception. The parallels between music training and reading suggest that music training could bolster reading abilities in both typical and at-risk children (Patel, 2011, 2014; Tallal & Gaab, 2006; Tierney & Kraus, 2013). In support of these theories, behavioral evidence with pre- and early-literate children suggests that music-related skills, such as rhythm perception and production, are linked to more advanced reading-related skills (Anvari, Trainor, Woodside, & Levy, 2002). Moreover, music training and music-based interventions have been found to improve reading-related skills (e.g., phonological awareness) in at-risk children (Gordon, Fehd, & McCandliss, 2015). One possible mechanism by which a music-reading transfer may occur is through a domain-general enhancement of sensory processing in the auditory system (Patel, 2011, 2014; Tallal & Gaab, 2006; Tierney & Kraus, 2013). Indeed, neural indices of auditory processing are related to reading ability in childhood, including typical & atypical readers, and, interestingly, in children with a history of music training (Tierney & Kraus, 2013). Collectively, these findings suggest that music training may help facilitate literacy

in young readers by enhancing the neural processing of the sounds important for reading development, namely speech. Despite these promising findings, to my knowledge, no authors have generated developmental predictions on how music training might interact with reading ability across the lifespan. Consequently, it remains unclear just what the nature of the relationship between reading, music training, and auditory processing is as ontogeny unfolds. For instance, one possibility is that, on average, musicians are better readers, an advantage that persists into adulthood. However, another possibility is that music training increases the rate of literacy during the period of reading development, but non-musically trained children eventually catch up to their musically trained peers at a later stage in development. Cross-sectional data from emerging readers alone cannot tease apart these two competing explanations, nor can data obtained from longitudinal studies that fall short of adulthood. In order to address these two hypotheses, here, we investigated whether music training confers benefits to reading development that persist into adulthood. In samples of mature readers, we investigated whether neural indices of auditory processing and a history of music training related to participants' performance on a behavioral battery of reading-related tasks. Analyses suggest that, even into adulthood, auditory processing and a history of music training are related to specific skills that subserve reading (e.g., rapid naming, phonological decoding, reading comprehension). While the data reported here are from a nascent, on-going research project, they, nevertheless, suggest that musical training may impart long-term effects on reading development, and that functioning of the subcortical auditory system underlies both low- and high-level reading skills, even into adulthood. Future research directions are discussed.

1 THE DEVELOPMENT OF READING

Reading is a high-level cognitive capacity that involves accessing and mapping phonological, orthographic, and semantic representations in real-time. Consequently, the development of reading is thought to involve acquiring and storing these representations in long-term memory (Ehri, 1992; Share & Stanovich, 1995; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997). For a child learning a spoken language, this process arguably begins in infancy, even at a pre-verbal stage, as the child receives linguistic and speech input from other spoken-language users. The development of the child's phonological system – a cognitive system of internal representations which reflect specific, discrete units of speech, such as the phoneme and syllable – is thought to originate from this early sensory and linguistic experience (Benasich & Tallal, 2002; Kuhl, 2004; Kuhl et al., 2014; Moon, Lagercrantz, & Kuhl, 2013; Tsao, Liu, & Kuhl, 2004). For reading acquisition to proceed, the phonological system must interface with a system of representations that reflect discrete, visual forms of written language (e.g., grapheme). This orthographic system is developed through speech-to-text, or sound-to-symbol, mappings obtained through reading experience and formal education (Schrank, 2010). Lastly, for readers to comprehend written language, the phonological and orthographic systems both interface, in parallel (e.g., phonology-to-meaning, orthography-to-meaning mappings), with the semantic system, a cognitive system of meaning (Friel-Patti & Finitzo, 1990; Hornickel & Kraus, 2013; Rueckl, 2002; Seidenberg, 2007; Seidenberg & McClelland, 1989). Thus, the emerging reader is ultimately tasked with developing a global reading system that maps between phonological, orthographic, and semantic sub-systems, as formalized in the canonical model of reading – the Triangle Model (Seidenberg, 2007). However, early

in ontogeny, before the emergence of a global reading system, future reading development hinges upon several rudimentary pre-reading skills: phonological awareness, decoding, and rapid naming. Phonological awareness reflects explicit knowledge about the constituent parts of spoken language and the capacity to manipulate these parts to create larger linguistic structures, such as combining phonemes to create syllables, or combining syllables to create lexical items. Decoding reflects sound-symbol knowledge – that is, correctly mapping the auditory and visual forms of a given language. And, finally, rapid naming – a poorly understood skill thought to reflect phonological access or cognitive speed of processing (Torgesen, Wagner, & Rashotte, 1994; Torgesen et al., 1997; Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993). These skills—phonological awareness, decoding, and rapid naming—have been studied widely and are now considered to be reliable predictors of future and current reading levels in children (Bruck & Treiman, 1990; Stahl & Murray, 1994, Bradley & Bryant, 1983).

For emerging readers who are simultaneously acquiring a spoken language while acquiring reading-related subskills, the development of reading (and language) is thought to partially be mediated by basic auditory processing mechanisms, such as detecting rapid acoustic changes in speech (e.g., formant transitions, amplitude rise times) and sensitivity to speech rhythm and prosody (Holliman, Wood, & Sheehy, 2010; Huss, Verney, Fosker, Mead, & Goswami, 2011; Protopapas, 2014; Ramus, 2002; Ramus, Nespor, & Mehler, 1999; Tallal & Gaab, 2006; Tallal, Miller, & Fitch, 1993). Many of these skills involve the neural processing of important acoustic cues thought to facilitate speech perception, more generally, and the segmentation of linguistic units from the speech stream, more specifically. Further, speech processing is theorized to underlie reading

development in spoken-language users by way of building up a robust phonological system (Boets, Wouters, van Wieringen, De Smedt, & Ghesquière, 2008; Gervain & Mehler, 2010; Goswami, 2011; Saffran, Aslin, & Newport, 1996). For example, rapid spectrotemporal transitions at formant frequencies in speech are acoustic cues thought to aid the discrimination of speech units at the phonemic level, such as the ability to distinguish between /ba/ vs. /da/ (Tallal & Gaab, 2006). For the emerging reader, accurately processing and responding to these rapid acoustic fluctuations might, thus, serve as the basis of phonological knowledge. Moreover, speech processing is thought to facilitate accurate sound-to-text and sound-to-meaning mappings. Thus, an auditory system that does not encode the acoustic nuances of the speech signal might engender difficulties for emerging readers, as children attempt to relate what they hear to what they see (e.g., phonological-orthographic mapping) (Hornickel & Kraus, 2013; Kraus & Anderson, 2013; Tierney & Kraus, 2013). Consequently, reading theorists have proposed that the development of the auditory system is inextricably linked to the development of reading skills, particularly for children learning a spoken language (Banai & Ahissar, 2013; Benasich & Tallal, 2002; Boets et al., 2011; Tallal et al., 1993). Indeed, research over the past two decades supports this general position. For instance, the capacity of the auditory system to encode the spectrotemporal features of speech is related to higher level language abilities, like reading-related skills (Banai et al., 2009; Hornickel, Anderson, Skoe, Yi, & Kraus, 2012; Hornickel & Kraus, 2013).

If the auditory system plays a significant role in speech processing and reading development, it is possible that other auditory-based skills or other forms of auditory training might influence reading outcomes. Musical training, like reading, is another

sensorimotor and auditory-based activity that children often participate in during the formative years of reading development. Given the strong association between reading development on auditory processing, several authors have suggested that reading and music aptitude might rely on shared, underlying skills (Patel, 2008, 2011, 2014; Tallal & Gaab, 2006; Tierney & Kraus, 2013). Moreover, several authors have suggested that music and reading share similar task demands (e.g., decoding, manipulating a combinatorial system), suggesting that training in one domain might generalize to another (e.g., Anvari et al., 2002; Corrigall & Trainor, 2011). Consistent with these theoretical positions, a body of emerging work in the child-development literature suggests that, even at pre-reading stages of development, music and reading skills are intimately related.

2 MUSIC AND READING-RELATED SKILLS IN PRE-LITERATE AND EARLY READERS

Perhaps surprisingly, multiple studies have now demonstrated that children's basic timing and pitch abilities, traits often associated with musical aptitude, are strongly associated with reading-related skills during pre- and early-literate stages of reading development (Anvari et al., 2002; David, Wade-Woolley, Kirby, & Smithrim, 2007; Forgeard et al., 2008). These associations have been uncovered in cohorts of typical and atypical readers. For instance, in one study with a group of 4- and 5-year-old pre-literate readers, Anvari, Trainor, Woodside, & Levy (2002) found that rhythm and pitch abilities (e.g., rhythm production, rhythm discrimination, melody discrimination, chord discrimination) were correlated with measures of phonological awareness and reading development (e.g., letter identification). Similarly, David, Wade-Woolley, Kirby, and

Smithrim (2006) tracked a group of English-speaking first graders through the fifth grade and found that rhythm production predicted reading-related skills (e.g., phonological awareness, rapid naming), and, in some instances, overall reading level. Moreover, in a group of 8-year-old English-speaking children, Douglas and Willatts (1994) found that rhythmic and tonal skills were correlated with reading and phonological ability. Interestingly, rhythmic skills were found to be more strongly related than tonal skills. Similarly, in a group of children aged 8 to 13 associations between rhythmic, but not tonal, skills were related to general cognitive abilities (e.g., auditory memory and attention) thought to be important for reading (Strait, Hornickel, & Kraus, 2011). In another 2011 study, Huss, Verney, Fosker, Mead, & Goswami (2011) studied children's sensitivity to beat structures in music and found that metrical sensitivity predicted phonological awareness and reading development. A follow-up study, conducted a year later, found that children with dyslexia, a reading disorder in which reading-aged children typically present with phonological deficits, in the sample had poorer musical beat perception than younger children of the same reading competence. Interestingly, perception of musical beat structure was found to significantly predict both phonological awareness and reading-comprehension skills (Goswami, Huss, Mead, Fosker, & Verney, 2013). Similarly, Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus (2014) found that preschoolers' ability to entrain to a beat was associated with phonological awareness, rapid naming, auditory short-term memory, and the neural encoding of speech in the subcortical auditory system. Finally, in a review of the developmental dyslexia literature, Hämäläinen, Salminen, & Leppänen (2013) found that impairments in rhythm and meter perception were reported in all of the included

studies, while deficits in pitch perception were reported in just over half of the reviewed material (Hämäläinen et al., 2013). (See also, Goswami et al., 2013; Leong & Goswami, 2014).

While the reviewed studies reveal a relationship between musical *aptitude* and reading, other studies indicate that formal musical *training* is related to improvements in reading ability. For example, Forgeard et al. (2008) studied music and reading-related skills in a cohort of typical and dyslexic readers. In the typical readers, a strong association between melodic, phonological, and reading skills was found, while rhythmic skills were only associated with reading skills. Importantly, children that had a history of music training had a stronger relationship between these two domains, suggesting that formal music training might enhance the relationship between music- and reading-related skills. In another study, Corrigall & Trainor (2011) found that the length of music training in a cohort of 6- to 9-year-old children was related to reading comprehension, even when controlling for important confounding factors, such as socio-economic status (SES), IQ, and the numbers of hours a week spent reading. (However, the length of music training was not related to decoding skills, as the authors initially predicted.) Finally, in a large sample (n = 184) of third-graders, behavioral measures of auditory processing (e.g., frequency discrimination) were found to explain ~13% of the variance in reading-related ability. Interestingly, children with a history of musical training performed better on the auditory tasks, though these enhanced auditory skills were not associated with stronger reading-related skills (Banai & Ahissar, 2013).

3 SUBCORTICAL AUDITORY PROCESSING AND READING-RELATED SKILLS

As reviewed, in typical and atypical readers alike, a relationship between music and reading has emerged at the behavioral level. Interestingly, electrophysiological research with typical and atypical populations indicates that these relationships may extend to the neurobiological level. In a series of studies, Kraus and colleagues report that reading development, at least for children learning a spoken language, may rely on the functional integrity of the subcortical auditory system (Banai et al., 2009; Hornickel, Anderson, et al., 2012; Hornickel, Chandrasekaran, Zecker, & Kraus, 2011; Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009; Hornickel, Knowles, & Kraus, 2012; Strait et al., 2011). For instance, for the speech-evoked auditory brainstem response (ABR), Banai et al. (2009) found that poorer phonological decoding was associated with longer absolute response latencies and a weakened representation of speech fine-structure (i.e., reduced response amplitudes at the frequencies of speech harmonics) in the speech-evoked frequency-following response (FFR). The FFR is a phase-locked auditory-evoked potential that reflects the spectrotemporal properties of speech. For frequencies in the speech range, the FFR is thought to be primarily, though not exclusively, generated by subcortical generators (Coffey, Herholz, Chepesiuk, Baillet, & Zatorre, 2016; Tichko & Skoe, 2017). Similarly, Hornickel, Anderson, et al. (2012) found that poorer reading fluency was related to a weakened representation of fine-structure in speech-evoked FFR. Moreover, children with poor neural discrimination of stop consonants (i.e., less spectrally distinct phase-locked neural responses evoked by different CVs, such as /ga/, /ba/, and /da/) displayed poorer reading behaviors, such as poorer phonological awareness, reading fluency, and speech-in-noise perception (Hornickel et al., 2009). In

addition to spectrally degraded neural responses, children with poor reading skills exhibit more variable FFRs to speech relative to children with good reading skills (Hornickel & Kraus, 2013; Neef et al., 2017). In a 2013 study, Hornickel & Kraus (2013) found that the response consistency of the FFR (i.e., less variable neural responses to speech) was much greater in children with better reading skills. This finding is particularly intriguing, as it suggests that variability in reading skills is not only related to averaged neural responses, but also to differences in the dynamics of subcortical auditory processing. More recently, *KIAA0319*, a dyslexia risk gene, was found to be associated with greater neural inconsistency in the speech-evoked FFR in a large sample of pre-literate and literate children (n = 159) (Neef et al., 2017). Collectively, these studies suggest that the acquisition of reading-related skills (e.g., phonological awareness, decoding, reading fluency) may hinge on the stability and functioning of the auditory system. Moreover, these studies point to a putative developmental pathway, by which *KIAA0319* leads to inconsistent neural encoding of the speech, which then impinges upon reading development – inconsistent subcortical auditory functioning could be a neurobiological proclivity that impedes successful mapping of phonology to orthography (Hornickel & Kraus, 2013).

4 SUBCORTICAL AUDITORY PROCESSING AND MUSIC TRAINING

While poor readers, relative to their typical-reading peers, often exhibit anemic and inconsistent neural responses to complex sounds, such as speech, children and adults who have undergone specialized auditory training, such as music training, often exhibit the opposite pattern – enhanced and more consistent neural representation of sound in

the auditory system (Parbery-Clark, Anderson, Hittner, & Kraus, 2012; Samelli et al., 2012; Skoe & Kraus, 2013). In another series of studies, Kraus and colleagues demonstrated that adult musicians, compared to adult non-musicians, have faster neural responses and a more faithful representation of sound in the auditory system, as assessed by multiple neural indices of auditory processing, including the speech-evoked ABR and FFR (Musacchia, Sams, Skoe, & Kraus, 2007; Wong, Skoe, & Russo, 2007). While poor readers display poorer neural discrimination of speech syllables, musicians exhibit enhanced neural discrimination relative to non-musicians (Chandrasekaran, Hornickel, & Skoe, 2009; Parbery-Clark, Tierney, Strait, & Kraus, 2012). In one particular study with adult musicians, greater neural discrimination, as indexed by the speech-evoked FFR, was found to be related to better speech-in-noise perception (Parbery-Clark et al., 2012). Moreover, musicians' neural responses more accurately reflect the dynamic properties of complex sounds (Bidelman & Krishnan, 2010; Weiss & Bidelman, 2015; Wong, Skoe, & Russo, 2007): speech-evoked FFRs recorded in a group of musicians were found to more accurately track fluctuations of the speech fundamental frequency (F0) relative to a group of non-musicians (Wong et al., 2007).

Similar differences have also been observed with adolescent (Tierney, Krizman, & Skoe, 2013) and child (Strait, Parbery-Clark, Hittner, & Kraus, 2012) populations. In a group of 7- to 13-year-olds, children with a history of music training were found to have enhanced FFRs to speech harmonics and better speech-in-noise perception relative to children who had no or little musical training (Strait, Parbery-Clark, Hittner, & Kraus, 2012). Moreover, more robust neural responses in the musician group were related to better auditory working memory and speech-in-noise perception, suggesting that music

may enhance sensory processing of the speech signal, and other acoustic input, in a top-down manner (Brashears, Berlin, & Hood, 2003; Perrot & Collet, 2014; Strait et al., 2012).

5 LONGITUDINAL STUDIES

The findings above have led some to conclude that music training directly strengthens auditory functioning (Lee, Skoe, Kraus, & Ashley, 2009; Musacchia, Sams, Skoe, & Kraus, 2007; Schellenberg, 2008; Strait & Kraus, 2011; Tierney, Bergeson, & Pisoni, 2008). However, a valid criticism of cross-sectional studies, like those reviewed above, is their weak ability to establish causal links between group-level features and significant relationships (i.e., these designs are purely correlational). To elaborate, significant differences between musicians and non-musicians might not be an effect of music training per se, but, rather, could arise from factors unrelated to music training (e.g., socio-economic status (SES), personality traits, differences in motivation, intelligence) (Schellenberg, 2008; Tierney & Kraus, 2013). To address these limitations of prior work, more recent research has employed experimental or quasi-experimental designs, often coupling a longitudinal approach with random assignment or subject-matching (Bhide, Power, & Goswami, 2013; Cogo-Moreira, Brandão de Ávila, Ploubidis, & Mari, 2013; Habib et al., 2016; Moreno, Friesen, & Bialystok, 2011; Overy, 2003; Rautenberg, 2013; Register, Darrow, Swedberg, & Standley, 2007). These designs afford a stronger framework for probing the causal effects of music training and music-based interventions on reading development. In one study using random assignment, second-graders were randomly assigned to participate in either a music-based reading program or the typical reading curriculum developed for students of this age (Register et al., 2007). Students in

the music-based-lesson group made greater gains in word decoding and word knowledge than the control class. Additionally, pre- and post-tests revealed that second-graders with a deficit in reading improved significantly on word decoding, word knowledge, and reading comprehension. However, all of the subjects with reading deficits were in the treatment class, making it difficult to draw additional conclusions about the class' remedial power, given that an appropriate control group was not used (Register et al., 2007). In another study involving ten public schools and 235 children with reading difficulties, schools that were randomly assigned to incorporate music lessons into their curriculum observed an improvement of phonological awareness and an increased rate of correct words read per minute in their students with reading impairments (Cogo-Moreira et al., 2013). Moreover, in a longitudinal study, over 150 German-speaking children were randomly assigned to one of three conditions: musical training, visual arts, or no extracurricular class (Rautenberg, 2013). Across the three conditions, children's rhythmic abilities were correlated with decoding skills. However, children that participated in the music training program displayed increases in word-reading accuracy, relative to the visual arts and no-class conditions. Further, these enhancements were associated with temporal processing, such as discriminating between different rhythmic patterns and tone durations. No effect of musical training, however, was found on word-reading speed.

Moreover, in a now seminal paper, Overy (2003) reported the effects of a musical intervention for children with dyslexia. Using various vocal-music and rhythm-focused musical games, Overy found that dyslexic children improved in the skills that subserve music and reading, such as rhythm copying, rapid auditory processing, phonological ability, and spelling ability, but cumulative reading skill (e.g., WORD literacy tests),

ultimately, did not improve significantly (Overy, 2003). More recently, Bhide et al. (2013) developed a novel rhythm-based computer game and compared its effect on reading abilities to a letter-based computer game in a group of 6- and 7-year-olds with poor reading skills. In general, both types of interventions showed similar improvements across a battery of reading-related tasks. Similarly, Habib et al. (2016) developed a novel musical training program for children with dyslexia. Two versions of the program were implemented: an intense, three-day program and a protracted six-week program, each totaling 18 hours of training time. Both programs were found to improve reading skills, though each seemed to train different sets of skills. The consolidated sessions engendered gains in categorical perception and temporal processing, while the prolonged sessions lead to increases in auditory attention, phonological awareness, and repetition of pseudo-words.

While enhancements have been documented at the behavioral level, other studies have documented neurobiological changes in children who have undergone musical training. In one study, children were randomly assigned to music or painting class. After training, the mis-match negativity (MMN) was found to be more robust in the musical trained group for syllable duration and voice-on-set time, suggesting increased temporal processing of speech for the musically trained group (Chobert, François, Velay, & Besson, 2014). (Interestingly though, Huss et al., 2011 found no difference in behavior on a duration-tone-judgement task (400 – 600 ms), a measure of temporal processing, between a group of dyslexics and controls.)

The available data suggests that music training or music-based interventions could be a source of remediation for children presenting with reading deficits or a source of

enrichment for children who wish to improve their already-strong reading skills. However, it remains unclear whether adopting a music-based approach is as efficacious as traditional, letter- or phonological-based approaches to reading instruction. Moreover, in contrast to the studies above, not all studies found gains in reading-related skills after a period of musical training. For instance, Moreno et al. (2011) group-matched 4- to 6-year-old children on IQ and SES tests, before assigning them to a music or visual-arts training program. After 20 days of training, no difference in phonological awareness (e.g., Woodcock-Johnson III Rhyming test) was found. However, a slight advantage for the musically trained group was found on a visual-auditory learning task (e.g., Visual-Auditory Learning test (VAL), Woodcock-Johnson, 1977), suggesting that music might foster word-to-symbol mapping (see Moreno et al., 2011 for a discussion). The VAL task is thought to tap paired-associate learning that occurs during reading acquisition (i.e., mapping sound to text). During the task, children learn arbitrary mappings between familiar words in the child's lexicon and unfamiliar visual symbols. After children learn these mappings, they decode a novel sequence of the visual symbols into their correct lexical forms. As task difficulty increases, additional and more complex symbols are incorporated into the test (Moreno et al., 2011; Schrank, 2010). Relevant here, I argue that this mode of learning is similar to the process of learning to read sheet music during formal music training (see discussion).

Despite the inconsistent findings among training studies, a recent meta-analysis of 13 studies investigating music training and reading development found a small effect size (d = .20) of music training on phonological awareness skills (Gordon et al., 2015). Moreover, rhyming skills, a specific subskill of phonological awareness, were found to be

moderated by the number of musical training hours. (The latter finding may explain why Moreno et. al 2011 did not find an effect of music training on phonological awareness skills: the training program used in that study lasted only 20 days.) No aggregate effect, however, was found on music training and reading fluency, despite multiple studies implicating a transfer effect (Gordon et al., 2015).

6 MUSIC TRAINING AND CROSS-DOMAIN PLASTICITY

As outlined, multiple lines of research have begun to converge on the notion that musical training might bolster reading development. However, thus far, any detailed discussion of putative mechanisms by which this transfer could occur has been avoided: How might music training facilitate reading development? Given the robust relationships between auditory processing, music training, and reading skills, multiple authors have proposed that music training might strengthen general sound-based skills (e.g., perception of amplitude rise time, speech segmentation, prosodic processing, pitch perception) and cognitive abilities (e.g., auditory working memory, attention) that promote reading (Patel, 2011, 2014; Tallal & Gaab, 2006; Tierney & Kraus, 2013). Moreover, several researchers believe that the tasks demands of music and reading (e.g., decoding, manipulating a combinatorial system) are similar (e.g., Anvari et al., 2002; Corrigall & Trainor, 2011), suggesting expertise in one domain (e.g., music) spills over into tasks with related demands (e.g., reading).

In one particular model developed by Tallal & Gaab (2006), the causal influences between the domains of music processing, auditory processing, and reading/language development are schematically mapped out, creating multiple pathways by which musical

training could influence reading outcomes. In this model, arrows reflect putative paths of causality or positive correlations between connecting domains. There, music training is seen to influence reading development by modulating reading skills directly or by modulating reading skills indirectly by way of music processing, auditory processing, or both. Casual pathways in the model are further defined by possible underlying mechanisms: for instance, Tallal & Gaab (2006) posit that musical training might enhance speech perception, which ultimately engenders reading improvements. Moreover, the model addresses other cognitive factors that may related to music development and may shape reading development (e.g., improved attention, sequencing skills). Though the authors do not address the relationship between ontogeny and the development of these domains in their model, what makes Tallal & Gaab (2006) particularly appealing for developmental theories of music-reading transfer is the multiple pathways through which music training could influence reading development. This notion of multiple pathways leading to the same outcome relates, if only tangentially, to the notion of equifinality in developmental theory (Gottlieb & Lickliter, 2007; Gottlieb, Wahlsten, & Lickliter, 2007; Van Geert, 2003).

Another popular framework, the OPERA hypothesis, posits that the sensorimotor demands of musical training enhance overlapping sensorimotor and cognitive systems involved in speech and music processing (Patel, 2011, 2014). According to Patel (2011, 2014), intensive forms of non-linguistic auditory training (e.g., musical training) often place higher demands on the sensory and cognitive networks underlying speech perception, than speech processing would alone. This, in turn, drives experience-dependent neural plasticity, producing long-lasting changes in both brain structure and function that support

language and reading skills (Patel, 2014). Using the OPERA acronym, Patel enumerates five specific conditions for inducing cross-domain plasticity: music and speech processing involves **o**verlapping anatomical brain structures; music training places **p**recision on pitch and rhythm processing in a way that speech perception does not; music is an inherently rewarding and **e**motional activity; music training is highly **r**epetitious; and music training requires periods of sustained, focused **a**ttention (Patel, 2011, 2014). While the OPERA hypothesis is invoked here to explain how music training might bolster reading skills, Patel asserts that, under similar conditions, *any* activity could facilitate cross-domain plasticity (e.g., dance training, mindfulness training). The OPERA hypothesis is a useful framework for explaining a number of empirical findings on brain plasticity in musicians and affords a general theoretical framework for conducting future research. Despite this utility, the OPERA hypothesis does not make specific claims regarding the neurobiological mechanisms by which a music-speech transfer effect would occur. In Patel's own words, "OPERA makes no claims about precisely which changes are involved, or precisely how corticofugal projections are involved in such changes. These are important questions, but how adaptive plasticity is manifested in subcortical networks is a distinct question from why such plasticity is engaged in the first place." (Patel, 2011, pg. 6). Moreover, the OPERA hypothesis does not account for developmental changes that could influence the transfer of music and reading skills, an unfortunate omission, as formal music training often begins early in development, and the emergence of music and language abilities follows a similar developmental course across the lifespan (Brandt, Gebrian, & Slevc, 2012). Thus, it is likely that language- and music-related skills interact throughout ontogeny. For instance, developmental research has demonstrated that, in both the

speech and music domain, infants' perception of native and non-native contrasts, such as phonemic pairs or musical rhythms, are fine-tuned over the first year of life (Hannon & Trehub, 2005; Werker & Tees, 1984). Moreover, rhythmic skills and musical training are associated with differences in grammatical knowledge in children (Gordon et al., 2014; Jentschke & Koelsch, 2009). Considering the developmental literature, I contend that any theory of cross-domain plasticity must account for ontogeny.

As Patel readily acknowledges, the OPERA hypothesis does not provide a mechanistic account of cross-domain plasticity. However, a number of proposals do posit specific neurobiological mechanisms by which a music-speech transfer effect might occur. While developed largely independently, these theories converge on a specific, shared neurobiological mechanism underlying speech and music processing: neural synchrony in cortical and subcortical brain areas to complex auditory signals. Synchrony is a general principle of dynamical systems that has been observed in electronic circuits (e.g., phase-locked loops), ecological systems (e.g., fireflies flashing) (Strogatz, 1994) and, relevant here, in neurobiological systems (e.g., frequency-following response) (Batra, Kuwada, & Maher, 1986; Davis & Hirsh, 1976; Hoormann, Falkenstein, Hohnsbein, & Blanke, 1992). Neural synchrony is now thought to underlie many aspects of speech and music perception (Doelling & Poeppel, 2015; Giraud et al., 2007; Large & Tretakis, 2005; Large, 2010; Large, Herrera, & Velasco, 2015).

6.1 Putative Mechanisms of Reading-Music Transfer: Neural Synchrony

At the structural level, music and speech share a similar, though not equivalent, temporal organization. Rhythm in music refers to how musical events are arranged in

time. Musical rhythmic structure is hierarchical, with different levels of rhythmic organization occurring on multiple, nested timescales. Two of the most prominent timescales for musical processing are the pulse (0-4 Hz), which refers to the underlying beat of a musical piece, and meter, which refers to the vacillating strength of musical beats (e.g., strong-weak-weak pattern of a waltz; slower rhythms < 2 Hz, faster rhythms 4-8 Hz) (Large et al., 2015; London, 2004). Music also contains rapid spectral fluctuations thought to contribute to the multi-dimensional perception of musical timbre (Miller & Carterette, 1975; Samson, Zatorre, & Ramsay, 2002). Similar to the temporal structure of music, speech also consists of alternating strong-and-weak patterns that correspond to prosodic (0.9 – 2.5 Hz) or syllabic (2.5 – 12 Hz) features, and rapid acoustic fluctuations that reflect phonemic information (12 – 40 Hz) (Leong & Goswami, 2014; Poeppel, 2003; Rosen, 1992). Although, in comparison to music, speech tempi are more quasi-periodic. Importantly, these timescales shared by music and speech map almost directly on to the prominent frequency bands of electrophysiology in the human brain: Delta (0.5 – 4 Hz), Theta (4-10 Hz), and Gamma (~35-80 Hz).

Current theories of music and speech processing highlight the role of neural synchrony to the rhythmic characteristics of speech and music at multiple, hierarchal levels in the auditory system and on multiple, hierarchal timescales (Goswami, 2011; Large & Jones, 1999; Large & Snyder, 2009; Leong & Goswami, 2014; MacNeilage, 2000; Poeppel, 2003; Tierney & Kraus, 2013). A popular account of speech perception is the Asymmetrical in Time Hypothesis (ATH), first proposed by Poeppel (2003). ATH propounds that the entrainment of endogenous cortical oscillations to salient spectrotemporal features of speech facilitates the sampling of information from the

speech signal in a time- and hemisphere-specific manner. In the ATH framework, high-frequency Gamma oscillations (~35-80 Hz) originating primarily from the left hemisphere of the brain, are thought to sample information from the speech signal at the phonetic rate, while low-frequency Theta oscillations (4-10 Hz) originating asymmetrically in the right hemisphere are thought to sample information at the syllabic rate (Poeppel, 2003).

Expanding the ATH to clinical populations, Goswami (2011) proposed a Temporal Sampling Hypothesis for Developmental Dyslexia (THS). According to THS, poor neural synchrony to speech in Theta and Delta bands disrupts temporal sensitivity to syllabic stress and prosody, respectively, subsequently impeding speech segmentation. These neurobiological impairments then manifest as deficits in phonological knowledge during reading development (Goswami, 2011). Consistent across Poeppel’s and Goswami’s Temporal Sampling Hypotheses is the role of cortical entrainment to temporal information in the speech signal. However, a contrast between these two theoretical positions is the privilege of syllabic or phonemic timescales for acquiring a phonological system. According to Goswami and colleagues, reading ability fundamentally arises from the speech processing done at the syllabic level, as evidence suggests that this level of processing is impaired in dyslexic populations (Leong & Goswami, 2014). Thus, emerging readers might rely on rhythmic cues, such as strong and weak syllabic stresses, to segment speech, thereby creating a robust, phonological system (Huss, Verney, Fosker, Mead, & Goswami, 2011). However, Poeppel and colleagues contend that the phonological system is primarily built up from articulatory and acoustic features (Poeppel, Idsardi, & van Wassenhove, 2008), suggesting that neural synchrony at faster rates, such as Gamma, may be paramount for extracting relevant features from the speech signal

that ultimately underpin reading development. (Though, see Giraud & Poeppel (2012) for an updated model that involve parallel processing at syllabic and phonemic rates.)

Interestingly, cortical oscillations in the Gamma, Theta, and Delta frequency ranges are also thought to underlie rhythm and meter perception in music (Large, Herrera, & Velasco, 2015; Large & Jones, 1999; Large & Snyder, 2009). According to Neural Resonance Theory, the entrainment of intrinsic, neural oscillations in these frequency bands across sensorimotor regions in the brain to exogenous, musical rhythms results in the perception of musical pulse and meter (Large & Snyder, 2009). Thus, it is plausible that musical training results in a domain-general enhancement to neural synchrony on these timescales, ultimately facilitating neural coupling to both speech and music. Further, I speculate that this enhanced neural synchrony might be modulated by glutamate and choline, two excitatory and inhibitory neurotransmitters. In a recent study, the presence of glutamate and choline was found to relate to variability in reading level among school-aged children (Pugh et al., 2014). Of interest, glutamate and choline are thought to modulate Theta oscillations in cortex, offering a putative mechanism by which neural entrainment in Theta oscillations might be modulated (see discussion, Pugh et al., 2014).

While the reviewed theoretical work of Goswami, Poeppel, Large, and colleagues is primarily concerned with neural synchrony in cortical regions, a related theory emphasizes neural synchrony in the subcortical auditory system. Drawing upon empirical findings relating features of the ABR and FFR to reading-related skills, Tierney & Kraus (2013) proposed Neural Synchrony Theory (NST), a framework which posits that reading development rests on the fidelity of neural encoding of complex sounds, like speech, within the subcortical auditory system. Akin to theories of cortical entrainment, nuclei in

subcortical auditory pathways have been shown to synchronize their firing patterns to the spectrotemporal features of sound. Populations with reading and language impairments often exhibit poor neural response times, less robust neural responses, and less consistent neural responses to speech, findings taken to reflect poorer neural synchrony (Banai et al., 2009; Hornickel, Anderson, Skoe, Yi, & Kraus, 2012; Hornickel et al., 2011; Hornickel & Kraus, 2013). According to these NST, musical training is thought to improve rhythmic skills, which enhances neural consistency in the subcortical auditory system, subsequently benefiting reading abilities.

To conclude, a number of models have attempted to elucidate how music training might enhance reading-related skills. (Patel, 2011, 2014; Tallal & Gaab, 2006; Tierney & Kraus, 2013). Most, if not all of these theories, emphasize auditory processing as a primary, though perhaps not sufficient, mechanism. Further, theoretical work on speech and music perception highlights a potential dynamic feature of the brain that might support cross-domain plasticity: synchrony of neural systems to speech and music input at timescales important for their respective processing (Goswami, 2011; Large & Snyder, 2009; Poeppel, 2003).

7 MUSIC AND READING-RELATED SKILLS IN MATURE READERS

If music training improves reading abilities, perhaps by enhancing auditory processing at multiple, hierarchical levels in the auditory system, then we might expect to find an association between a history of musical training, subcortical auditory processing (e.g., ABR, FFR), and reading-related skills in *mature* readers. While little reading research has been conducted with adult musicians, several studies suggest a link

between subcortical auditory processing, musical training, and reading ability in this population. For instance, adult musicians are more sensitive to speech rhythm (Marie et al., 2011), while dyslexic musicians, compared to dyslexic non-musicians, have better basic auditory processing (e.g., rise time onset detection; perception of intensity, rhythm, and frequency) and reading-related skills (e.g., word and non-word naming) (Bishop-Liebler, Welch, Huss, Thomson, & Goswami (2014). Moreover, in unimpaired adult readers, the maturational status of the subcortical auditory system has been argued to relate to individual differences in reading (Skoe, Brody, & Theodore, 2017). No study has yet, however, has investigated the relationship between variability in music training and reading skills in an unimpaired, musically trained, adult population. Moreover, to my knowledge, no study has attempted to uncover the nature of the relationship between these three domains statistically: namely, whether auditory processing is a mediator or moderator of musical training and reading skills.

8 PREDICTIONS AND MOTIVATION FOR CURRENT STUDY

Despite the extensive findings and theories summarized above, to my knowledge, no authors have generated developmental predictions regarding how music training might interact with reading ability across the lifespan. Indeed, implicit in many of the current proposals is an assumption that the relationship between the brains, bodies, and environments of musically active children are equivalent (i.e., fixed, unchanging) throughout the primary years of reading acquisition. (Surely, the brain and body of an emerging reader who begins musical training at age four should not be considered equal to reader who began music training at age 12!) Consequently, the nature of the

relationship between reading, music training, and auditory processing remains unclear, especially as ontogeny unfolds. In attempt to make concrete how the domains of music and reading interact across development, here, I propose two, theoretical reading-acquisition functions to generate developmental predictions on music-reading interactions. One possibility is that, on average, musically trained individuals are better readers, an advantage that persists into adulthood (Figure 1a). However, another possibility is that music training increases the initial rate of literacy development, but less or non-musically trained children eventually catch up to their musically trained peers at a later stage in ontogeny (Figure 1b). In addition, I assert that music training interacts with reading development in a graded fashion, with more extensive training associated with greater reading outcomes. Cross-sectional data from emerging readers alone cannot tease apart these two competing explanations, nor can data obtained from longitudinal studies that fall short of adulthood. In order to begin to address these two hypotheses, here, we investigated whether music training confers benefits to reading development that persist into adulthood and whether such putative benefits are related to auditory processing. In samples of mature readers, we investigated whether neural indices of auditory processing and a history of music training related to participants' performance on a behavioral battery of reading-related tasks.

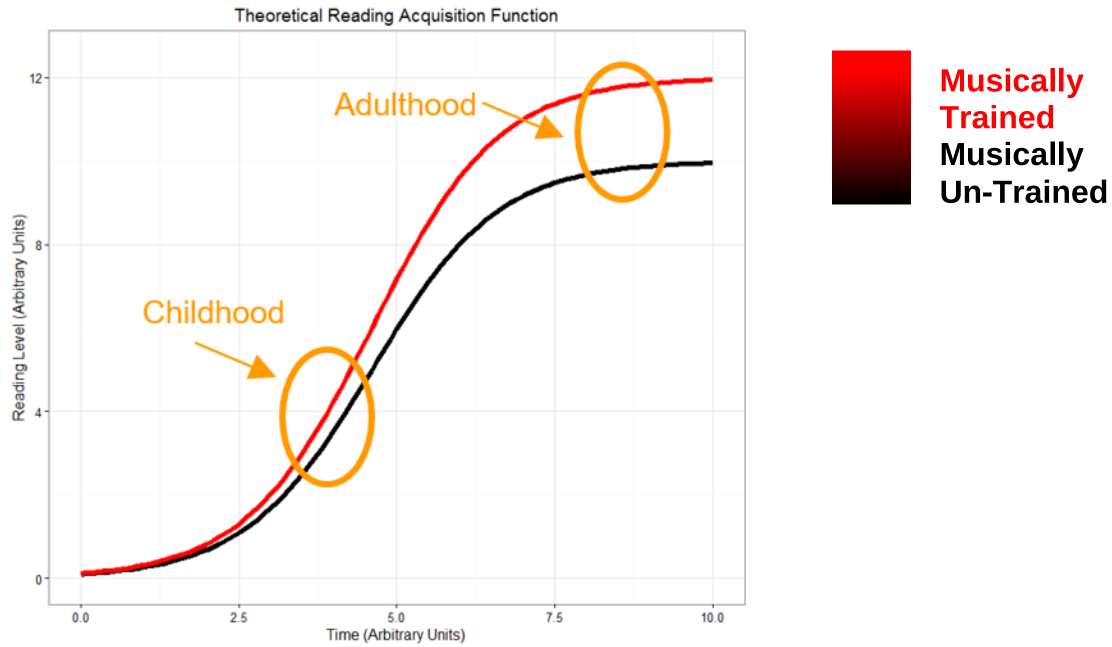

Figure 1a. Theoretical Reading-Acquisition Function. One possible effect of musical training on reading development. Here, children who are receiving musical training display an increased, overall enhancement in reading ability that persists into adulthood. While only two functions are plotted here, this effect is predicted to be graded, with more extensive musical training associated with greater reading gains. Moreover, I predict this gradient to be non-linear: a minimum amount of training to might be required to see an effect of music training on reading, and there might be a ceiling effect, whereby additional training above a certain threshold no longer engenders reading benefits.

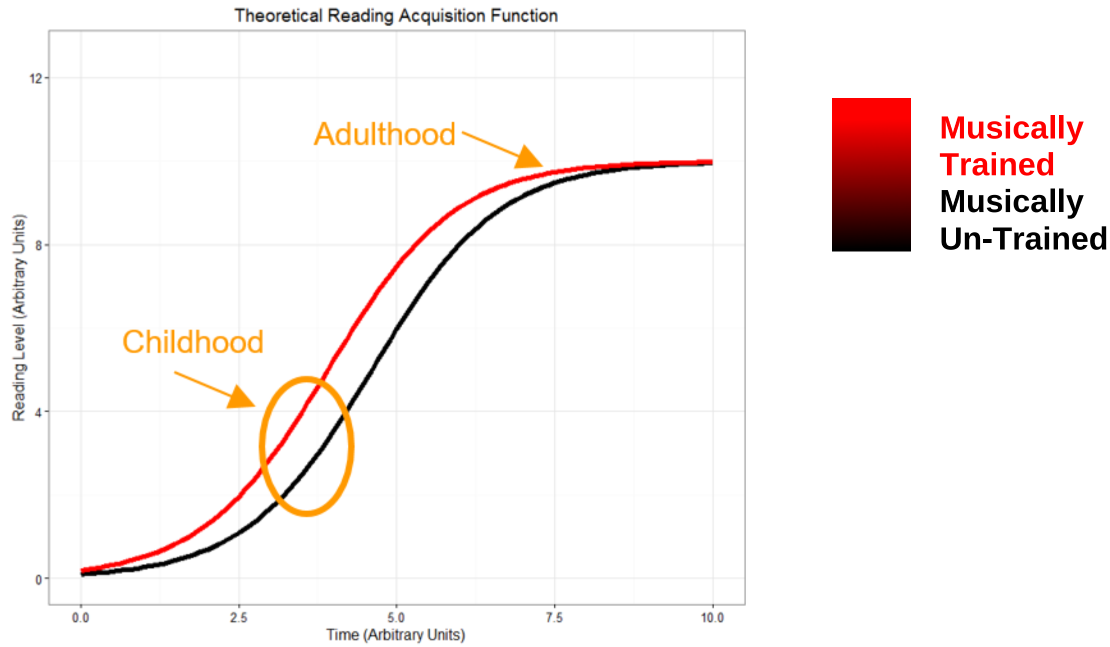

Figure 1b. Theoretical Reading-Acquisition Function. A second possible effect of musical training on reading development. Here, children who are receiving musical training display a faster rate of reading acquisition than children who do not, but ultimately the non-musically trained children catch up to the musically trained. While only two functions are plotted here, this effect is predicted to be graded, with more extensive musical training associated with greater reading gains. Moreover, I predict this gradient to be non-linear: a minimum amount of training to might be required to see an effect of music training on reading, and there might be a ceiling effect, whereby additional training above a certain threshold no longer engenders reading benefits.

In the studies that follow, we operate largely from the framework provided by Tallal & Gaab (2006) and Tierney & Kraus (2013). Here, we predicted that, in adult readers, a history of music training would positively relate to reading-related skills: specifically, we hypothesized that earlier musical training, longer musical training, and the proficiency of musical training obtained would be associated with stronger reading competence, both global reading abilities and specific reading-related skills, such as decoding and phonological awareness (i.e., the first, proposed theoretical reading-acquisition function, Figure1a). We expected musical-training history to relate to decoding and phonological awareness given the previous findings with younger populations (Corrigall & Trainor,

2011; Gordon et al., 2015). Moreover, we posited this relationship would be mediated or moderated by subcortical auditory processing, as assessed by the click-evoked ABR: specifically, we expected the developmental status (i.e., response latencies of the ABR) and the stability (i.e., response consistency of the ABR) of the auditory system to relate to reading and reading-related skills. We also adopted a paradigm to test whether relationships between auditory processing and reading level were related at the phonemic level or the syllabic level of speech processing (Abrams, Nicol, Zecker, & Kraus, 2009; Leong & Goswami, 2014).

The analysis is structured to answer three research questions: 1) Do differences in music-training history relate to specific reading-related skills and general reading ability? 2) Is auditory processing related to specific reading-related skills and general reading ability? and 3) Do differences in music-training history relate to auditory processing? First, we report results from a small sample of adult readers who met the demographic criteria of each of the three research questions. Then, we expanded our analysis to include a larger data set to further examine our predictions. A larger, overarching goal of this research was to develop a framework for a future longitudinal assessments.

9 METHODS

9.1 Participants

Monolingual adult readers (n = 19) who completed a behavioral battery of reading tests, an auditory brainstem (ABR) protocol assessing neural synchrony in the brainstem,

and an extensive music-language questionnaire (hereby referred to as the “musically trained sample”) were considered for analysis. The results from this analysis, including demographic information, are reported below. All participants in the musically trained sample had undergone musical training during their childhood. Given the limited sample size of the above data set, the analysis was then expanded to include a larger sample of adult participants collected in collaboration with the Auditory Brain Research (ABR) Lab and the Laboratory for Spoken Language Processing (SLaP Lab) at the University of Connecticut (hereby referred to as the “expanded dataset”). Integrating this data set into our analysis enabled us to test several predications generated from the theoretical reading-acquisition models with a more representative sample of the college-aged population. This sample, n = 120, included monolingual adult participants who were run through the ABR protocol (n = 118), a behavioral battery of reading tests to assess reading-specific and global literacy abilities (n = 51), or both (n = 50). Most, but not all, of the participants also completed one of two follow-up questionnaires that assessed language and musical backgrounds: an abridged version detailed participants’ beginning age of music training and their primary instrument, and the extensive questionnaire which probed participants’ formal music training (i.e., academic) and language backgrounds. All participants reported no personal history of reading disorders, except one participant who reported a history of dyslexia. All methods and protocols were approved by the Institutional Review Board (IRB) at the University of Connecticut.

9.2 Auditory Brainstem Response (ABR) Protocol:

In humans, scalp-recorded neural responses evoked by a broadband click stimulus elicit a brief, subcortical potential called the auditory brainstem response (ABR). The human ABR is a far-field, auditory-evoked response that reflects the synchronous discharge of neurons originating along the vestibulocochlear nerve and the brainstem responding to the onset of an auditory stimulus. When plotted in the time domain, the ABR to a click stimulus (100-microsecond square wave) has a distinct morphology consisting of five waves which generally occur over the first ~10 ms of stimulation (Figure 2). Each wave is thought to reflect neural activity from specific neural generators along auditory pathways. Earlier waves reflect more peripheral activity (e.g., wave I and II), while later waves (e.g., wave III, IV, V) are thought to reflect more central activity. In the present study, six stimulus presentation rates were used to record click ABRs and to tap different timescales of speech processing that reflect theoretical speech units, such as syllabic (e.g., 6.9, 10.9, 15.4 Hz) and phonemic (e.g., 31.25, 46.5, 61.5 Hz) timescales (Goswami, 2011; Poeppel et al., 2008). While previous work has focused on the speech-evoked FFR, this protocol afforded more control to assess not only *where* processing in the subcortical auditory system may be related to reading abilities and musical history (i.e., peripheral or central structures) but also at which timescales are thought to underlie speech perception and reading development (i.e., phonemic vs. syllabic, rapid auditory processing vs. prosodic auditory processing).

Adopting the procedure of Skoe, Brody, and Theodore (2017), the ABR protocol consisted of 100-microsecond rarefaction clicks that were presented at 80 dB SPL in the right ear of each participant. Six stimulus presentation rates were used 6.9, 10.9, 15.4,

31.25 Hz, 46.5 and 61.5 Hz to tap either phonemic or syllabic timescales of temporal processing. A three-electrode vertical, ipsilateral montage was used to record the far-field ABR from the scalp of participants: the active electrode was located at Cz, while the reference was placed on the right ear lobe (A2). Neural responses were digitized at a 24-kHz sampling rate, and then filtered online from 100 to 1500 Hz. The final waveform used to derive all ABR indices was averaged online using 2000 artifact-free trials.

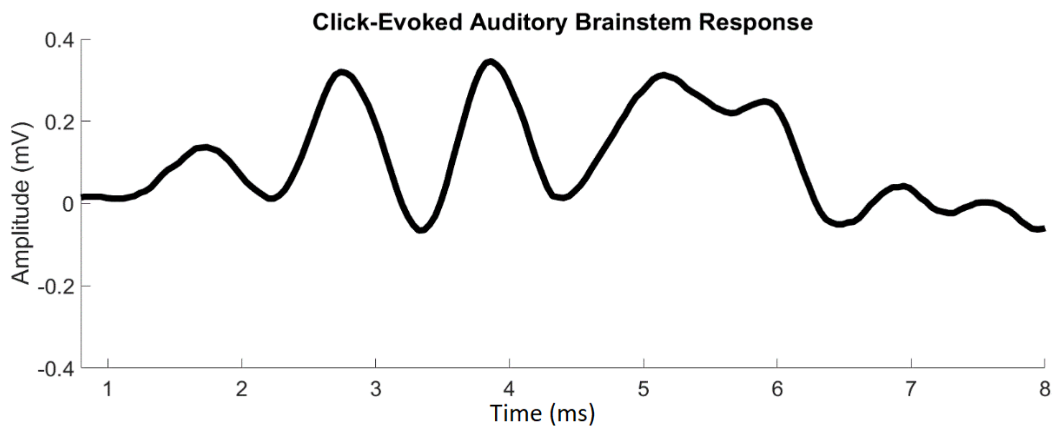

Figure 2. Representative Auditory Brainstem Response (ABR). A representative auditory brainstem response (ABR) evoked by a brief, click stimulus. Note its five-wave morphology. Each wave is the result of synchronous neural firing from neural populations in the subcortical auditory system.

ABR indices included the absolute wave latencies of the ABR and a measure of response consistency (RC) for each of the six presentation rates. In an attempt localize where in the auditory system (e.g., more peripheral, more central) relationships between reading and a history of music training would emerge, the current study considered only the latencies of wave I—thought to originate from the auditory nerve—and wave V—thought to originate from the lateral lemniscus and inferior colliculus (Hood, 1998). The response consistency (RC) measure was derived by binning the full ABR recording into

smaller, 1000-trial epochs and calculating a correlation coefficient across the bins: a greater coefficient suggests that participants' ABRs were more consistent and repeatable across the entire recording session (Hornickel, Knowles, et al., 2012; Hornickel & Kraus, 2013). All participants run through the ABR protocol exhibited otoscopy in the clinically normal range and normal bilateral air conduction thresholds <=20 dB HL for octaves from 250 to 8000 Hz.

9.3 Standardized Reading Battery:

To assess adults' reading skills, participants completed a comprehensive behavioral battery that assessed phonological awareness, decoding skills, word-reading skills, rapid naming, reading comprehension, and non-verbal IQ (Table 1). For all tests, excluding the CTOPP test, the standardized mean = 100, SD = 15. A composite global reading score was derived from the standardized scores on all reading tests (Kadam, Orena, Theodore, & Polka, 2016; Skoe, Brody, & Theodore, 2017):

TEST	**SUBTEST**	**DESCRIPTION**
TONI-3	Non-Verbal IQ	Untimed task. Select illustration to complete puzzle.
Woodcock Reading Mastery Tests (WRMT-III)	Word ID	Untimed task. Read aloud a word list.
	Word Attack	Untimed task. Read aloud a list of non-words (e.g., "pnir")
	Passage Comprehension	Untimed task. Read aloud a short passage with a blank word, then fill in the blank with a word that best fits.
Comprehensive Test of Phonological Processing (CTOPP)	Elision	Untimed task. Say part of word after saying the whole word (e.g., Say the word 'spider'. Now say 'spider' without saying 'der')
	Blending Words	Untimed task. Put sounds of a word together to make one word (e.g. 'can'+'dy'='candy')
	Non-Word Repetition	Untimed task. Repeat back a list of non-words.
TOWRE (Test of Word Reading Efficiency)	Sight Word Efficiency	Timed task (45 sec limit). Read aloud a list of words as quickly as possible

	Phonemic Decoding	Timed task (45 sec limit). Read aloud a list of non-words as quickly as possible
RAN (Rapid Automatized Naming)	RAN Numbers	Timed task. Read aloud a list of numbers as quickly as possible
	RAN Letters	Timed task. Read aloud a list of letters as quickly as possible
	RAS 2-set	Timed task. Read aloud a list that contains both numbers and letters as quickly as possible

Table 1. Behavioral Reading Battery. Descriptions of the individual tests used to probe participants' non-verbal IQ, reading-related skills, and global reading ability in the present study. Specific reading skills assessed included word reading, reading comprehension, decoding, phonological awareness, and rapid naming. A global reading composite score was derived from the standard scores of each test.

9.4 Music and Language Questionnaire:

A comprehensive music questionnaire, developed by the authors, was administered to all participants run through the ABR and reading protocols (n = 19), and, in some cases, to the participants in the expanded data set. The questionnaire was adapted from those used by Kraus and colleagues. For our analyses, four variables were selected that we believe adequately capture the musical history of our participants: the minimum age that participants started musical training, the total years of music training, a self-reported maximum proficiency measure on their primary instrument, and the number of years since music training. These measures enabled us to study the natural variability in adult readers' music-training histories and relate this variability to reading ability in a continuous manner.

9.5 Preliminary Reading Analyses: Principal Components Analysis

First, participants' raw test scores on each reading test were converted into standardized and percentile scores using algorithms supplied by the manufacturer. To assess overall reading ability, a composite reading score was calculated for each participant by computing the arithmetic mean across the percentile test scores (Kadam et al., 2016; Skoe et al., 2017). This reading composite score is thought to provide a gross measure of reading ability for each participant. To corroborate the validity of the reading composite as a global measure, a principal components analysis (PCA) was conducted with the standardized reading scores on all subjects, included in our small and expanded data sets, who were run through the reading battery, n = 51. The PCA yielded four principal components that explained ~76% of the total variance in the standardized reading measures, with the first component explaining ~37% of the variance. Importantly, each reading sub-test loaded positively onto the first component with a magnitude between 0.10 – 0.30, suggesting that the first component reflected a global measure of reading ability. A Pearson's correlation between the reading composite scores and the first principal found a highly linear positive relationship between the two measures, *r(51)* = 0.93, suggesting that the reading composite measure did indeed tap participants' general reading ability. To examine the unaccounted variability in the other principal components, additional correlation, partial correlation, and regression analyses considered the standardized test scores directly for each test within the reading battery.

9.6 Correlation Analyses

To test the predictions of the two, theoretical reading-acquisition functions, statistical measures of dependence were calculated between auditory processing, reading ability, and music-training history. First, data was visually inspected using scatterplots, boxplots, and violin plots. Then, for each analysis, Pearson's R value, uncorrected probability values, and the MPT exact probability values, the latter explained below, were computed. These are reported in tables that follow. Regression diagnostics were conducted to examine potential outliers on relationships found to be significant with the MPT exact probability value. Observations with studentized residuals > |2| were removed from the analysis. Statistics were then re-calculated without outliers to assess the effects of the outlying observations. Finally, for all correlations that were determined to be statistically significant with the MPT exact p-value, planned partial correlation or regression analyses were conducted to control for the non-verbal IQ, age (days), sex (dummy-coded), or the musical-training history of participants. In the following analyses, the MPT for correlations was conducted in the statistical programming environment RStudio using a modified function originally written by Yoder, Blackford, Waller, & Kim (2004). All remaining analyses and visualizations were conducted in RStudio using the data.table, dplyr, reshape, ggplot2, stargazer, psych, Hmsic, and lm.beta libraries.

While the current study was conducted with specific predictions in mind, the sheer numbers of variables renders the analyses a bit exploratory. One concern of exploratory research with high-dimensional data is addressing the Type-I error rate, the probability of incorrectly rejecting the null hypothesis at least once (i.e., a false positive) during hypothesis testing. To control for multiple comparisons and to reduce the Type-I error

rate, the multivariate permutation test (MPT) for correlations was used to estimate statistical significance for all correlational analyses (Yoder et al., 2004). The MPT for correlations is a permutation method used to control the family-wise error rate (FWER) (i.e., Type-I error) without significantly reducing statistical power relative to other methods (e.g., Bonferroni correction). Moreover, the technique is robust for small samples and for data that are non-independent. For any analysis that correlated multiple independent variables to a single dependent variable of interest (e.g., correlating all ABR indices to the reading composite score), the MPT for correlations was instantiated for 10,000 permutations. A two-tailed test with an alpha level of 0.05 (FWER < 0.05) was used to compute the MPT exact probability value and determine statistical significance.

10 RESULTS

The results are, first, presented from our core, musically trained sample of 19 adult readers. After which, *post hoc* analyses that explored relationships between our three domains of inquiry (e.g., musical-training history, auditory processing, and reading-related skills) in the expanded data set are presented. Supplemental tables labeled with alpha-numeric names (e.g., Supplemental Table 3A, Supplemental Table 4F) are reported at the end of the manuscript, while tables labeled with digits (e.g., Table 3) are presented in-line. All figures and visualizations are presented in-line. **To help the reader process the extensive number of findings, Table 4, located at the end of the results section, provides a summary of the four, robust relationships that emerged from our analysis.** These relationships are evaluated as evidence for or against our theoretical reading-acquisition functions.

10.1 Musically Trained Sample

10.1.1 Descriptive Analyses

Monolingual adult readers (n = 19; female = 15) aged 19 – 22 years (mean age = 20.53 years, SD = 0.84 years) who completed the reading battery, ABR protocol, and the extensive music-language questionnaire were considered for analysis. Descriptive statistics, presented in Table 2, were calculated for measures of reading, music-training history, and auditory processing (e.g., ABR indices). One subject did not complete the non-verbal IQ test due to experimenter error, while another did not complete the ABR protocol due to high levels of electrical noise during the recording session. Moreover, one subject did complete the ABR protocol to the 10.9 Hz presentation rates, although all other rates were completed. In cases involving these missing data, pair-wise deletion was used. Overall, participants exhibited a large degree of variability in both global reading abilities and specific reading-related subskills. For instance, the reading composite score, used to assess global reading ability, ranged from 50.45 to 80.27 percentile (mean = 64.96, SD = 8.49), while the standard scores of the *WRMT III Passage Comprehension* task, a measure of reading comprehension, ranged from 82 – 121 units (mean = 107.5, SD = 11.53). (Table 2, Figure 3.)

Moreover, participants' musical histories proved to be equally diverse: the minimum age at which participants began music training ranged from 2 – 13 years (mean year = 8.05, SD = 3.26); the total years of musical training ranged from 7 – 20 years

(mean = 11.21, SD = 3.69); the number of since years music training ranged from 0 – 3 years (mean = 0.42, SD = 0.84); and the self-reported musical proficiency on the primary instrument on a 1-to-10 Likert scale ranged from 6 – 10 (mean = 8.16, SD = 1.89). Over two thirds of participants reported instrumental training as their primary mode of musical training (n =14), while the remaining subjects reported vocal training (n = 5) as their primary mode of musical training. To assess whether the music variables covaried, Pearson's R was calculated between all measures variables and represented as a correlation matrix (Figure 4). Participants' maximum proficiency on their primary instrument correlated significantly with two other music training variables: total years of music training, $r(19) = 0.49$, $p = 0.04$, and the minimum age participants began music training, $r(19) = -0.51$, $p = 0.02$, suggesting that participants who began playing music earlier and for longer reached a higher level of musical proficiency. Additionally, total years of training was related to the minimum age music training began, $r(19) = -.89$, $p < 0.001$, suggesting that participants who played music longer started earlier.

Finally, summary statistics of the ABR indices suggested that all participants were in the normative range of ABR latencies, with wave-I latencies varying between 1 – 2 ms and wave-V latencies varying between 5 – 6 ms (Hood, 1998; Skoe & Kraus, 2013; Skoe, Krizman, Anderson, & Kraus, 2013) (Table 2, Figure 5). To assess whether participants' wave-V latencies of the ABR differed significantly from published norms (e.g., 5.69 ms from Skoe, Krizman, Anderson, et al., 2013), a one-sample t-test was performed for wave-V latencies recorded at the 31.25 Hz presentation rate, for which published norms are available. Our mean wave-V latency (31.25 Hz presentation rate) of 5.70 ms was not significantly different from the published norm of 5.69 ms, $t(17) = 0.16$, $p = 0.87$, 95% CI

[5.59, 5.80]. Nor was our mean wave-I latency (31.25 Hz presentation rate) (mean = 1.67) significantly different from our in-house norms (mean =1.66), $t(17) = 0.57$, $p = 0.58$, 95% CI [1.62, 1.721]. Finally, to assess whether the sample was in the normative range for non-verb IQ, a one-sample t-test was performed on the mean standardized *TONI* scores (non-verbal IQ). Our mean score (104.5) did not differ significantly from the standardized mean score of 100, $t(17) = 1.65$, $p = 0.12$, 95% CI [98.61, 110.23].

Table 2: Musically Trained Sample: Summary Statistics

Statistic	N	Mean	St. Dev.	Min	Max
age	19	20.526	0.841	19	22
TONI4	18	104.500	11.526	85	130
RANNumbers	19	111.000	4.922	103	122
RANLetters	19	109.895	4.943	102	117
RAS2set	19	113.632	6.103	103	125
CTOPPElision	19	10.263	1.240	7	12
CTOPPBlendingWords	19	11.737	1.408	9	13
CTOPPNonwordRepetition	19	10.421	1.774	7	14
TOWRESightWordEfficiency	19	113.105	10.974	98	130
TOWREPhonemicDecoding	19	106.000	8.609	91	123
WRMTIIIWordID	19	101.526	7.684	92	118
WRMTIIIWordAttack	19	98.632	9.154	79	112
WRMTIIIPassageComprehension	19	107.474	11.534	82	121
ReadingComp	19	64.962	8.488	50.455	80.273
L_6.9	18	1.648	0.108	1.490	1.865
L_10.9	17	1.654	0.092	1.490	1.823
L_15.4	18	1.659	0.107	1.490	1.865
L_31.25	18	1.673	0.097	1.532	1.823
L_46.5	18	1.661	0.103	1.490	1.865
L_61.5	18	1.729	0.186	1.282	2.032
V_6.9	18	5.643	0.267	5.155	6.196
V_10.9	17	5.635	0.235	5.196	6.154
V_15.4	18	5.603	0.233	5.238	6.154
V_31.25	18	5.698	0.216	5.321	6.196
V_46.5	18	5.837	0.251	5.404	6.404
V_61.5	18	5.916	0.264	5.488	6.445
RC_6.9	18	0.786	0.206	0.253	0.958
RC_10.9	17	0.828	0.149	0.355	0.972
RC_15.4	18	0.776	0.187	0.369	0.978
RC_31.25	18	0.739	0.222	0.095	0.979
RC_46.5	18	0.801	0.212	0.209	0.959
RC_61.5	18	0.677	0.310	−0.163	0.966
Minage	19	8.053	3.257	2	13
Maxtotalyears	19	11.211	3.691	7	20
Maxprof	19	8.684	1.250	6	10
Maxcurrentprof	19	8.158	1.893	2	10
YrsSinceTrain	19	0.421	0.838	0	3

Table 2. Descriptive statistics for measures of reading, music-training history, and auditory processing. Summary statistics for participants' age (years), non-verbal IQ (TONI standard scores) reading skills (RANNumbers:ReadingComp

standard scores), ABR indices (I_6.9:V_61.6 response latencies (ms); RC_6.9:RC_61.5 response consistency (correlation coefficient)), and history of musical training (Minage:YrsSinceTrain in years).

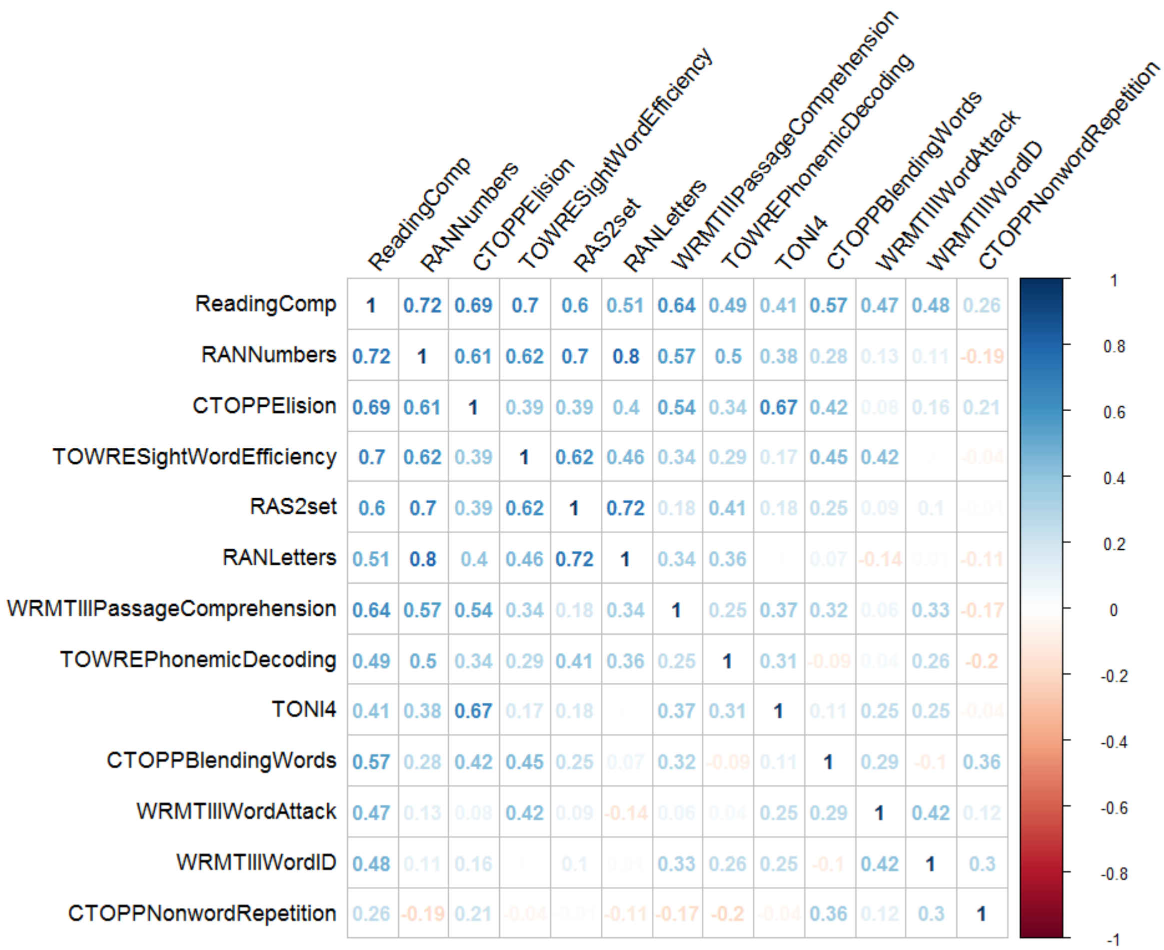

Figure 3. Correlation Matrix of Reading Composite Score and Each Reading Subtest. Investigating inter-relations between the reading composite score (e.g., ReadingComp) and the standard scores on each reading subtest (e.g., RANNumbers:CTOPPNonwordRepetition) on all subjects in the core, musically trained sample of adult readers, n = 19.

Figure 4. Correlation Matrix of Musical-Training History. Investigating relationships between participants' total year of musical training (Maxtotalyears), proficiency on their primary instrument (Maxprof), years since musical training (YrsSinceTrain), and the age at which participants began music instrument (Minage), n = 19.

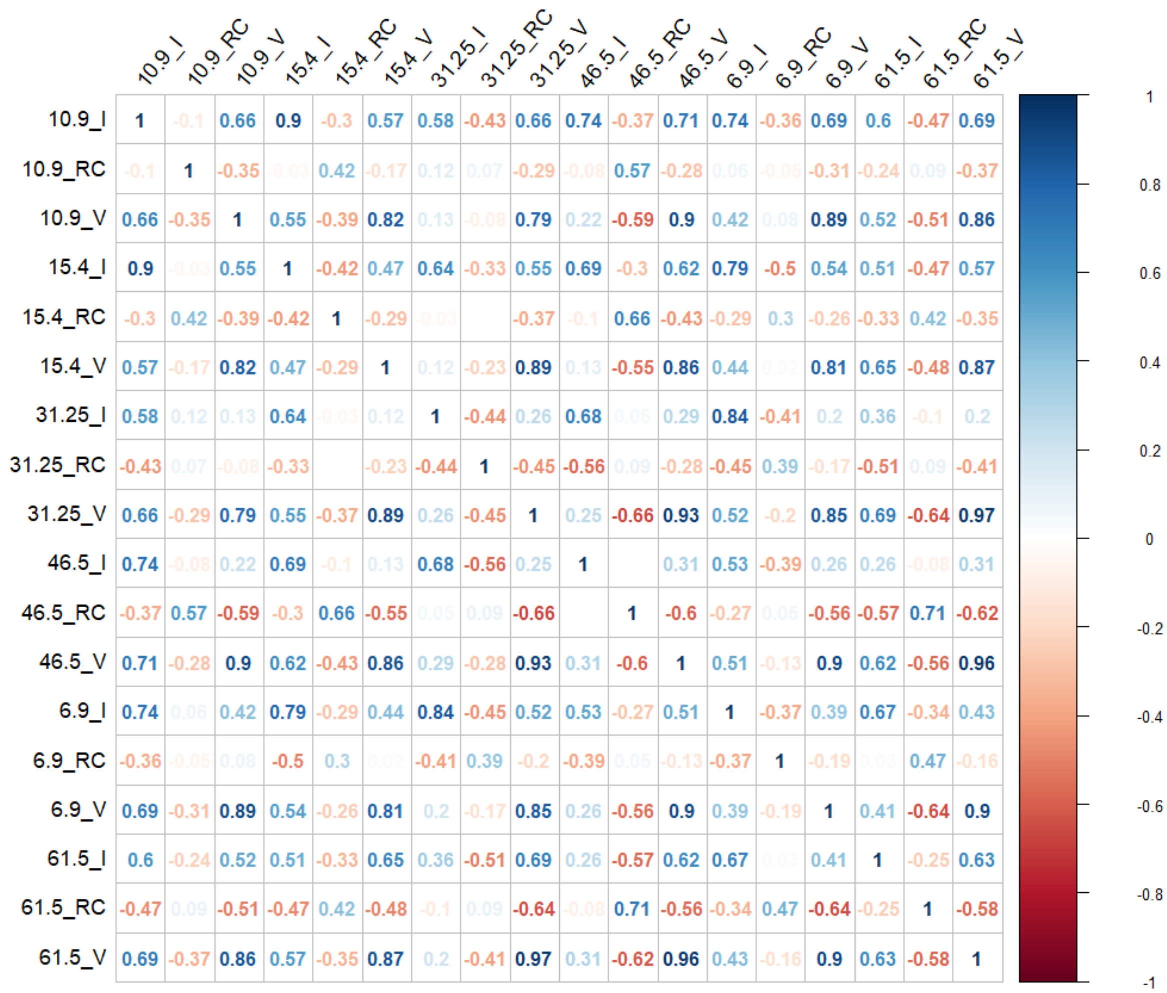

Figure 5. Correlation Matrix of the Auditory Brainstem Response Metrics. Investigating inter-relations between the ABR indices (e.g., wave-V latencies, wave-I latencies, response consistency (RC) for six presentation rates) from the core, musically trained sample of adult readers, n = 19.

10.1.2 Musically trained sample: Is music-training history related to specific reading-related skills and general reading ability?

First, we investigated relations between a history of music training and reading ability. Pearson correlations were computed between the music-training measures and the reading composite & standardized reading scores (Supplemental Tables 1A-1L). As

shown in Supplemental Table 1I & 1J, participants' maximum self-reported proficiency on their primary instrument was strongly associated with rapid naming skills: Max proficiency on participants' primary instrument and *RAN Letters*, $r(19) = 0.63$, uncorrected $p < .0001$, MPT exact $p < .0001$; Max proficiency on primary instrument and *RAN 2 SET*, $r(19) = 0.61$, uncorrected $p = .01$, MPT exact $p = .01$ (Figure 6a and 6b). For these two findings, regression diagnostics were conducted. For max proficiency and *RAN 2 SET*, no studentized residuals were > |2|, suggesting no outliers affected the relationship. For maximum proficiency on primary instrument and *RAN Letters*, one studentized residual was slightly > |2| at 2.008. Removing this observation was found to have negligible effect on the relationship, $r(18) = 0.63$, uncorrected $p < .0001$, MPT exact $p = .01$. Consequently, this observation was left in the analysis. No other significant correlations between the music-history measures, reading subtests, and reading composite score were found.

Next, several analyses were conducted to probe whether musical proficiency related to rapid naming skills beyond participants' age and non-verbal IQ. Firstly, age was not significantly related to the *RAN 2 Set* test, $r(19) = -0.26$, $p = 0.30$, nor was non-verbal IQ, $r(18) = 0.18$, $p = 0.47$. Additionally, age did not significantly relate to *RAN Letters*, $r(19) = -0.06$, $p = 0.79$, nor did participants' non-verbal IQ, $r(18) = -0.002$, $p = 0.99$. Next, to assess whether max proficiency on participants' primary instrument explained additional variance on the *RAN 2 Set* and the *RAN Letters* tasks beyond non-verbal IQ and participant age, *ad hoc* analyses were conducted. Given the small number of observations relative to the number of independent variables, partial correlations were computed instead of implementing multiple, hierarchical regression (Field, Miles, & Field,

2012). Here, partial correlations were used to assess the influence of age and non-verbal IQ on the relationship between musical proficiency and rapid naming skills, individually.

Maximum proficiency on primary musical instrument was related to the *RAN 2 Set* test, even after controlling for non-verbal IQ, $pr(18) = 0.59$, $p = 0.01$, and participants' age, $pr(18) = 0.59$, $p = 0.01$. Similarly, maximum proficiency on primary musical instrument was related to the *RAN Letters* test after controlling for non-verbal IQ, $pr(18) = 0.61$, $p < 0.01$, and participants' age, $pr(18) = 0.61$, $p < 0.01$. Together, these analyses indicate that musical proficiency is related to rapid-naming skills, even after accounting for participants' non-verbal IQ and age.

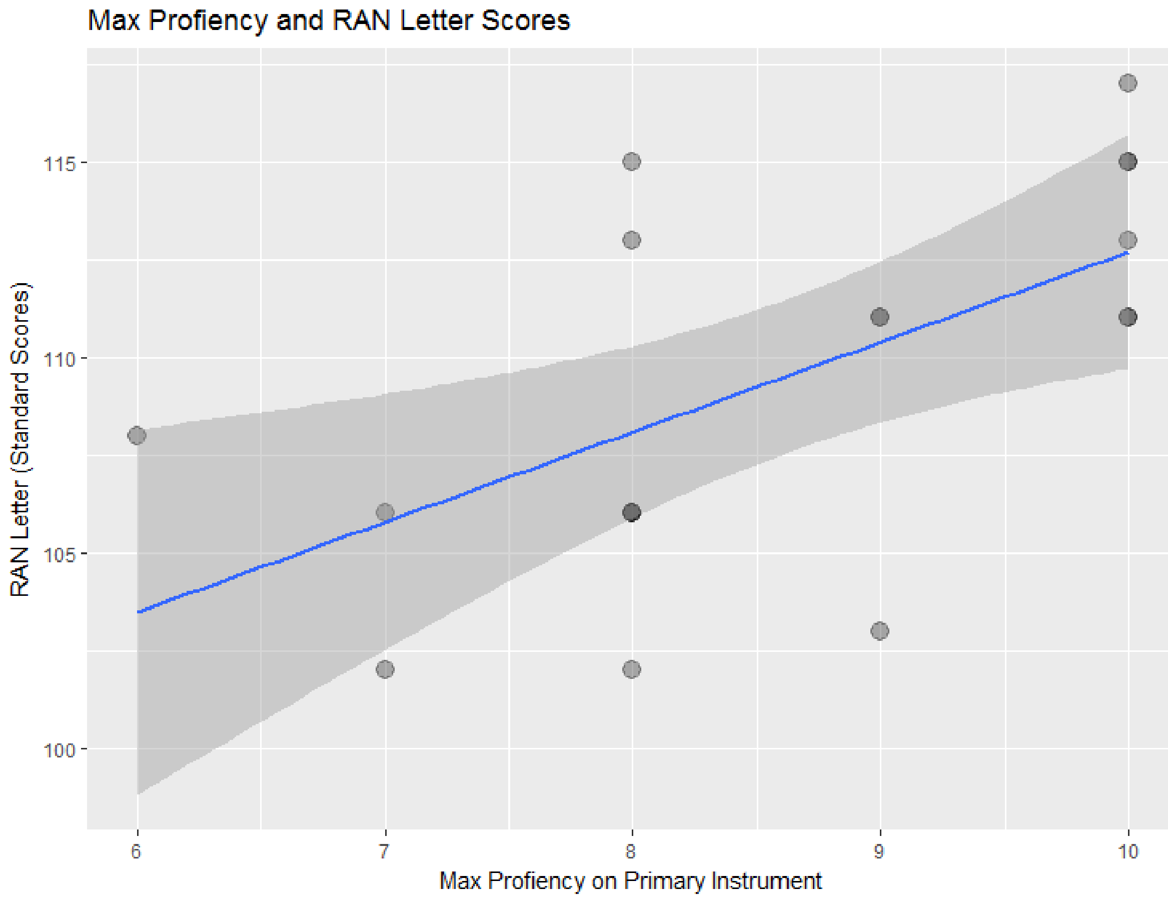

Figure 6a. **Self-Reported Maximum Proficiency Reached on Primary Instrument and Standard Scores on the RAN Letters Reading Subtest**. Adult readers, n = 19, who reported a higher mastery over their primary musical instrument performed better on the RAN Letters rapid naming task, $r(19) = 0.63$, uncorrected $p < .0001$, MPT exact $p < .0001$. While 19 observations are plotted here, some observations are overlapping.

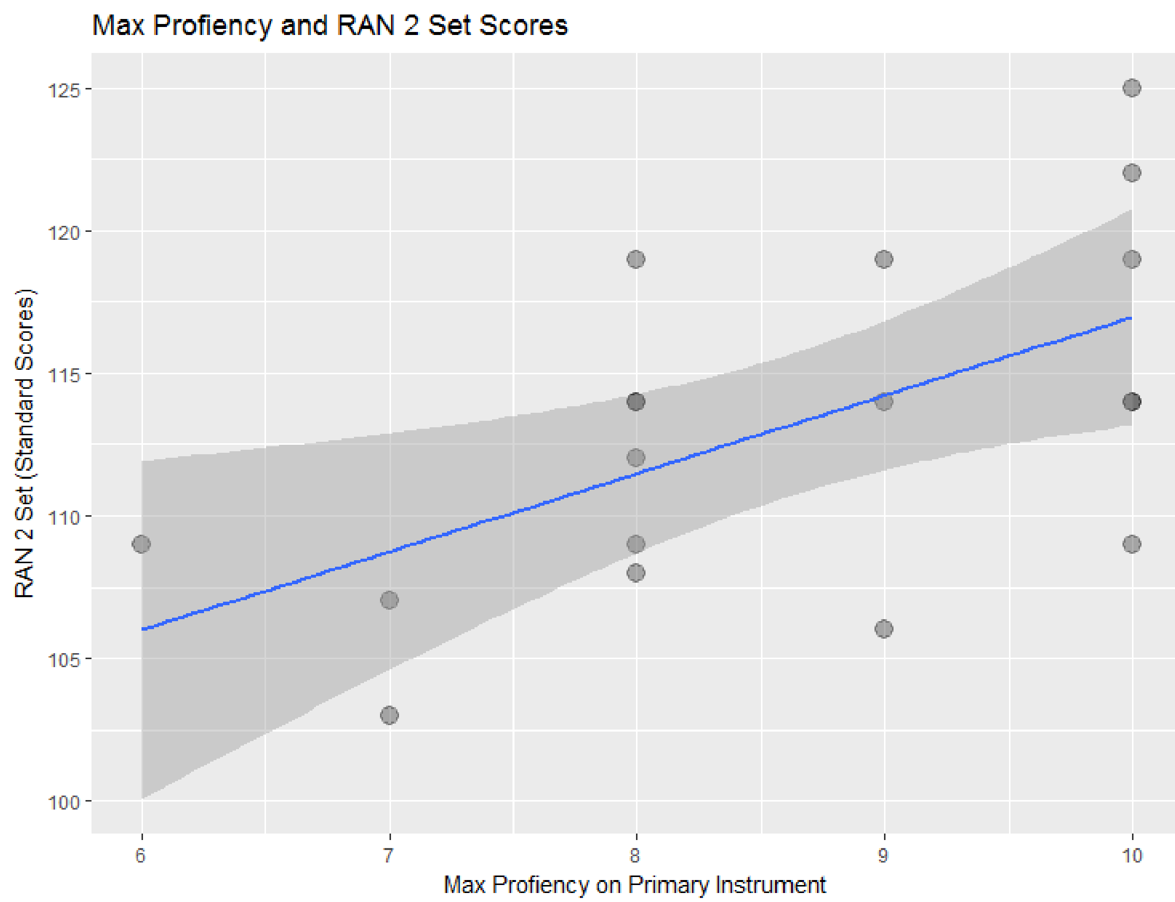

Figure 6b. Self-Reported Maximum Proficiency Reached on Primary Instrument and Standard Scores on the RAN 2Set Reading Subtest. Adult readers, n = 19, who reported a higher mastery over their primary musical instrument performed better on the *RAN 2 Set* rapid naming task, *r*(19) = 0.61, uncorrected p = .01, MPT exact p = .01. While 19 observations are plotted here, some observations are overlapping.

10.1.3 Musically trained sample: Is auditory processing related to specific reading-related skills and general reading ability?

Second, we investigated relations between auditory processing and reading ability. Pearson correlations were computed between the ABR measures (e.g., Wave-I latencies, Wave-V latencies, and response consistency measure for each presentation rate), the reading composite and standardized reading scores (Supplemental Tables 2A-2L). While

no ABR measures were significantly related to the reading composite score (i.e., global reading ability), ABR measures were found to be significantly related to a number of the reading subtests: *RAN Numbers* and RC (46.5 Hz), *r*(18), uncorrected p = 0.02, MPT exact p = 0.25; *RAN Letters* and RC (46.5 Hz), *r*(18), uncorrected p = 0.04, MPT exact p < 0.36; *CTOPP Blending Words* and RC (46.5 Hz), *r*(18) = 0.49, uncorrected p = 0.04, MPT exact p = 0.34, RC (61.5 Hz), *r*(18) = 0.48, uncorrected p = 0.04, MPT exact p = 0.35; *CTOPP Elision* and wave-I latencies (46.5 Hz), *r*(18) = 0.57, uncorrected p = 0.01, MPT exact p = 0.18, RC (31.25 Hz), *r*(18) = -0.48, uncorrected p = 0.05, MPT exact p = 0.4; *WRMT-III Passage Comprehension* and wave-I latencies (6.9 Hz), *r*(18) = 0.51, uncorrected p = 0.03, MPT exact p = 0.25, wave-I latencies (10.9 Hz), *r*(18) = 0.52, uncorrected p = 0.03, MPT exact p = 0.22, wave-I latencies (15.4 Hz), *r*(18) = 0.51, uncorrected p = 0.03, MPT exact p = 0.25, wave-I latencies (31.25 Hz), *r*(18) = 0.67, uncorrected p < 0.0001, MPT exact p = 0.04, wave-I latencies (46.5 Hz), *r*(18) = .58, uncorrected p = 0.01, MPT exact p = 0.14, wave-V latencies (6.9 Hz), *r*(18) = 0.51, uncorrected p = 0.03, MPT exact p = 0.24.

However, after controlling for multiple comparisons using the MPT test for correlations, only one robust relationship emerged: Wave-I latencies (31.25 Hz) and performance on the *WRMTIII Passage Comprehension* test, *r*(18) = 0.67, uncorrected p < 0.001, MPT exact p = 0.04 (Figure 7). For this finding, regression diagnostics were conducted. One studentized residual was slightly > |2| at -2.06. Removing this observation was found to have negligible effect on the relationship, *r*(17) = 0.65, uncorrected p < .0001, MPT exact p = .04. Consequently, this observation was left in the analysis.

Next, participant age, non-verbal IQ, and the music-training measures were considered as potential confounding variables on the relationship between wave-I latencies and the *WRMTIII Passage Comprehension* test. Age was not significantly related to performance on the *WRMTIII Passage Comprehension* test, $r(19) = -0.06$, $p = 0.81$, 95% CI [-0.50, 0.41], nor was non-verbal IQ, $r(18) = 0.37$, $p = .13$, 95% CI [-0.12, 0.71]. In addition, musical-training history was also not related to reading comprehension skills: minimum age of music training *WRMTIII Passage Comprehension* test, $r(19) = -0.10$, $p = 0.67$, 95% CI [-0.53, 0.37]; maximum proficiency on primary instrument and performance on the *WRMTIII Passage Comprehension* test, $r(19) = 0.25$, $p = 0.30$, 95% CI [-0.23, 0.63]; total years of musical training and performance on the *WRMTIII Passage Comprehension* test, $r(19) = -0.04$, $p = 0.86$, 95% CI [-0.49, 0.42]; and years since training and performance on the *WRMTIII Passage Comprehension* test, $r(19) = 0.27$, $p = 0.27$, 95% CI [-.021, 0.64]. Unfortunately, given the small number of males in our sample ($n = 4$), we were not able to control for participant sex, a potential confounding variable, as sex differences have been found in the ABR (Hood, 1998).

Again, as a consequence of the small number of observations relative to the number of independent variables, partial correlations were computed to control for known confounding variables, instead of implementing multiple, hierarchical regression (Field et al., 2012). Here, partial correlations were used to assess the influence of age, non-verbal IQ, and musical-training history on the relationship between wave-I latencies (31.25 Hz) and reading comprehension skills, individually. The relationship between wave-I latencies (31.25 Hz) and reading comprehension skills remained significant, even after accounting for participants' age, $pr(18) = 0.68$, $p < 0.01$, non-verbal IQ, $pr(17) = 0.68$, $p <0.01$, age

musical training began, *pr*(18) = 0.68, p <0.01, total years of musical training, *pr*(18) = 0.67, p < 0.01, max proficiency obtained on primary musical instrument, *pr*(18) = 0.67, p <0.01, and the years since music training, *pr*(18) = 0.65, p <0.01. Together, these analyses suggest that peripheral auditory processing is related to reading comprehension skills, even after considering non-verbal IQ (TONI scores), participants' age, and musical-training history.

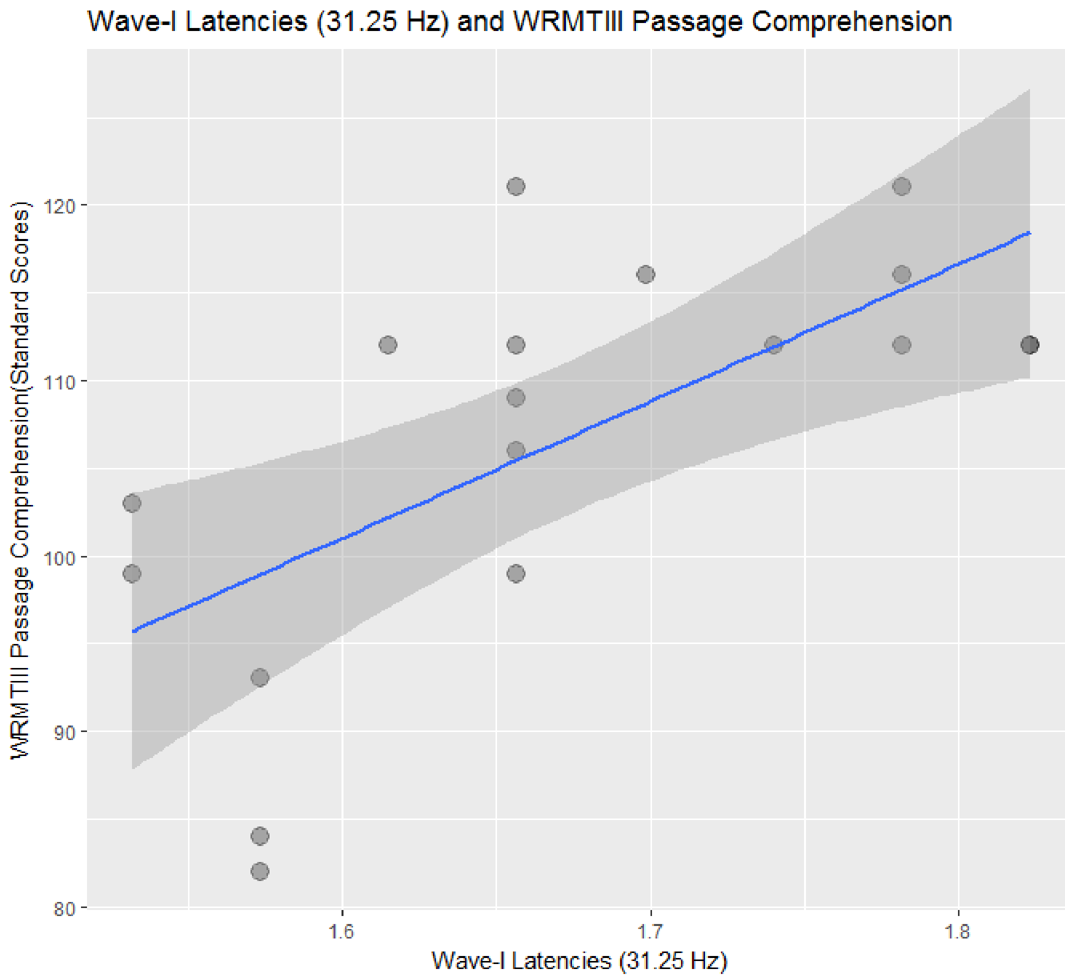

Figure 7. Wave-I Latencies (31.25 Hz) and Standard Scores on the WRMTIII Passage Comprehension Reading Subtest. Adult readers, n = 18, with longer wave-I latencies (31.25 Hz) performed better on the *WRMTIII Passage Comprehension*, *r*(18) = 0.67, uncorrected p < 0.001, MPT exact p = .04. While 18 observations are plotted here, some observations are overlapping.

10.1.4 Musically trained sample: Is music-training history related to auditory processing?

Finally, to investigate relations between auditory processing and a history of music training, Pearson correlations were computed between the music-history measures and the ABR indices (e.g., wave-I latencies, Wave-V latencies, and response consistency measure for each presentation rate) (Supplemental Tables 3A–3Q). No significant correlations were found.

10.2 Expanded Data Set

While the above findings were derived from a small sample (n = 19) that was compiled specifically to test the predictions of our theoretical reading-acquisition functions, the small sample size renders the data difficult to generalize from. As a follow-up analysis, we integrated our small data set with a much larger data set, creating a total n = 120. Summary statistics are presented in Table 3. These additional data, while not deliberately collected for the present study, enabled us to evaluate the theoretical reading-acquisition functions on a much larger scale. Given the imperfections of the data set, confounding variables, such all music-training-history variables or non-verbal IQ, at times, cannot be fully ruled out.

Table 3: Expanded Data Set: Summary Statistics

Statistic	N	Mean	St. Dev.	Min	Max
age	94	20.532	1.927	18	30
TONI4	50	98.860	10.604	80	130
RANNumbers	51	111.824	4.646	102	122
RANLetters	51	110.000	4.133	102	117
RAS2set	51	113.490	5.471	103	125
CTOPPElision	51	10.176	1.797	2	12
CTOPPBlendingWords	51	11.725	1.756	8	14
CTOPPNonwordRepetition	51	10.412	2.032	5	14
TOWRESightWordEfficiency	51	110.137	19.213	1	130
TOWREPhonemicDecoding	51	108.471	9.969	90	130
WRMTIIIWordID	51	105.647	10.927	82	129
WRMTIIIWordAttack	51	100.275	10.938	75	121
WRMTIIIPassageComprehension	51	109.431	12.311	66	123
ReadingComp	51	66.799	11.077	41.727	84.909
L_6.9	118	1.648	0.102	1.449	1.907
L_10.9	117	1.656	0.112	1.407	1.950
L_15.4	118	1.669	0.117	1.449	2.156
L_31.25	118	1.679	0.124	1.365	2.030
L_46.5	118	1.676	0.139	0.991	2.160
L_61.5	118	1.722	0.142	1.282	2.160
V_6.9	118	5.614	0.250	4.821	6.196
V_10.9	117	5.621	0.238	5.030	6.237
V_15.4	118	5.615	0.225	5.030	6.154
V_31.25	118	5.697	0.217	5.150	6.240
V_46.5	118	5.831	0.220	5.240	6.450
V_61.5	118	5.927	0.233	5.150	6.445
RC_6.9	118	0.817	0.172	−0.045	1.000
RC_10.9	117	0.783	0.220	−0.140	1.000
RC_15.4	118	0.785	0.223	−0.223	1.000
RC_31.25	118	0.739	0.196	0.082	1.000
RC_46.5	118	0.808	0.188	−0.142	1.000
RC_61.5	118	0.726	0.246	−0.163	1.000
Minage	86	9.163	2.954	2	18
Maxtotalyears	93	6.952	4.878	0.000	20.000
Maxprof	83	6.349	3.195	0	10
Maxcurrentprof	82	5.305	3.438	0	10
YrsSinceTrain	58	4.069	3.995	0	17

Table 3. Summary statistics for the expanded data set. Descriptive statistics for measures of reading, music-training history, and auditory processing. Summary statistics for participants' age (years), non-verbal IQ (TONI standard scores) reading

skills (RANNumbers:ReadingComp standard scores), ABR indices (I_6.9:V_61.6 response latencies (ms); RC_6.9:RC_61.5 response consistency (correlation coefficient)), and history of musical training (Minage:YrsSinceTrain in years).

10.2.1 Expanded data set: Is music-training history related to specific reading-related skills and general reading ability?

Monolingual adult readers (n = 33) aged 18 – 30 years (mean age = 20.97 years, SD = 2.45 years) who completed the reading battery and the music-language questionnaire were considered for analysis. Out of this sample, only 19 subjects had completed the extensive music-language questionnaire, while the remaining 15 had completed the abridged version or no questionnaire at all. The inclusion of these data expanded our sample size only on the following music-training variables: maximum total years of musical training, minimum age of musical training, and years since training. Consequently, no new participants were added to the maximum proficiency on primary instrument variable. To assess whether the entire sample was in the normative range for non-verb IQ, a one-sample t-test was performed on the mean standardized TONI score (non-verbal IQ). Our mean score (100.53) did not differ significantly from the standardized mean score of 100, $t(31) = 0.28$, $p = 0.78$, 95% CI [96.61, 104.45]. To investigate relations between a history of music training and reading ability, Pearson correlations were computed between the music-training measures and the reading composite & standardized reading scores (Supplemental Tables 4A-4I). While the previously reported relationships between max proficiency and rapid naming (e.g., *RAN 2 Set, RAN* Letters) remained significant (as no additional subjects were added to this particular relationship), even with the inclusion of these participants, no additional findings emerged.

10.2.2 Expanded data set: Is auditory processing related to specific reading-related skills and general reading ability?

Monolingual adult subjects (n = 50) aged 18 – 30 years (mean age = 20.82 years, SD = 2.24 years) that were run through both the reading battery and ABR testing protocol were included in the analysis. Over half of this sample completed either the abridged or extensive music questionnaire, n = 33. For these subjects, the minimum age at which music training began ranged from 2 – 13 years (mean year = 8.49, SD = 2.94); the total years of musical training ranged from 3 – 20 years (mean = 9.26, SD = 3.99); the number of since years music training ranged from 0 – 17 years (mean = 2.51, SD = 4.11); and the self-reported musical proficiency on the primary instrument on a 1-to-10 Likert scale ranged from 6 – 10 (mean = 8.68, SD =1.25). To assess whether the sample was in the normative range for non-verb IQ, a one-sample t-test was performed on the mean standardized TONI score (non-verbal IQ). Our mean score (98.86) did not differ significantly from the standardized mean score of 100, $t(49) = -0.76$, $p = 0.45$, 95% CI [95.84, 101.87].

To investigate relations between auditory processing and reading ability, Pearson correlations were computed between the ABR measures (e.g., Wave-I latencies, Wave-V latencies, and response consistency measure for each presentation rate), the reading composite, and standardized reading scores (Supplemental Tables 5A-5K). Consistent with Skoe, Brody, & Theodore (2017), wave-V latencies recorded at the higher stimulus presentation rates (e.g., 31.25, 46.5, 61.5 Hz) were significantly correlated with the

reading composite score: 31.25 Hz, *r*(50) = 0.34, uncorrected p = 0.02; 46.5 Hz, *r*(50) = 0.30, uncorrected p = 0.03; 61.5 Hz, *r*(50) = 0.33, uncorrected p = 0.02. However, it should be noted that after controlling for family-wise error using the MPT for correlations, these significant correlations were rendered insignificant. Moreover, wave-I latencies were not found, at any presentation rate, to be significantly correlated with the reading composite score.

Next, to elucidate the relationship between auditory processing and specific reading subskills, Pearson correlations were computed between ABR measures and each reading-related test. ABR measures were found to be significantly related to a number of the reading subtests: *CTOPP Blending Words*: wave-I latencies (31.25 Hz) *r*(50) = 0.26, uncorrected p = 0.04., wave-I latencies (46.5 Hz), *r*(50) = 0.32, uncorrected p = 0.02., wave-V latencies (15.4 Hz), *r*(50) = 0.29, uncorrected p = 0.04. *CTOPP Non-word Repetition*, response consistency (46.5 Hz), *r*(50) = 0.29, uncorrected p = 0.04, wave-V latencies (10.9 Hz), *r*(49) 0.33, uncorrected p = 0.02, wave-V latencies, *r*(50) = 0.30, uncorrected p = 0.03, wave-V latencies (31.25 Hz), *r*(50) = 0.43, uncorrected p < 0.001, wave-V latency (46.5 Hz), *r*(50) = 0.33, uncorrected p = 0.02, wave-V latency (61.5 Hz), r(50) = 0.29, uncorrected p = 0.04. *WRMTIII Passage Comprehension*, wave-I latencies (15.4 Hz), *r*(50) = 0.31, uncorrected p = 0.03, wave-I latencies (31.25 Hz), *r*(50) = 0.34, uncorrected p = 0.01, wave-I latencies (46.5 Hz), *r*(50) = 0.35, uncorrected p = 0.01, response consistency (31.25 Hz), *r*(50) = -0.29, uncorrected p = 0.04, wave-V latencies (61.5 Hz), *r*(50) = 0.31, uncorrected p = 0.03; and *WRMTIII Word ID*, wave-Vs latencies (31.25 Hz), *r*(50) = 0.28, uncorrected p = 0.05, wave-V latencies (46.5 Hz), *r*(50) = 0.31, uncorrected p = 0.03, wave-V latencies (61.5 Hz), *r*(50) = 0.32, uncorrected p = 0.03 (see

Tables Q2b). However, many of these relationships were rendered insignificant after, again, correcting for multiple comparisons, with only one significant correlation remaining: Wave-V latencies (31.25 Hz presentation rate) were significantly correlated to the *CTOPP Non-Word Repetition* task, a measure of phonological decoding, $r(50) = 0.43$, uncorrected p-value < .001, MPT exact p-value = 0.03 (Figure 8). To test for outliers in this relationship, regression diagnostics were performed. Observations with a studentized residual > |2| were removed from the analysis. Two observations were found to have -2.58 and -2.08. Even with these two observations removed, the relationship between wave-V latencies (32.5 Hz) and the *CTOPP Non-Word Repetition* task remained moderately and significantly related, $r(48) = 0.40$, uncorrected p-value < .001, MPT exact p-value = 0.05. Given that the studentized residuals were close to the |2| threshold and had a negligible impact on the relationship, the two observation were preserved for additional analyses.

Next, several analyses were conducted to probe whether wave-V latencies related to phonological decoding skills beyond participants' age, participants' sex, and non-verbal IQ. Age was found to be significantly related to the *CTOPP Non-Word Repetition* task, $r(49) = -.30$, uncorrected p = 0.035, suggesting that younger participants performed better than older participants. To investigate whether auditory processing explained additional variance in phonological decoding skills beyond non-verbal IQ, participant age, and participant sex, hierarchal multiple regression was used. In step one, the standard scores of *CTOPP Non-Word Repetition* test were regressed onto the standard *TONI* scores (non-verbal IQ), participant age, and participant sex. In step two, the standard scores of *CTOPP Non-Word Repetition* test were regressed onto the standardized *TONI* scores (non-verbal IQ), participant age, participant sex, and wave-V latencies (31.25 Hz). The

model at step one was not a significant fit, *F(3, 45)* = 2.27, p = 0.09, but explained 7-13% of the variance, R^2= 0.13, adj. R^2 = 0.07. As expected, participant's age was found to be a significant predictor, b = -0.29, β = -0.32, t = -2.28, p = 0.03, 95% CI [-0.55, -0.03]. In step two, participant's age, participant sex, non-verbal IQ, and wave-V latencies (31.25 Hz) were entered into the model. Overall, the model was a significant fit, *F(4, 44)* = 4.303, p < 0.01, explaining 22-28% of the variance, R^2= 0.28, adj. R^2 = 0.22. Age was, again, found to be a significant predictor, b = -0.25, β = -0.27, t = -2.15, p = 0.04, 95% CI [-0.49, -0.02]. Moreover, wave-V latencies were also found to be a significant predictor, b = 3.47, β = 0.42, t = 3.03, p < 0.01, 95% CI [1.16, 5.77]. Importantly, the inclusion of wave-V latencies (3.25 Hz) explained an additional ~15% of the variance, ΔR^2= 0.149, a difference which was found to be significant, *F(1, 44)* = 9.16, p < 0.01. Thus, the regression analyses indicate that wave-V latencies are related to phonological decoding, even after account for participants' non-verbal IQ, age, and sex.

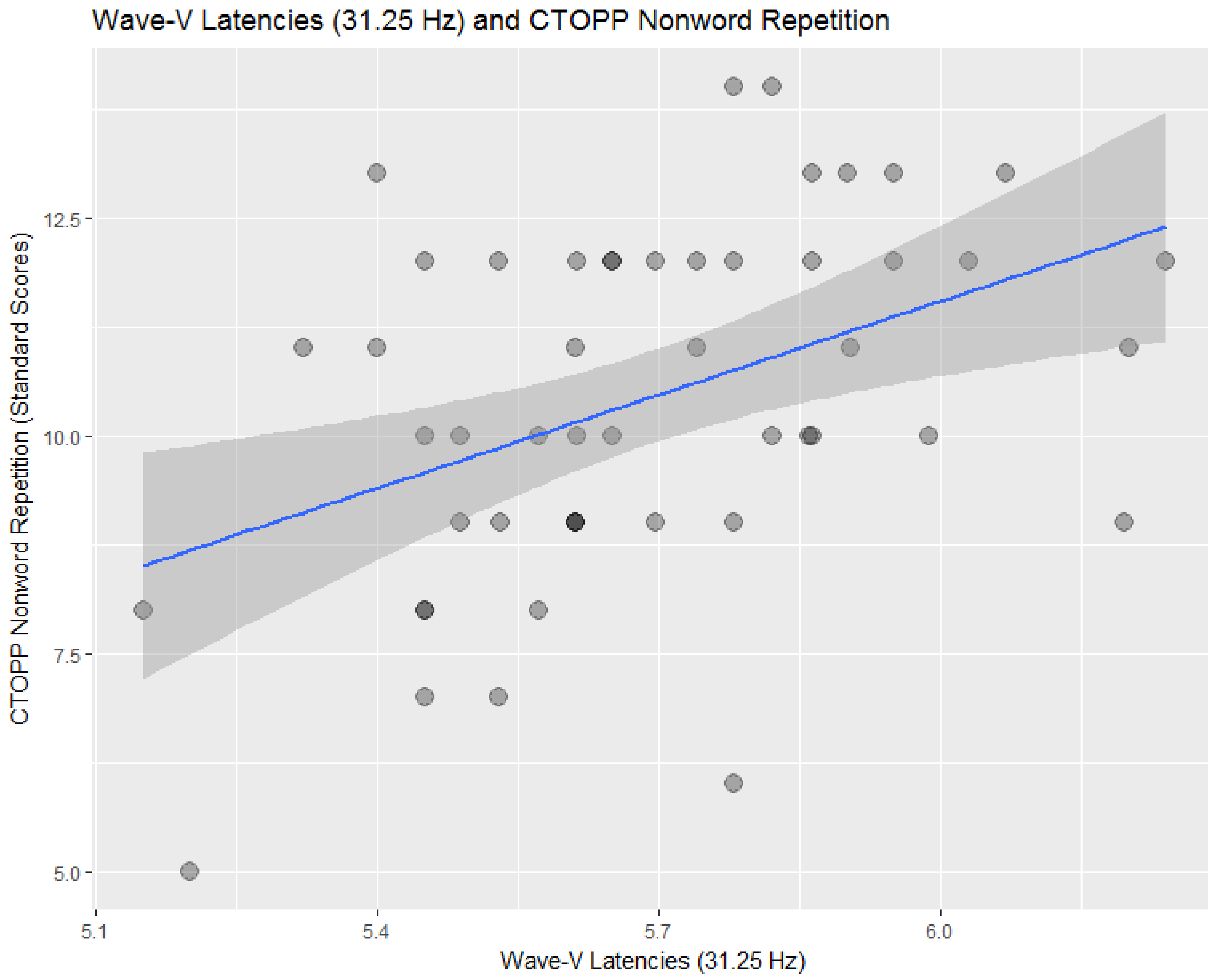

Figure 8. Wave-V Latencies (31.25 Hz) and Standard Scores on the CTOPP Nonword Repetition Reading Subtest. Pearson's correlation between wave-V latencies (31.25 Hz presentation rate) and standard scores for the *CTOPP Non-Word Repetition* test, $r(50) = 0.43$, uncorrected p-value < 0.001, MPT exact p-value = 0.03. Adult readers with longer latencies, indicative of a more developmentally mature auditory system, had stronger phonological decoding abilities. While 50 observations are plotted here, some observations are overlapping.

10.2.3 Expanded data set: Is music training history related to auditory processing?

Monolingual adult subjects (n = 86) aged 18 – 30 years (mean age = 20.6 years, SD = 2.03 years) that completed the ABR testing protocol and either the extensive or abridge music-language questionnaire were included in the analysis. For these subjects, the minimum age at which music training began (n = 86) ranged from 2 – 18 years (mean

year = 9.16, SD = 2.95); the total years of musical training (n = 80) ranged from 1 – 20 years (mean = 7.91, SD = 4.43); the number of since years music training (n = 58) ranged from 0 – 17 years (mean = 4.07, SD = 4.00); and the self-reported musical proficiency (n = 71) on the primary instrument on a 1-to-10 Likert scale ranged from 0 – 10 (mean = 6.13, SD = 2.93). Only 33 of these subjects were run through the *TONI* non-verbal IQ test, enabling us, in part, to assess whether the sample deviated significantly from the standardized non-verbal IQ score (100), $t(32) = 0.28$, $p = 0.78$, 95% CI = 96.61 - 104.45.

To investigate relations between auditory processing and a history of music training, Pearson correlations were computed between the music-history measures and the ABR indices (e.g., wave-I latencies, Wave-V latencies, and response consistency measure for each presentation rate). As shown in Supplemental Table 6A – 6R, more recent musical training was associated with greater response consistency: Years since training and RC_46.5, $r(55) = -0.268$, uncorrected $p = 0.04$, MPT exact $p = .09$. However, this relationship was no longer significant after controlling from multiple comparisons. No other significant correlations were found.

10.3 Summary of Robust Relationships

To conclude, a number of robust relationships emerged between music training, neural indices of auditory processing (ABR), and specific reading subskills (e.g., rapid naming, phonological decoding, and reading comprehension.) These findings are summarized below.

Summary of Robust Relationships

Sample	IV	DV	N	R	P	MPT Exact P
Musically Trained	Max proficiency	RAN Letters	19	.63	<.0001	<.0001
Musically Trained	Max proficiency	RAN 2 Set	19	.61	.01	.01
Musically Trained	Wave-I latencies (31.25 Hz)	WRMTIII Passage Comprehension	18	.67	<.001	.04
Expanded Data Set	Wave-V latencies (31.25 Hz)	CTOPP Non-Word Repetition	50	.43	<.001	.03

Table 4. Summary of Robust Relationships. Above, a table summarizing robust relationships between music-training history, ABR indices, and reading subtests that emerged after accounting for the FWER. Participant's self-reported maximum proficiency on their primary instrument was related to rapid naming skills (e.g., RAN Letters, RAN 2 Set). Additionally, ABR indices related to the developmental status of the peripheral and central portions of the subcortical auditory system (i.e., response latencies) were related to reading comprehension (e.g., WRMT-III Passage Comprehension) and phonological decoding skills (e.g., CTOPP Non-Word Repetition), respectively. These relationships

were only found for temporal processing at one specific, phonemic rate (31.25 Hz), suggesting that the capacity of the auditory system to process information on this timescale is related to skills that underlie reading, even into adulthood. Moreover, these relationships persisted when age, sex, and non-verbal IQ were controlled for.

11 DISCUSSION

The present series of analyses tested the hypothesis that music training confers an overall benefit to the development of reading and reading-related skills, enhancements that persist into adult life. Here, two theoretical reading-acquisition functions were proposed: one predicting that music training enhances overall reading ability—with the primary assumption that more musical training is associated with stronger overall reading ability. The other suggesting that musical training only affects the rate of reading acquisition without leading to an overall increase in reading abilities once adulthood is reached (i.e., less musically trained readers catch up to more experienced musically trained peers during adolescence or adulthood). Two samples were analyzed: one sample (n = 19) of adult readers with rich musical backgrounds (i.e., the “musically trained sample”), and a larger sample (n = 120) with adult readers who participated in an ABR protocol, reading protocol, or both (i.e., “the expanded data set”). In the smaller, musically trained, core sample, our analyses found two robust relationships between music-training history, reading skills, and electrophysiological measures of auditory processing that support a soft position of the first theoretical reading-acquisition function: namely, that music training may produce long-term benefits on certain skills that underlie reading. Firstly, adult musicians’ proficiency on their primary instrument was related to rapid naming skills, even after controlling for non-verbal IQ and age. Rapid naming is fundamental subskill of reading that is highly predictive of children’s future reading outcomes (Manis, Doi, & Bhadha, 2000; Manis,

Seidenberg, & Doi, 1999; Torgesen et al., 1997). Why might music training proficiency relate to rapid naming? While rapid naming remains a poorly understood skill, reading theorists believe it either reflects speed of cognitive processing or phonological retrieval (Torgesen et al., 1994, 1997; Wagner et al., 1993). Here, I offer a third interpretation that extends beyond the phonological-retrieval interpretation: rapid naming is a form of symbolic decoding. The three rapid naming tests employed in the present studies require participants to quickly read aloud single letters or digits – a process that involves the real-time decoding of visual, symbolic representations into their auditory form. Similarly, formal music training often requires training in sight-reading, a skill that involves decoding musical notation into their correct auditory forms (e.g., producing a musical note or chord on an instrument or with the voice). I speculate that music instruction trains up this ability to rapidly decode symbolic information and generate a motor plan to produce a sound (e.g., an utterance, or a musical note). This skill may ultimately be related to the musical proficiency measure, with more proficient musicians having stronger music-notation-reading skills. (In support of this interpretation, we have begun to explore the comprehensive musical histories of the 19 musically trained participants. Out of the participants so far reviewed, 100% reported the ability to read music, n = 7). This view of rapid naming is similar to that of Bowers, Golden, Kennedy, & Young (1994) and Wolf, Bowers, & Biddle (2000): these authors argue that naming-speed is also related to orthographic processing, not solely phonological access or retrieval. Additional support for this interpretation comes from the child-development literature. For instance, Moreno et al. (2011) found that children who received 20 days of music training performed better on a visual-auditory learning task relative to children

who participated in visual arts training, a benefit the authors believe reflected enhanced word-to-symbol mapping.

While I argue that this finding might support a soft view of the first theoretical reading-acquisition function, it should be noted that the musical proficiency variable conveys no developmental information: that is, it is unclear *when* in development peak proficiency was obtained for the musically trained in our sample. However, in this sample, musical proficiency was negatively related to minimum age of music training and positively related to total years of training, suggesting that earlier and more music training is associated with higher musical proficiency. (For our music measures that did tap development more directly (e.g., minimum age beginning musical training), no relationships between rapid naming skills were found. This might be a consequence of low statistical power.) Future work could address this limitation more directly by assessing at what age peak proficiency was obtained. Finally, future work could address experimentally whether "reading" in one domain – music or language – transfers over to the other. In addition, research could also assess whether improvement in sight-reading relates to gains in rapid-naming skills.

Another possible interpretation of the relationship between musical expertise and rapid-naming ability is that music training enhances auditory-motor synchronization (i.e., timing skills), which, then, trains up rapid-naming skills. Indeed, in one study, better rapid naming skills were found to be related to beat entrainment in children (Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014). However, other studies found no association between rapid naming skills and formal music training in children and adolescents (Rauscher & Hinton, 2012; Tierney, Krizman, & Kraus, 2015)

Secondly, peripheral auditory processing was found to be related to reading comprehension. Specifically, wave-I latencies (31.25 Hz) were found to be positively correlated with performance on the *WRMTIII Passage Comprehension* test. While developmental data on wave-I latencies is scarce, similar to longer wave-V latencies, I speculate that perhaps longer wave-I latencies are indicative of a more mature peripheral auditory system. Thus, this association suggests that adult readers with more developmentally mature peripheral auditory systems have better reading-comprehension skills. (Another possible interpretation is that longer wave-I latencies reflect noise-induced damage to the peripheral auditory structures resulting from musical training. However, our sample did not different significantly from published wave-I norms for this age range.) Moreover, this relationship only emerged for processing rates pertaining to phonemic structure in speech. Why might peripheral auditory processing at phonemic rates be related to high-level reading skills, such as comprehension? Several authors have proposed that robust auditory encoding facilitates sound-to-meaning mapping (Friel-Patti & Finitzo, 1990; Hornickel & Kraus, 2013). This view might explain why low-level auditory processing could be related to high-level reading skills involving meaning. However, there is a paucity of research investigating low-level peripheral neural correlates of auditory processing with reading comprehension. Some evidence, though, indirectly links the development of the peripheral auditory system with the development of reading-comprehension skills: One study found that children who received cochlear implants (CI) had better reading-comprehension skills, relative to deaf readers who did not. However, the children with

CIs had poorer comprehension skills relative to hearing children (Vermeulen, van Bon, Schreuder, Knoors, & Snik, 2007).

In the smaller, core sample, a history of music training and auditory processing were independently related to reading ability (e.g., rapid naming, reading comprehension). However, there was no evidence that musical training was associated with auditory processing, as assessed by the various indices of the ABR. This is perhaps perplexing, given the breadth of evidence that suggests otherwise (Skoe & Kraus, 2012). Why might music training relate to reading-related skills, but not to neural indices of auditory processing? While here we employed the click-evoked ABR, previous work primarily used the speech-evoked FFR. It is possible that the click stimulus is not a sensitive measure enough to track relationships between musical-training history and auditory processing. Additionally, it is possible that, in this sample, the pathway through which musical training bolstered reading skills was not through enhancing low-level auditory processing, but through higher level cognitive abilities, such as working memory or attention. While our study did not use tests to probe these abilities in our participants, previous work has shown that they are related to a history of musical training and music perception (Bigand, Delbé, Poulin-Charronnat, Leman, & Tillmann, 2014; Kraus, Strait, & Parbery-Clark, 2012; Parbery-Clark, Skoe, Lam, & Kraus, 2009).

While we exercise caution in interpreting the remaining significant correlations reported with uncorrected probability values, there were a number of findings that warrant discussion and future research. The consistency of subcortical neural responses (RC at 46.5 Hz presentation) was related to both rapid naming skills and phonological awareness, suggesting that the ability of the auditory system to respond to

rapid auditory information at a phonemic rate corresponds to phonological and rapid-naming behavior. Moreover, wave-I latencies recorded to stimuli across the phonemic and syllabic rates were related to reading comprehension. Considered together, this may indicate that the anatomical region of auditory processing matters more than the timescale of auditory processing. Finally, wave-V latencies (6.9 Hz) at a syllabic rate were also related to reading comprehension.

When the analysis was expanded to include a larger sample, an additional robust finding emerged. Central auditory processing was found to be related to phonological decoding skills, even after controlling for non-verbal IQ and age. (However, we were unable to control for a history of music training in this particular analysis.) Specifically, wave-V latencies of the ABR recorded at a phonemic rate (31.25 Hz) were found to be positively correlated with performance on the *CTOPP Non-Word Repetition* task. This positive association (i.e., longer latencies in this age range) suggests that adult readers with more developmentally mature central auditory systems have better phonological decoding skills. Why might central auditory processing of auditory information on a phonemic timescale be related to phonological decoding? Given that the phonemic unit is thought to be the basis of phonological knowledge (Poeppel, 2003), one possibility is that this relationship reflects phonological access – the ability to quickly retrieve phonological representations during reading and map them to orthographic representations. While this is a possible interpretation, other subcortical structures, such as the arcuate fasciculus, have been implicated in phonological access (Boets et al., 2013). Of relevance, the morphology of the arcuate fasciculus is related to musical-training history (Halwani, Loui, Rüber, & Schlaug, 2011), suggesting that music training

could enhance phonological access by inducing plasticity in the arcuate fasciculus. Future work could assess the relationship between the arcuate fasciculus, the ABR, musical training, and reading-related skills. Another possible interpretation is the quality of the phonological representations themselves: a more robust auditory system—perhaps a more developmentally mature auditory system—might respond to speech in a more consistent way, engendering less ambiguous phonological representations. (In support of this conclusion, one measure of neural response consistency, recorded at a phonemic rate (46.5 Hz), was significantly related to phonological decoding skills, but not after calculating the MPT exact p-value.) Interestingly though, response consistency (46.5 Hz) and wave-V latencies (31.25 Hz) were not significantly related). However, the acquisition of phonological representations is thought to occur earlier in development, thus suggesting this finding may reflect a residual relationship.

Yet again, there were a number of significant findings that emerged from the uncorrected probability values that are worth discussing. Firstly, central auditory processing (e.g., wave-V latencies) was found to be related to overall reading ability and multiple reading subskills, such as phonological decoding, reading comprehension, and word reading. Interestingly, the majority of these relationships were related to auditory potentials recorded at phonemic rates. For instance, central auditory processing (e.g., wave-V latencies) at phonemic rates were found to be significantly related to global reading ability, as assessed by the reading composite score. This finding is consistent with and an extension of Skoe, Brody & Theodore (2017). Moreover, wave-V latencies at the phonemic presentation rates were also found to be related to specific reading subskills, such as phonological decoding skills, reading comprehension, and word

identification. Secondly, while peripheral auditory processing (e.g. wave-I latencies) was not related to overall reading ability, several significant correlations emerged with specific reading-related subtests, such as phonological decoding, passing comprehension (consistent with the finding in the smaller sample), and word reading. Lastly, greater neural consistency was associated with more recent musical training. Participants who had played a musical instrument more recently had more repeatable ABRs. This finding, while not significant after the MPT for correlations, is consistent with the literature demonstrating that musicians with more recent training have more robust auditory-evoked potentials (Skoe & Kraus, 2012).

Overall, some dimensions of our results are consistent with studies conducted with children and adolescents, while others are not. Most importantly, we did not find a relationship between musical training and auditory processing, despite selecting measures that theoretically tap similar auditory processes (Bidelman & Alain, 2015; Musacchia, Sams, Skoe, & Kraus, 2007; Skoe & Kraus, 2012, 2013; Strait et al., 2012). However, in these studies, complex auditory stimuli (e.g., synthesized speech) were used, in contrast to the click stimulus used here. Moreover, unlike past work, we did not find a relationship between musical training and phonological awareness or decoding skills (Gordon, Fehd, & McCandliss, 2015). Additionally, we report relationships between 1) peripheral auditory encoding and reading comprehension and 2) central auditory encoding and phonological-decoding skills. To my knowledge, no study has reported similar findings regarding the peripheral auditory system, as previous work emphasized auditory processing in more central structures (e.g., wave-V latencies). While work involving peripheral structures is severely under researched, two studies with musically

trained children, found an association between musical training and reading comprehension (Corrigall & Trainor, 2011; Register et al., 2007), consistent with the notion that music training could enhance sensorineural processing of sound that, then, relates to higher level reading skills, such as reading comprehension (i.e., sound-to-meaning mapping). Finally, associations between neural measures of auditory processing and reading ability only emerged for phonemic rates, consistent with phoneme-based theories of reading and language acquisition (Poeppel, 2003; Poeppel et al., 2008).

Regarding our developmental predictions, the current study, overall, does not support a hard position of the first theoretical reading-acquisition function: global reading level was not related to musical-training history. However, several reading subskills, were found to be related to musical training, most notably, rapid naming, which might support a soft version of this position. While we predicted this relationship may be mediated or moderated by auditory processing, no measure of auditory processing was related to rapid naming. Instead, auditory processing was independently related to both reading comprehension and phonological decoding skills. We are left, then, to consider the plausibility of the second theoretical-acquisition function: namely, that musical training influences the rate of reading acquisition of particular reading subskills, but does not confer a global enhancement to reading level that persists into adulthood. In the context of the available developmental literature, music training might enhance the acquisition of phonological knowledge that then, later, promotes future reading development.

12 LIMITATIONS AND FUTURE WORK

While we investigated relationships between auditory processing, music training, and reading skills primarily with a small, core pilot sample, a major limitation of the current study was the small number of participants (n = 19) who met the criteria in all three domains of inquiry. In the future, we plan to expand this sample and investigate whether auditory processing mediates or moderates musical training history and reading-related skills with structural-equation modeling (SEM) or moderation and mediation in regression. Moreover, our participants all reported a history of musical training, making it difficult to draw comparisons to individuals who have never participated in music instruction. Future work, thus, could actively recruit non-musicians as a control group. Inclusion of these participants would also allow us to make comparisons at the group level, while also taking a continuous approach for specific music-training variables (Boebinger, Evans, Rosen, & Manly, 2015; Ruggles, Freyman, & Oxenham, 2014; Slater et al., 2015). Moreover, inclusion of non-musically trained readers would enable us to assess whether there is a threshold effect of musical training (i.e., a minimum amount needed to engender reading benefits) or a ceiling effect (i.e., an overall limit on reading benefits that music training may confer), as has been implicated in developmental work (Gordon et al., 2015). Another limitation of our sample is that we are perhaps tapping a limited range of reading ability than is truly reflected at the population level. Here, we recruited entirely from a college-age population at a major university. It is likely that in the “real world,” reading ability is much more variable than observed here. Moreover, we believe our analyses be expanded to include atypical readers, such as those with a history of developmental dyslexia.

Additionally, our use of a broadband click stimulus to evoke neural responses may not adequately reflect the spectrotemporal dynamics of natural speech. Expanding our stimulus set to include speech stimuli with formant transitions or fundamental frequency pitch contours might be a more ecologically valid way of assessing the neural encoding of speech dynamics, e.g., (Kraus et al., 2014; Wong et al., 2007). Moreover, this would allow us to make a direct comparison regarding the sensitivity of the click-evoked ABR and the speech-evoked FFR to predict reading behaviors in musically trained populations. Thirdly, we did not take into account history of reading or socio-economic status (SES) in our participants (Goswami, 2015). SES is related to both brainstem function and reading skills (Skoe, Krizman, & Kraus, 2013). Another limitation is that we did not explore the possibility that variability in reading could arise from variability in reading experience: for instance, participants who read less are less likely to become skilled readers (see: Goswami, 2015). Moreover, those who are musically proficient may also, on average, read more than those who are less musically proficient. Still, there is some evidence that music skills are still related to reading-related skills, even when controlling for reading experience. For instance, Corrigall & Trainor (2011) found that the length of music training in a cohort of 6- to 9-year-old children, even when the numbers of hours spent reading was controlled for.

We also did not account for higher cognitive abilities that might be related to both reading ability and music training (e.g., working auditory memory, attention) (Chan, Ho, & Cheung, 1998; Hanna-Pladdy & MacKay, 2011; Ho, Cheung, & Chan, 2003; Parbery-Clark et al., 2009). And finally, given the correlational nature of this work, we were unable to assess musical skills directly – future work could use assess of rhythm and pitch skills

in adult readers (e.g., beat entrainment), and associate those with a history of music training, auditory processing, and reading-related skills.

13 WORKS CITED

Abrams, D. A., Nicol, T., Zecker, S., & Kraus, N. (2009). Abnormal Cortical Processing of the Syllable Rate of Speech in Poor Readers. *Journal of Neuroscience*, *29*(24), 7686–7693.

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of Experimental Child Psychology*, *83*(2), 111–130.

Banai, K., & Ahissar, M. (2013). Musical Experience, Auditory Perception and Reading-Related Skills in Children. *PLoS ONE*, *8*(9), 1–11.

Banai, K., Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Reading and subcortical auditory function. *Cerebral Cortex (New York, N.Y. : 1991)*, *19*(11), 2699–707.

Batra, R., Kuwada, S., & Maher, V. L. (1986). The frequency-following response to continuous tones in humans. *Hearing Research*, *21*, 167–177.

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

Bhide, A., Power, A., & Goswami, U. (2013). A Rhythmic Musical Intervention for Poor Readers: A Comparison of Efficacy With a Letter-Based Intervention. *Mind, Brain, and Education*, *7*(2), 113–123.

Bidelman, G. M., & Krishnan, A. (2010). Effects of reverberation on brainstem representation of speech in musicians and non-musicians. *Brain Research*, *1355*, 112–25.

Bidelman, G. M., & Alain, C. (2015). Musical Training Orchestrates Coordinated

Neuroplasticity in Auditory Brainstem and Cortex to Counteract Age-Related Declines in Categorical Vowel Perception. *J Neurosci*, *35*(3), 1240–1249.

Bigand, E., Delbé, C., Poulin-Charronnat, B., Leman, M., & Tillmann, B. (2014). Empirical evidence for musical syntax processing? Computer simulations reveal the contribution of auditory short-term memory. *Frontiers in Systems Neuroscience*, *8*(June), 94.

Boebinger, D., Evans, S., Rosen, S., & Manly, T. (2015). Musicians and non-musicians are equally adept at perceiving masked speech, *137*(1).

Boets, B., Op de Beeck, H. P., Vandermosten, M., Scott, S. K., Gillebert, C. R., Mantini, D., … Ghesquiere, P. (2013). Intact But Less Accessible Phonetic Representations in Adults with Dyslexia. *Science*, *342*(6163), 1251–1254.

Boets, B., Vandermosten, M., Poelmans, H., Luts, H., Wouters, J., & Ghesquière, P. (2011). Preschool impairments in auditory processing and speech perception uniquely predict future reading problems. *Research in Developmental Disabilities*, *32*(2), 560–70.

Boets, B., Wouters, J., van Wieringen, A., De Smedt, B., & Ghesquière, P. (2008). Modelling relations between sensory processing, speech perception, orthographic and phonological ability, and literacy achievement. *Brain and Language*, *106*(1), 29–40.

Bowers, P., Golden, J., Kennedy, A., & Young, A. (1994). Limits upon orthographic knowledge due to processes indexed by naming speed. In *The varieties of orthographic knowledge 1 Theoretical and developmental issues Neuropsychology and cognition Vol 8* (pp. 173–218).

Brandt, A., Gebrian, M., & Slevc, L. R. (2012). Music and early language acquisition. *Frontiers in Psychology*, *3*(September), 327.

Brashears, S. M., Berlin, C. I., & Hood, L. J. (2003). Olivocohlear Efferent Suppression in Classical Musicians. *Journal of the American Academy of Audiology*, *14*(6).

Chan, A. S., Ho, Y. C., & Cheung, M. C. (1998). Music training improves verbal memory. *Nature*, *396*(6707), 128.

Chandrasekaran, B., Hornickel, J., & Skoe, E. (2009). Context-dependent encoding in the human auditory brainstem relates to hearing speech in noise: Implications for developmental dyslexia. *Neuron*, *64*(3), 311–319.

Chobert, J., François, C., Velay, J. L., & Besson, M. (2014). Twelve months of active musical training in 8-to 10-year-old children enhances the preattentive processing of syllabic duration and voice onset time. *Cerebral Cortex*, *24*(4), 956–967.

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

Cogo-Moreira, H., Brandão de Ávila, C. R., Ploubidis, G. B., & Mari, J. D. J. (2013). Effectiveness of music education for the improvement of reading skills and academic achievement in young poor readers: a pragmatic cluster-randomized, controlled clinical trial. *PloS One*, *8*(3), e59984.

Corrigall, K., & Trainor, L. (2011). Associations between length of music training and reading skills in children. *Music Perception*, *29*(2), 147–155.

David, D., Wade-Woolley, L., Kirby, J. R., & Smithrim, K. (2007). Rhythm and reading development in school-age children: a longitudinal study. *Journal of Research in*

Reading, *30*(2), 169–183.

Davis, H., & Hirsh, S. K. (1976). The Audiometric Utility of Brain Stem Responses to Low-Frequency Sounds. *International Journal of Audiology*, *15*(3), 181–195.

Doelling, K. B., & Poeppel, D. (2015). Cortical entrainment to music and its modulation by expertise. *Proceedings of the National Academy of Sciences*, 201508431.

Ehri, L. C. (1992). Reconceptualizing the development of sight word reading and its relationship to recoding. In *Reading acquisition* (pp. 107–143).

Field, A., Miles, J., & Field, Z. (2012). *Discovering Statistics Using R*. *Statistics* (Vol. 58).

Forgeard, M., Schlaug, G., Norton, A., Rosam, C., Iyengar, U., & Winner, E. (2008). The relation between music and phonological processing in normal-reading children and children with dyslexia. *Music Perception: An Interdisciplinary Journal*, *25*(4), 383–390.

Friel-Patti, S., & Finitzo, T. (1990). Language Learning in a Prospective Study of Otitis Media with Effusion in the First Two Years of Life. *Journal of Speech Language and Hearing Research*, *33*(1), 188.

Gervain, J., & Mehler, J. (2010). Speech perception and language acquisition in the first year of life. *Annual Review of Psychology*, *61*, 191–218.

Giraud, A.-L., Kleinschmidt, A., Poeppel, D., Lund, T. E., Frackowiak, R. S. J., & Laufs, H. (2007). Endogenous cortical rhythms determine cerebral specialization for speech perception and production. *Neuron*, *56*(6), 1127–34.

Giraud, A.-L., & Poeppel, D. (2012). Cortical oscillations and speech processing: emerging computational principles and operations. *Nature Neuroscience*, *15*(4), 511–7.

Gordon, R. L., Fehd, H. M., & McCandliss, B. D. (2015). Does music training enhance literacy skills? A meta-analysis. *Frontiers in Psychology*, *6*(December), 1–16.

Gordon, R. L., Shivers, C. M., Wieland, E. a., Kotz, S. a., Yoder, P. J., & Devin McAuley, J. (2014). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, n/a-n/a.

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, *15*(1), 3–10.

Goswami, U. (2015). Sensory theories of developmental dyslexia: three challenges for research. *Nat Rev Neurosci*, *16*(1), 43–54.

Goswami, U., Huss, M., Mead, N., Fosker, T., & Verney, J. P. (2013). Perception of patterns of musical beat distribution in phonological developmental dyslexia: Significant longitudinal relations with word reading and reading comprehension. *Cortex*, *49*, 1363–1376.

Gottlieb, G., & Lickliter, R. (2007). Probabilistic epigenesis. *Developmental Science*, *10*(1), 1–11.

Gottlieb, G., Wahlsten, D., & Lickliter, R. (2007). Development : A Developmental Psychobiological Systems View. *Handbook of Child Psychology*, 210–257.

Habib, M., Lardy, C., Desiles, T., Commeiras, C., Chobert, J., & Besson, M. (2016). Music and Dyslexia: A New Musical Training Method to Improve Reading and Related Disorders. *Frontiers in Psychology*, *7*(January).

Halwani, G. F., Loui, P., Rüber, T., & Schlaug, G. (2011). Effects of Practice and Experience on the Arcuate Fasciculus: Comparing Singers, Instrumentalists, and Non-Musicians. *Frontiers in Psychology*, *2*(JUL), 1–9.

Hämäläinen, J. A., Salminen, H. K., & Leppänen, P. H. T. (2013). Basic Auditory Processing Deficits in Dyslexia: Systematic Review of the Behavioral and Event-Related Potential/ Field Evidence. *Journal of Learning Disabilities*, *46*(5), 413–427.

Hanna-Pladdy, B., & MacKay, A. (2011). The relation between instrumental musical activity and cognitive aging. *Neuropsychology*, *25*(3), 378–386.

Hannon, E., & Trehub, S. (2005). Tuning in to musical rhythms: Infants learn more readily than adults. *… of Sciences of the United States …*, *102*(35), 12639–12643.

Ho, Y.-C., Cheung, M.-C., & Chan, A. S. (2003). Music training improves verbal but not visual memory: Cross-sectional and longitudinal explorations in children. *Neuropsychology*, *17*(3), 439–450.

Holliman, A. J., Wood, C., & Sheehy, K. (2010). Does speech rhythm sensitivity predict children's reading ability 1 year later? *Journal of Educational Psychology*, *102*(2), 356–366.

Hood, L. (1998). *Clinical Applications of the Auditory Brainstem Response*. Singular Publishing Group.

Hoormann, J., Falkenstein, M., Hohnsbein, J., & Blanke, L. (1992). The human frequency-following response (FFR): Normal variability and relation to the click-evoked brainstem response. *Hearing Research*, *59*(2), 179–188.

Hornickel, J., Anderson, S., Skoe, E., Yi, H., & Kraus, N. (2012). Subcortical representation of speech fine structure relates to reading ability. *Neuroreport*, *23*(1), 6–9.

Hornickel, J., Chandrasekaran, B., Zecker, S., & Kraus, N. (2011). Auditory brainstem measures predict reading and speech-in-noise perception in school-aged children.

Behavioural Brain Research, *216*(2), 597–605.

Hornickel, J., Knowles, E., & Kraus, N. (2012). Test-retest consistency of speech-evoked auditory brainstem responses in typically-developing children. *Hearing Research*, *284*(1–2), 52–8.

Hornickel, J., & Kraus, N. (2013). Unstable representation of sound: a biological marker of dyslexia. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *33*(8), 3500–4.

Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Subcortical differentiation of stop consonants relates to reading and speech-in-noise perception. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(31), 13022–7.

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011a). Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology. *Cortex*, *47*(6), 674–689.

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011b). Music, rhythm, rise time perception and developmental dyslexia: perception of musical meter predicts reading and phonology. *Cortex*, *47*(6), 674–689.

Jentschke, S., & Koelsch, S. (2009). Musical training modulates the development of syntax processing in children. *NeuroImage*, *47*(2), 735–744.

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. *The Journal of the Acoustical Society of America*, *139*(1), EL6-EL12.

Kraus, B. N., & Anderson, S. (2013). For Reading Development, Auditory Processing Is

Fundamental.

Kraus, N., Slater, J., Thompson, E. C., Hornickel, J., Strait, D. L., Nicol, T., & White-Schwoch, T. (2014). Music Enrichment Programs Improve the Neural Encoding of Speech in At-Risk Children. *Journal of Neuroscience*, *34*(36), 11913–11918.

Kraus, N., Strait, D. L., & Parbery-Clark, A. (2012). Cognitive factors shape brain networks for auditory skills: Spotlight on auditory working memory. *Annals of the New York Academy of Sciences*, *1252*(1), 100–107.

Kuhl, P. K. (2004). Early language acquisition: cracking the speech code. *Nature Reviews Neuroscience*, *5*(11), 831–843.

Kuhl, P. K., Williams, K. A., Lacerda, F., Stevens, K. N., Kuhl, P. K., Williams, K. A., … Lindblom, B. (2014). Linguistic Experience Alters Phonetic Perception in Infants by 6 Months of Age, *255*(5044), 606–608.

Large, E., & Tretakis, A. (2005). Tonality and nonlinear resonance. *Annals of the New York Academy of …*, *1060*, 53–56.

Large, E. W. (2010). *Neurodynamics of Music*. *Dynamical Systems* (Vol. 36).

Large, E. W., Herrera, J. A., & Velasco, M. J. (2015). Neural networks for beat perception in musical rhythm. *Frontiers in Systems Neuroscience*, *9*(November), 1–14.

Large, E. W., & Jones, M. R. (1999). The dynamic of attending: How People Track Time-Varying Events. *Psychological Research*.

Large, E. W., & Snyder, J. S. (2009). Pulse and meter as neural resonance. *Annals of the New York Academy of Sciences*, *1169*, 46–57.

Lee, K. M., Skoe, E., Kraus, N., & Ashley, R. (2009). Selective subcortical enhancement of musical intervals in musicians. *The Journal of Neuroscience : The Official Journal*

of the Society for Neuroscience, *29*(18), 5832–5840.

Leong, V., & Goswami, U. (2014). Assessment of rhythmic entrainment at multiple timescales in dyslexia: evidence for disruption to syllable timing. *Hearing Research*, *308*, 141–61.

London, J. (2004). *Hearing in Time: Psychological Aspects of Musical Meter*. *Hearing in Time: Psychological Aspects of Musical Meter*.

MacNeilage, P. F. (2000). On the Origin of Internal Structure of Word Forms. *Science*, *288*(5465), 527–531.

Manis, F. R., Doi, L. M., & Bhadha, B. (2000). Naming speed, phonological awareness, and orthographic knowledge in second graders. *Journal of Learning Disabilities*, *33*(4), 325–333, 374.

Manis, F. R., Seidenberg, M. S., & Doi, L. M. (1999). See Dick RAN: Rapid Naming and the Longitudinal Prediction of Reading Subskills in First and Second Graders. *Scientific Studies of Reading*, *3*(2), 129–157.

Miller, J., & Carterette, E. (1975). Perceptual space for musical structures. *The Journal of the Acoustical Society of America*, *58*, 711–720.

Moon, C., Lagercrantz, H., & Kuhl, P. K. (2013). Language experienced in utero affects vowel perception after birth: a two-country study. *Acta Paediatrica (Oslo, Norway : 1992)*, *102*(2), 156–60.

Moreno, S., Friesen, D., & Bialystok, E. (2011). Effect of music training on promoting preliteracy skills: preliminary causal evidence. *Music Perception*, *29*(2), 165–172.

Musacchia, G., Sams, M., Skoe, E., & Kraus, N. (2007). Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. *Proceedings*

of the National Academy of Sciences of the United States of America, *104*(40), 15894–8.

Neef, N. E., Müller, B., Liebig, J., Schaadt, G., Grigutsch, M., Gunter, T. C., … Friederici, A. D. (2017). Dyslexia risk gene relates to representation of sound in the auditory brainstem. *Developmental Cognitive Neuroscience*.

Overy, K. (2003). Dyslexia and Music: From Timing Deficits to Musical Intervention. *Annals of the New York Academy of Sciences*, *29*, 1–9.

Parbery-Clark, A., Anderson, S., Hittner, E., & Kraus, N. (2012). Musical experience strengthens the neural representation of sounds important for communication in middle-aged adults. *Frontiers in Aging Neuroscience*, *4*(OCT), 1–12.

Parbery-Clark, A., Skoe, E., Lam, C., & Kraus, N. (2009). Musician enhancement for speech-in-noise. *Ear and Hearing*, *30*(6), 653–661.

Parbery-Clark, A., Tierney, A., Strait, D. L., & Kraus, N. (2012). Musicians have fine-tuned neural distinction of speech syllables. *Neuroscience*, *219*, 111–9.

Patel, A. D. (2008). *Music, Language and the Brain*. Oxford University Press.

Patel, A. D. (2011). Why would Musical Training Benefit the Neural Encoding of Speech? The OPERA Hypothesis. *Frontiers in Psychology*, *2*(June), 1–14.

Patel, A. D. (2014). Can nonlinguistic musical training change the way the brain processes speech? The expanded OPERA hypothesis. *Hearing Research*, *308*, 98–108.

Perrot, X., & Collet, L. (2014). Function and plasticity of the medial olivocochlear system in musicians: A review. *Hearing Research*, *308*, 27–40.

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.

Poeppel, D., Idsardi, W. J., & van Wassenhove, V. (2008). Speech perception at the interface of neurobiology and linguistics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1493), 1071–1086.

Protopapas, A. (2014). From temporal processing to developmental language disorders: mind the gap. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, *369*(1634), 20130090.

Pugh, K. R., Frost, S. J., Rothman, D. L., Hoeft, F., Del Tufo, S. N., Mason, G. F., … Fulbright, R. K. (2014). Glutamate and Choline Levels Predict Individual Differences in Reading Ability in Emergent Readers. *Journal of Neuroscience*, *34*(11), 4082–4089.

Ramus, F. (2002). Language discrimination by newborns: Teasing apart phonotactic, rhythmic, and intonational cues, *2*, 1–14.

Ramus, F., Nespor, M., & Mehler, J. (1999). Correlates of linguistic rhythm in the speech signal. *Cognition*, 1–36.

Rauscher, F. H., & Hinton, S. C. (2012). Music Instruction and its Diverse Extra-Musical Benefits. *Music Perception: An Interdisciplinary Journal*, *29*(2), 215–226.

Rautenberg, I. (2013). The effects of musical training on the decoding skills of German-speaking primary school children. *Journal of Research in Reading*, *0*(0), n/a-n/a.

Register, D., Darrow, A., Swedberg, O., & Standley, J. (2007). The Use of Music to Enhance Reading Skills of Second Grade Students and Students with Reading Disabilities. *Journal of Music Therapy*, *44*(1), 23–37.

Rosen, S. (1992). Temporal Information in Speech: Acoustic, Auditory and Linguistic

Aspects. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *336*(1278), 367–373.

Rueckl, J. G. (2002). The Dynamics of Visual Word Recognition. *Ecological Psychology*, *14*(1–2), 5–19.

Ruggles, D. R., Freyman, R. L., & Oxenham, A. J. (2014). Influence of musical training on understanding voiced and whispered speech in noise. *PloS One*, *9*(1), e86980.

Saffran, J., Aslin, R., & Newport, E. (1996). Statistical learning by 8-month-old infants. *Science*.

Samelli, A., Carvallo, R. M., de Beija, C., Rabelo, C., Matas, C., Gomes, R., & Magliaro, F. L. (2012). Audiological and electrophysiological assessment of professional pop/rock musicians. *Noise and Health*, *14*(56), 6.

Samson, S., Zatorre, R. J., & Ramsay, J. O. (2002). Deficits of musical timbre perception after unilateral temporal-lobe lesion revealed with multidimensional scaling. *Brain : A Journal of Neurology*, *125*, 511–523.

Schellenberg, E. (2008). Commentary on“ Effects of Early Musical Experience on Auditory Sequence Memory” by Adam Tierney, Tonya Bergeson-Dana, and David Pisoni, *3*(4), 1998–2000.

Schrank, F. A. (2010). Woodcock-Johnson III Tests of Cognitive Abilities. *Handbook of Pediatric Neuropsychology*, 371–401.

Seidenberg, M. S. (2007). Connectionist models of reading. *Oxford Handbook of Psycholinguistics*, 235–250.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review*, *96*(4), 523–68.

Share, D. L., & Stanovich, K. E. (1995). Cognitive processes in early reading development: Accommodating individual differences into a model of acquisition, *1*(1), 1–57.

Skoe, E., Brody, L., & Theodore, R. M. (2017). Reading ability reflects individual differences in auditory brainstem function, even into adulthood. *Brain and Language*, *164*, 25–31.

Skoe, E., & Kraus, N. (2012). A Little Goes a Long Way: How the Adult Brain Is Shaped by Musical Training in Childhood. *Journal of Neuroscience*, *32*(34), 11507–11510.

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

Skoe, E., Krizman, J., Anderson, S., & Kraus, N. (2013). Stability and plasticity of auditory brainstem function across the lifespan. *Cerebral Cortex*, (Table 1), bht311-.

Skoe, E., Krizman, J., & Kraus, N. (2013). The impoverished brain: disparities in maternal education affect the neural response to sound. *The Journal of Neuroscience*, *33*(44), 17221–31.

Slater, J., Skoe, E., Strait, D. L., O'Connell, S., Thompson, E., & Kraus, N. (2015). Music training improves speech-in-noise perception: Longitudinal evidence from a community-based music program. *Behavioural Brain Research*, *291*, 244–252.

Strait, D. L., Hornickel, J., & Kraus, N. (2011). Subcortical processing of speech regularities underlies reading and music aptitude in children. *Behav Brain Funct*, *7*(1), 44.

Strait, D. L., & Kraus, N. (2011). Can you hear me now? Musical training shapes functional

brain networks for selective auditory attention and hearing speech in noise. *Frontiers in Psychology*, *2*(JUN), 1–10.

Strait, D. L., Parbery-Clark, A., Hittner, E., & Kraus, N. (2012). Musical training during early childhood enhances the neural encoding of speech in noise. *Brain and Language*, *123*(3), 191–201.

Strogatz, S. H. (1994). Nonlinear Dynamics and Chaos. *Book*, 1–505.

Tallal, P., & Gaab, N. (2006). Dynamic auditory processing, musical experience and language development. *Trends in Neurosciences*, *29*(7), 382–390.

Tallal, P., Miller, S., & Fitch, R. H. (1993). Neurobiological Basis of Speech: A Case for the Preeminence of Temporal Processing. *Annals of the New York Academy of Sciences*, *682*(1 Temporal Info), 27–47.

Tichko, P., & Skoe, E. (2017). Frequency-dependent fine structure in the frequency-following response: The byproduct of multiple generators. *Hearing Research*.

Tierney, A. T., Bergeson, T. R., & Pisoni, D. B. (2008). Effects of Early Musical Experience on Auditory Sequence Memory. *Empirical Musicology Review*, *3*(4), 178–186.

Tierney, A. T., & Kraus, N. (2013). *Music training for the development of reading skills. Progress in brain research* (1st ed., Vol. 207). Elsevier B.V.

Tierney, A. T., Krizman, J., & Kraus, N. (2015). Music training alters the course of adolescent auditory development. *Proceedings of the National Academy of Sciences*, *112*(32), 10062–10067.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1994). Longitudinal studies of phonological processing and reading. *Journal of Learning Disabilities*, *27*(5), 276–286.

Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Burgess, S., & Hecht, S. (1997). Contributions of Phonological Awareness and Rapid Automatic Naming Ability to the Growth of Word-Reading Skills in Second-to Fifth-Grade Children. *Scientific Studies of Reading*, *1*(2), 161–185.

Tsao, F.-M., Liu, H.-M., & Kuhl, P. K. (2004). Speech Perception in Infancy Predicts Language Development in the Second Year of Life: A Longitudinal Study. *Child Development*, *75*(4), 1067–1084.

Van Geert, P. (2003). Dynamic Systems Approaches and Modeling of Developmental Processes. *Handbook of Developmental Psychology*, 640–672.

Vermeulen, A. M., van Bon, W., Schreuder, R., Knoors, H., & Snik, A. (2007). Reading comprehension of deaf children with cochlear implants. *Journal of Deaf Studies and Deaf Education*, *12*(3), 283–302.

Wagner, R. K., Torgesen, J. K., Laughon, P., Simmons, K., & Rashotte, C. A. (1993). Development of Young Readers' Phonological Processing Abilities. *Journal of Educational Psychology*, *85*(1), 83–103.

Weiss, M. W., & Bidelman, G. M. (2015). Listening to the Brainstem: Musicianship Enhances Intelligibility of Subcortical Representations for Speech. *Journal of Neuroscience*, *35*(4), 1687–1691.

Werker, J., & Tees, R. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*.

Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming-Speed Processes, Timing, and Reading: A Conceptual Review. *Journal of Learning Disabilities*, *33*(4), 387–407.

Wong, P., Skoe, E., & Russo, N. (2007). Musical experience shapes human brainstem encoding of linguistic pitch patterns. *Nature Neuroscience*, *10*(4), 420–422.

Woodruff Carr, K., White-Schwoch, T., Tierney, A. T., Strait, D. L., & Kraus, N. (2014). Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. *Proceedings of the National Academy of Sciences*, *111*(40), 14559–14564.

Yoder, P. J., Blackford, J. U., Waller, N. G., & Kim, G. (2004). Enhancing Power While Controlling Family-Wise Error: An Illustration of the Issues Using Electrocortical Studies. *Journal of Clinical and Experimental Neuropsychology*, *26*(3), 320–331.

14 SUPPLEMENTAL TABLES

14.1 Q1_Musically Trained Sample.

N	Variable	r	p	MPT.exact.p
19	Maxprof	0.308	0.2	0.34
19	Maxtotalyears	0.325	0.17	0.4
19	Minage	-0.376	0.11	0.31
19	YrsSinceTrain	-0.14	0.57	0.58

Supplemental Table 1A. WRMT-III Word ID and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *WRMT-III Word ID*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	-0.424	0.07	0.2
19	Maxtotalyears	-0.248	0.31	0.31
19	Minage	0.254	0.29	0.55
19	YrsSinceTrain	0.253	0.3	0.5

Supplemental Table 1B. WRMT-III Word Attack and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *WRMT-III Word Attack*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	0.25	0.3	0.55
19	Maxtotalyears	-0.044	0.86	0.85
19	Minage	-0.104	0.67	0.8
19	YrsSinceTrain	0.266	0.27	0.62

Supplemental Table 1C. WRMT-III Passage Comprehension and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *WRMT-III Passage Comprehension*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	0.278	0.25	0.58
19	Maxtotalyears	-0.242	0.32	0.59
19	Minage	0.149	0.54	0.79

19	YrsSinceTrain	-0.047	0.85	0.86

Supplemental Table 1D. TOWRE – Sight Word Efficiency and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *TOWRE – Sight Word Efficiency*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	0.041	0.87	0.98
19	Maxtotalyears	-0.082	0.74	0.96
19	Minage	0	1	0
19	YrsSinceTrain	0.162	0.51	0.89

Supplemental Table 1E. TOWRE – Phonemic Decoding and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *TOWRE – Phonemic Decoding*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	-0.062	0.8	0.98
19	Maxtotalyears	-0.048	0.84	0.95
19	Minage	0.034	0.89	0.89
19	YrsSinceTrain	-0.238	0.33	0.69

Supplemental Table 1F. CTOPP – Nonword Repetition and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *CTOPP – Nonword Repetition*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	-0.051	0.84	0.89
19	Maxtotalyears	-0.353	0.14	0.36
19	Minage	0.299	0.21	0.49
19	YrsSinceTrain	0.101	0.68	0.9

Supplemental Table 1G. CTOPP – Elision and Music. . Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *CTOPP - Elision*.

N	Variable	r	p	MPT.exact.p

19	Maxprof	-0.176	0.47	0.71
19	Maxtotalyears	-0.342	0.15	0.38
19	Minage	0.221	0.36	0.72
19	YrsSinceTrain	0.052	0.83	0.79

Supplemental Table 1H. CTOPP – Blending Words and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *CTOPP – Blending Words*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	**0.61**	**0.01**	**0.02**
19	Maxtotalyears	0.203	0.4	0.41
19	Minage	-0.29	0.23	0.3
19	YrsSinceTrain	-0.37	0.12	0.25

Supplemental Table 1I. RAN – 2 Set and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *RAN – 2 Set*. Significant relationships are bolded.

N	Variable	r	p	MPT.exact.p
19	Maxprof	**0.633**	**<0.0001**	**0.01**
19	Maxtotalyears	0.285	0.24	0.47
19	Minage	-0.255	0.29	0.5
19	YrsSinceTrain	-0.056	0.82	0.84

Supplemental Table 1J. RAN – Letters and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *RAN - Letters*. Significant relationships are bolded.

N	Variable	r	p	MPT.exact.p
19	Maxprof	0.397	0.09	0.26
19	Maxtotalyears	0.064	0.79	0.96
19	Minage	-0.173	0.48	0.79
19	YrsSinceTrain	0.054	0.83	0.84

Supplemental Table 1K. RAN – Numbers and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores on the *RAN - Numbers*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	0.207	0.39	0.79
19	Maxtotalyears	-0.134	0.58	0.88
19	Minage	0.003	0.99	0.99
19	YrsSinceTrain	0.08	0.75	0.94

Supplemental Table 1L. Reading Composite and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the reading composite scores.

14.2 Q2_Musically Trained Sample.

N	Variable	r	p	MPT.exact.p
18	I_10.9	0.333	0.19	0.81
18	I_15.4	0.232	0.36	0.97
18	I_31.25	0.368	0.13	0.74
18	I_46.5	0.304	0.22	0.88
18	I_6.9	0.223	0.37	0.97
18	I_61.5	0.185	0.46	0.98
18	RC_10.9	-0.025	0.93	0.99
18	RC_15.4	0.214	0.39	0.97
18	RC_31.25	-0.072	0.78	1
18	RC_46.5	0.366	0.13	0.73
18	RC_6.9	0.02	0.94	0.94
18	RC_61.5	0.385	0.11	0.7
18	V_10.9	0.052	0.84	1
18	V_15.4	0.081	0.75	1
18	V_31.25	0.028	0.91	1
18	V_46.5	0.138	0.58	0.99
18	V_6.9	0.108	0.67	1
18	V_61.5	0.098	0.7	1

Supplemental Table 2A. Reading Composite Score and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the Reading Composite Score.

N	Variable	r	p	MPT.exact.p
18	I_10.9	-0.119	0.65	1
18	I_15.4	-0.088	0.73	0.92
18	I_31.25	0.144	0.57	1
18	I_46.5	0.107	0.67	0.95
18	I_6.9	-0.114	0.65	0.99
18	I_61.5	-0.275	0.27	0.94
18	RC_10.9	0.108	0.68	0.98
18	RC_15.4	0.114	0.65	1
18	RC_31.25	0.161	0.52	1
18	RC_46.5	**0.53**	**0.02**	0.25
18	RC_6.9	0.055	0.83	0.83
18	RC_61.5	0.451	0.06	0.47
18	V_10.9	-0.14	0.59	1
18	V_15.4	-0.251	0.32	0.96
18	V_31.25	-0.312	0.21	0.87
18	V_46.5	-0.132	0.6	1
18	V_6.9	-0.17	0.5	1
18	V_61.5	-0.233	0.35	0.97

Supplemental Table 2B. RAN Numbers and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *RAN Numbers* test. **Significant correlations are bolded.**

N	Variable	r	p	MPT.exact.p
18	I_10.9	-0.26	0.31	0.95
18	I_15.4	-0.223	0.37	0.98
18	I_31.25	0.156	0.54	0.94
18	I_46.5	-0.185	0.46	0.98
18	I_6.9	-0.076	0.76	0.76
18	I_61.5	-0.338	0.17	0.83
18	RC_10.9	0.087	0.74	0.98
18	RC_15.4	0.201	0.42	0.98
18	RC_31.25	0.173	0.49	0.96
18	**RC_46.5**	**0.483**	**0.04**	0.36
18	RC_6.9	-0.079	0.75	0.94
18	RC_61.5	0.318	0.2	0.86
18	V_10.9	-0.178	0.49	0.97
18	V_15.4	-0.36	0.14	0.77
18	V_31.25	-0.31	0.21	0.87

18	V_46.5	-0.212	0.4	0.98
18	V_6.9	-0.251	0.31	0.96
18	V_61.5	-0.302	0.22	0.88

Supplemental Table 2C. RAN Letters and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *RAN Letters* Test. **Significant correlations are bolded.**

N	Variable	r	p	MPT.exact.p
18	I_10.9	-0.258	0.32	0.95
18	I_15.4	-0.243	0.33	0.96
18	I_31.25	-0.239	0.34	0.96
18	I_46.5	-0.323	0.19	0.86
18	I_6.9	-0.287	0.25	0.91
18	I_61.5	-0.198	0.43	0.96
18	RC_10.9	-0.022	0.93	0.94
18	RC_15.4	0.142	0.57	0.98
18	RC_31.25	0.208	0.41	0.97
18	RC_46.5	0.415	0.09	0.59
18	RC_6.9	0.121	0.63	0.96
18	RC_61.5	0.429	0.08	0.55
18	V_10.9	-0.126	0.63	0.97
18	V_15.4	-0.12	0.64	0.88
18	V_31.25	-0.195	0.44	0.95
18	V_46.5	-0.18	0.48	0.96
18	V_6.9	-0.276	0.27	0.93
18	V_61.5	-0.189	0.45	0.96

Supplemental Table 2D. RAN 2 Set and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *RAN 2 Set* Test.

N	Variable	r	p	MPT.exact.p
18	I_10.9	0.322	0.21	0.81
18	I_15.4	0.336	0.17	0.8
18	I_31.25	0.33	0.18	0.81
18	I_46.5	0.404	0.1	0.6
18	I_6.9	0.217	0.39	0.95
18	I_61.5	0.151	0.55	0.98
18	RC_10.9	0.318	0.21	0.8
18	RC_15.4	0.175	0.49	0.98

18	RC_31.25	-0.056	0.83	0.99
18	RC_46.5	**0.488**	**0.04**	0.34
18	RC_6.9	-0.039	0.88	0.99
18	RC_61.5	**0.482**	**0.04**	0.35
18	V_10.9	-0.121	0.64	0.98
18	V_15.4	-0.03	0.91	0.91
18	V_31.25	-0.178	0.48	0.98
18	V_46.5	-0.068	0.79	1
18	V_6.9	-0.231	0.36	0.94
18	V_61.5	-0.138	0.58	0.97

Supplemental Table 2E. CTOPP Blending Words and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *CTOPP Blending Words* Test. **Significant correlations are bolded.**

N	Variable	r	p	MPT.exact.p
18	I_10.9	0.391	0.12	0.57
18	I_15.4	0.244	0.33	0.89
18	I_31.25	0.417	0.09	0.51
18	I_46.5	**0.569**	**0.01**	0.18
18	I_6.9	0.257	0.3	0.91
18	I_61.5	0.217	0.39	0.91
18	RC_10.9	-0.254	0.33	0.9
18	RC_15.4	0.417	0.08	0.54
18	RC_31.25	**-0.475**	**0.05**	0.4
18	RC_46.5	0.176	0.48	0.95
18	RC_6.9	-0.149	0.56	0.95
18	RC_61.5	0.169	0.5	0.94
18	V_10.9	-0.005	0.98	0.98
18	V_15.4	-0.012	0.96	1
18	V_31.25	0.036	0.89	1
18	V_46.5	-0.009	0.97	1
18	V_6.9	0.113	0.65	0.95
18	V_61.5	0.109	0.67	0.92

Supplemental Table 2F. CTOPP Elision and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *CTOPP Elision* Test. **Significant correlations are bolded.**

N	Variable	r	p	MPT.exact.p

18	I_10.9	0.225	0.39	0.97
18	I_15.4	0.249	0.32	0.95
18	I_31.25	0.204	0.42	0.97
18	I_46.5	0.093	0.71	0.97
18	I_6.9	0.29	0.24	0.88
18	I_61.5	0.334	0.17	0.79
18	RC_10.9	-0.388	0.12	0.7
18	RC_15.4	-0.341	0.17	0.8
18	RC_31.25	0.06	0.81	0.97
18	RC_46.5	-0.144	0.57	0.99
18	RC_6.9	-0.206	0.41	0.98
18	RC_61.5	0.123	0.63	0.99
18	V_10.9	0.106	0.68	0.98
18	V_15.4	0.141	0.58	0.98
18	V_31.25	0.142	0.57	0.99
18	V_46.5	0.166	0.51	0.98
18	V_6.9	-0.018	0.94	0.94
18	V_61.5	0.132	0.6	0.98

Supplemental Table 2G. CTOPP Non-Word Repetition and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *CTOPP Non-Word Repetition* Test.

N	Variable	r	p	MPT.exact.p
18	I_10.9	-0.113	0.67	0.99
18	I_15.4	-0.26	0.3	0.96
18	I_31.25	-0.125	0.62	1
18	I_46.5	-0.114	0.65	1
18	I_6.9	-0.116	0.65	1
18	I_61.5	0.065	0.8	0.99
18	RC_10.9	-0.031	0.91	0.99
18	RC_15.4	0.349	0.16	0.81
18	RC_31.25	-0.225	0.37	0.98
18	RC_46.5	0.255	0.31	0.96
18	RC_6.9	0.139	0.58	1
18	RC_61.5	0.302	0.22	0.9
18	V_10.9	-0.186	0.47	0.99
18	V_15.4	-0.124	0.62	1
18	V_31.25	-0.15	0.55	1
18	V_46.5	-0.18	0.47	0.99
18	V_6.9	-0.007	0.98	0.98

18	V_61.5	-0.093	0.71	0.99

Supplemental Table 2H. TOWRE Phonemic Decoding and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *TOWRE Phonemic Decoding* Test.

N	Variable	r	p	MPT.exact.p
18	I_10.9	0.185	0.48	1
18	I_15.4	0.217	0.39	0.99
18	I_31.25	0.096	0.7	1
18	I_46.5	0.054	0.83	1
18	I_6.9	0.032	0.9	0.99
18	I_61.5	-0.019	0.94	0.94
18	RC_10.9	0.079	0.76	1
18	RC_15.4	-0.239	0.34	0.99
18	RC_31.25	0.177	0.48	1
18	RC_46.5	0.152	0.55	1
18	RC_6.9	-0.165	0.51	1
18	RC_61.5	0.123	0.63	1
18	V_10.9	-0.047	0.86	1
18	V_15.4	-0.062	0.81	1
18	V_31.25	-0.063	0.8	1
18	V_46.5	0.045	0.86	0.99
18	V_6.9	-0.05	0.84	1
18	V_61.5	-0.058	0.82	1

Supplemental Table 2I. TOWRE Sightword Efficiency and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *TOWRE Sightword Efficiency* Test.

N	Variable	r	p	MPT.exact.p
18	**I_10.9**	**0.529**	**0.03**	0.22
18	**I_15.4**	**0.51**	**0.03**	0.25
18	**I_31.25**	**0.665**	**<0.001**	**0.04**
18	**I_46.5**	**0.576**	**0.01**	0.14
18	**I_6.9**	**0.506**	**0.03**	0.25
18	I_61.5	0.143	0.57	0.82
18	RC_10.9	0.291	0.26	0.79
18	RC_15.4	0.244	0.33	0.78
18	RC_31.25	-0.314	0.2	0.8
18	RC_46.5	0.282	0.26	0.76

18	RC_6.9	-0.163	0.52	0.88
18	RC_61.5	-0.033	0.9	0.9
18	V_10.9	0.275	0.28	0.76
18	V_15.4	0.303	0.22	0.79
18	V_31.25	0.292	0.24	0.81
18	V_46.5	0.384	0.12	0.59
18	**V_6.9**	**0.51**	**0.03**	0.24
18	V_61.5	0.356	0.15	0.68

Supplemental Table 2J. WRMTIII Passage Comprehension and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *WRMT-III Passage Comprehension* Test. **Significant correlations are bolded.**

N	Variable	r	p	MPT.exact.p
18	I_10.9	0.392	0.12	0.65
18	I_15.4	0.056	0.82	0.99
18	I_31.25	0.001	1	1
18	I_46.5	0.2	0.43	0.98
18	I_6.9	-0.03	0.91	0.98
18	I_61.5	0.219	0.38	0.98
18	RC_10.9	-0.16	0.54	0.99
18	RC_15.4	0.272	0.27	0.95
18	RC_31.25	0.123	0.63	1
18	RC_46.5	-0.112	0.66	0.99
18	RC_6.9	0.396	0.1	0.67
18	RC_61.5	0.073	0.77	1
18	V_10.9	0.238	0.36	0.97
18	V_15.4	0.17	0.5	0.99
18	V_31.25	0.071	0.78	0.99
18	V_46.5	0.132	0.6	0.99
18	V_6.9	0.189	0.45	0.99
18	V_61.5	0.135	0.59	0.99

Supplemental Table 2K. WRMTII Work Attack and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *WRMT-III Work Attack* Test.

N	Variable	r	p	MPT.exact.p
18	I_10.9	0.051	0.85	0.99
18	I_15.4	0.045	0.86	0.98

18	I_31.25	0.113	0.65	1
18	I_46.5	-0.063	0.8	1
18	I_6.9	0.117	0.64	1
18	I_61.5	0.219	0.38	0.97
18	RC_10.9	-0.22	0.4	0.98
18	RC_15.4	-0.146	0.56	1
18	RC_31.25	0.104	0.68	0.99
18	RC_46.5	-0.136	0.59	1
18	RC_6.9	0.264	0.29	0.96
18	RC_61.5	0.038	0.88	0.88
18	V_10.9	0.247	0.34	0.97
18	V_15.4	0.327	0.18	0.86
18	V_31.25	0.359	0.14	0.78
18	V_46.5	0.413	0.09	0.6
18	V_6.9	0.291	0.24	0.93
18	V_61.5	0.37	0.13	0.74

Supplemental Table 2L. WRMT III Word ID and ABR. Pearson's R, probability values, and MPT exact probability values between each ABR measure and the standard scores of the *WRTMT-III Word ID* Test.

14.3 Q3_Musically Trained Sample.

N	Variable	r	p	MPT.exact.p
18	Maxprof	-0.185	0.48	0.7
18	Maxtotalyears	-0.424	0.09	0.25
18	Minage	0.248	0.34	0.67
18	YrsSinceTrain	0.047	0.86	0.88

Supplemental Table 5A. Wave-I (10.9 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I (10.9 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	0.025	0.92	0.99
18	Maxtotalyears	-0.359	0.14	0.37
18	Minage	0.207	0.41	0.75
18	YrsSinceTrain	-0.012	0.96	0.96

Supplemental Table 3B. Wave-I (15.4 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I (15.4 Hz)*.

N	Variable	r	P	MPT.exact.p
18	Maxprof	0.055	0.83	0.99
18	Maxtotalyears	-0.001	1	1
18	Minage	0.041	0.87	0.96
18	YrsSinceTrain	0.174	0.49	0.89

Supplemental Table 3C. Wave-I (31.25 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I (31.25 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	-0.311	0.21	0.34
18	Maxtotalyears	-0.404	0.1	0.26
18	Minage	0.317	0.2	0.44
18	YrsSinceTrain	0.226	0.37	0.37

Supplemental Table 3D. Wave-I (46.5 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I (46.5 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	-0.19	0.45	0.74

18	Maxtotalyears	-0.133	0.6	0.73
18	Minage	-0.013	0.96	0.96
18	YrsSinceTrain	-0.243	0.33	0.71

Supplemental Table 3E. Wave-I (61.5 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I (61.5 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	0.03	0.91	0.9
18	Maxtotalyears	-0.216	0.39	0.77
18	Minage	0.041	0.87	0.98
18	YrsSinceTrain	0.196	0.44	0.78

Supplemental Table 3F. Wave-V (6.9 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V (6.9 Hz)*.

N	Variable	r	P	MPT.exact.p
18	Maxprof	-0.033	0.9	0.99
18	Maxtotalyears	-0.183	0.48	0.87
18	Minage	0.031	0.9	0.9
18	YrsSinceTrain	0.035	0.89	1

Supplemental Table 3G. Wave-V (10.9 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V (10.9 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	-0.039	0.88	0.98
18	Maxtotalyears	-0.076	0.77	0.99
18	Minage	-0.178	0.48	0.87
18	YrsSinceTrain	-0.003	0.99	0.99

Supplemental Table 3H. Wave-V (15.4 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V (15.4 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	0.067	0.79	0.8
18	Maxtotalyears	-0.104	0.68	0.94
18	Minage	-0.095	0.71	0.9
18	YrsSinceTrain	-0.112	0.66	0.97

Supplemental Table 3I. Wave-V (31.25 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V (31.25 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	0.021	0.93	1
18	Maxtotalyears	-0.201	0.42	0.82
18	Minage	-0.011	0.97	0.97
18	YrsSinceTrain	0.056	0.83	0.99

Supplemental Table 3J. Wave-V (46.5 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V (46.5 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	0.029	0.91	0.99
18	Maxtotalyears	-0.221	0.38	0.78
18	Minage	-0.002	0.99	0.99
18	YrsSinceTrain	-0.035	0.89	1

Supplemental Table 3K. Wave-V (61.5 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V (61.5 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	-0.167	0.51	0.87
18	Maxtotalyears	0.279	0.26	0.6
18	Minage	-0.166	0.51	0.76
18	YrsSinceTrain	-0.073	0.77	0.79

Supplemental Table 3L. RC (6.9 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the response consistency (RC) of the ABR *(6.9 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	0.141	0.59	0.82
18	Maxtotalyears	0.277	0.28	0.57
18	Minage	-0.378	0.13	0.33
18	YrsSinceTrain	0.084	0.75	0.73

Supplemental Table 3M. RC (10.9 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the response consistency (RC) of the ABR *(10.9 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	0.104	0.68	0.9
18	Maxtotalyears	0.233	0.35	0.75
18	Minage	-0.185	0.46	0.83
18	YrsSinceTrain	0.048	0.85	0.86

Supplemental Table 3N. RC (15.4 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the response consistency (RC) of the ABR *(15.4 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	0.121	0.63	0.94
18	Maxtotalyears	0.168	0.51	0.9
18	Minage	-0.059	0.81	0.82
18	YrsSinceTrain	0.07	0.78	0.95

Supplemental Table 3O. RC (31.25 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the response consistency (RC) of the ABR *(31.25 Hz)*.

N	Variable	r	p	MPT.exact.p
18	Maxprof	0.193	0.44	0.84
18	Maxtotalyears	0.175	0.49	0.79
18	Minage	-0.159	0.53	0.77
18	YrsSinceTrain	0.14	0.58	0.58

Supplemental Table 3P. RC (46.5 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the response consistency (RC) of the ABR *(46.5 Hz)*.

N	Variable	R	p	MPT.exact.p
18	Maxprof	-0.143	0.57	0.94
18	Maxtotalyears	0.086	0.73	0.97
18	Minage	0.024	0.93	0.92
18	YrsSinceTrain	0.036	0.89	0.99

Supplemental Table 3Q. RC (61.5 Hz) and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the response consistency (RC) of the ABR *(61.5 Hz)*.

14.4 Q1_Expanded Sample.

N	Variable	r	p	MPT.exact.p
19	Maxprof	0.308	0.2	0.39
27	Maxtotalyears	0.127	0.53	0.7
33	Minage	-0.111	0.54	0.54
27	YrsSinceTrain	0.132	0.51	0.83

Supplemental Table 6A. WRMTIII – Word ID and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *WRMT-III Word ID*.

N	Variable	r	p	MPT.exact. p
19	Maxprof	-0.424	0.07	0.13
27	Maxtotalyears	-0.062	0.76	0.94
33	Minage	0.235	0.19	0.47
27	YrsSinceTrain	0	1	1

Supplemental Table 4B. WRMTIII – Word Attack and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *WRMT-III Word Attack*.

N	Variable	r	p	MPT.exact. p
19	Maxprof	0.25	0.3	0.5
27	Maxtotalyears	-0.17	0.4	0.55
33	Minage	0.02	0.91	0.91
27	YrsSinceTrain	0.257	0.2	0.56

Supplemental Table 4C. WRMTIII – Passage Comprehension and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *WRMT-III Passage Comprehension*.

N	Variable	r	p	MPT.exact. p
19	Maxprof	0.278	0.25	0.48
27	Maxtotalyears	-0.233	0.24	0.48
33	Minage	0.145	0.42	0.71
27	YrsSinceTrain	0.045	0.82	0.83

Supplemental Table 4D. TOWRE – Sight Word Efficiency and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *TOWRE – Sight Word Efficiency*.

N	Variable	r	p	MPT.exact. p
19	Maxprof	0.041	0.87	0.87
27	Maxtotalyears	-0.101	0.62	0.93

33	Minage	-0.048	0.79	0.96
27	YrsSinceTrain	0.183	0.36	0.81

Supplemental Table 4E. TOWRE – Phonemic Decoding and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *TOWRE – Phonemic Decoding*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	-0.062	0.8	0.95
27	Maxtotalyears	-0.006	0.98	0.98
33	Minage	0.074	0.68	0.97
27	YrsSinceTrain	-0.178	0.37	0.82

Supplemental Table 4F. CTOPP – Nonword Repetition and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *CTOPP – Non-Word Repetition*.

N	Variable	r	p	MPT.exact.p
27	YrsSinceTrain	-0.086	0.67	0.97
33	Minage	0.288	0.1	0.45
27	Maxtotalyears	-0.059	0.77	0.96
19	Maxprof	-0.051	0.84	0.84

Supplemental Table 4G. CTOPP – Elision and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *CTOPP - Elision*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	-0.176	0.47	0.62
27	Maxtotalyears	-0.349	0.07	0.27
33	Minage	0.119	0.51	0.51
27	YrsSinceTrain	0.251	0.21	0.52

Supplemental Table 4H. CTOPP – Blending Words and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *CTOPP – Blending Words*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	**0.61**	**0.01**	**0.01**
27	Maxtotalyears	0.031	0.88	0.87
33	Minage	-0.169	0.35	0.71
27	YrsSinceTrain	0.087	0.66	0.87

Supplemental Table 4I. RAN – 2SET and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *RAN – 2Set*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	**0.633**	**<.0001**	**<.0001**
27	Maxtotalyears	0.1	0.62	0.63
33	Minage	-0.171	0.34	0.56
27	YrsSinceTrain	0.196	0.33	0.62

Supplemental Table 4J. RAN – Letters and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *RAN - Letters*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	0.397	0.09	0.17
27	YrsSinceTrain	0.336	0.09	0.19
33	Maxtotalyears	-0.08	0.69	0.87
27	Minage	-0.076	0.68	0.67

Supplemental Table 4K. RAN – Numbers and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the standard scores of *RAN - Numbers*.

N	Variable	r	p	MPT.exact.p
19	Maxprof	0.207	0.39	0.72
27	Maxtotalyears	-0.13	0.52	0.69
33	Minage	0.094	0.6	0.6
27	YrsSinceTrain	0.164	0.41	0.72

Supplemental Table 4L. Reading Composite Score and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the *Reading Composite* scores.

14.5 Q2_Expanded Sample.

N	Variable	Pearson's R	Uncorrected P	MPT Corrected P
49	I_10.9	0.052	0.72	0.99
50	I_15.4	0.101	0.48	0.97
50	I_31.25	0.225	0.12	0.64
50	I_46.5	0.187	0.19	0.75
50	I_6.9	0.041	0.78	0.99
50	I_61.5	0.153	0.29	0.88
49	RC_10.9	-0.028	0.85	0.98
50	RC_15.4	0.07	0.63	0.99

50	RC_31.25	-0.209	0.14	0.68
50	RC_46.5	0.122	0.4	0.95
50	RC_6.9	-0.005	0.97	0.97
50	RC_61.5	-0.08	0.58	0.99
49	V_10.9	0.225	0.12	0.64
50	V_15.4	0.24	0.09	0.59
50	V_31.25	**0.339**	**0.02**	0.16
50	V_46.5	**0.299**	**0.03**	0.3
50	V_6.9	0.235	0.1	0.61
50	V_61.5	**0.328**	**0.02**	0.19

Supplemental Table 5A. Reading Composite Score and ABR. Pearson's correlations between ABR measures and the reading composite score with uncorrected and corrected p-values. Significant correlations are bolded. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz). Significant relationships are bolded.

N	Variable	r	p	MPT.exact.p
49	I_10.9	0.032	0.83	1
50	I_15.4	0.041	0.78	1
50	I_31.25	0.127	0.38	0.98
50	I_46.5	0.135	0.35	0.98
50	I_6.9	-0.051	0.73	1
50	I_61.5	0.021	0.89	1
49	RC_10.9	-0.049	0.74	1
50	RC_15.4	-0.081	0.58	1
50	RC_31.25	0.012	0.94	1
50	RC_46.5	0.051	0.72	1
50	RC_6.9	0.018	0.9	1
50	RC_61.5	0.195	0.17	0.84
49	V_10.9	0.043	0.77	1
50	V_15.4	0.02	0.89	1
50	V_31.25	0.011	0.94	0.94
50	V_46.5	0.097	0.5	1
50	V_6.9	0.146	0.31	0.96
50	V_61.5	0.053	0.71	1

Supplemental Table 5A. RAN Numbers and ABR. Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *RAN - Numbers*. ABR measures included wave I & V latencies and the response consistency measure

(RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz).

N	Variable	r	p	MPT.exact.p
49	I_10.9	0.012	0.94	1
50	I_15.4	0.062	0.67	1
50	I_31.25	0.156	0.28	0.94
50	I_46.5	0.053	0.71	1
50	I_6.9	-0.033	0.82	1
50	I_61.5	-0.055	0.7	1
49	RC_10.9	-0.061	0.68	1
50	RC_15.4	-0.186	0.2	0.87
50	RC_31.25	-0.108	0.46	0.99
50	RC_46.5	-0.014	0.92	1
50	RC_6.9	-0.106	0.46	0.99
50	RC_61.5	0.143	0.32	0.97
49	V_10.9	0.012	0.93	1
50	V_15.4	-0.041	0.77	1
50	V_31.25	0.004	0.98	0.98
50	V_46.5	0.029	0.84	1
50	V_6.9	0.075	0.6	1
50	V_61.5	-0.011	0.94	0.99

Supplemental Table 5B. RAN Letters and ABR Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *RAN - Letters*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz).

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N	Variable	r	p	MPT.exact.p
49	I_10.9	0.002	0.99	0.99
50	I_15.4	0.055	0.7	1
50	I_31.25	0.118	0.41	0.99
50	I_46.5	0.066	0.65	1
50	I_6.9	-0.13	0.37	0.99
50	I_61.5	0.083	0.56	1
49	RC_10.9	0.05	0.73	1
50	RC_15.4	-0.07	0.63	1
50	RC_31.25	-0.044	0.76	0.99
50	RC_46.5	0.056	0.7	1
50	RC_6.9	0.081	0.58	1
50	RC_61.5	0.223	0.12	0.7
49	V_10.9	0.041	0.78	0.98
50	V_15.4	0.06	0.68	1

50	V_31.25	0.116	0.42	0.99
50	V_46.5	0.082	0.57	1
50	V_6.9	0.034	0.82	0.97
50	V_61.5	0.085	0.56	1

Supplemental Table 5C. RAS2Set and ABR Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *RAN – 2 Set*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz).

N	Variable	r	p	MPT.exact.p
49	I_10.9	0.217	0.13	0.6
50	I_15.4	0.263	0.06	0.41
50	I_31.25	**0.289**	**0.04**	0.32
50	I_46.5	**0.32**	**0.02**	0.21
50	I_6.9	0.196	0.17	0.68
50	I_61.5	0.266	0.06	0.42
49	RC_10.9	-0.144	0.32	0.85
50	RC_15.4	0.061	0.68	0.89
50	RC_31.25	-0.256	0.07	0.44
50	RC_46.5	0.076	0.6	0.92
50	RC_6.9	-0.097	0.5	0.92
50	RC_61.5	-0.009	0.95	0.95
49	V_10.9	0.253	0.08	0.43
50	V_15.4	**0.293**	**0.04**	0.31
50	V_31.25	0.266	0.06	0.41
50	V_46.5	0.131	0.36	0.85
50	V_6.9	0.186	0.2	0.69
50	V_61.5	0.234	0.1	0.52

Supplemental Table 5D. CTOPP Blending Words and ABR Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *CTOPP – Blending Words*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz). Significant relationships are bolded.

N	Variable	r	p	MPT.exact.p
49	I_10.9	-0.063	0.67	0.99
50	I_15.4	-0.018	0.9	1
50	I_31.25	0.068	0.64	1
50	I_46.5	0.159	0.27	0.91
50	I_6.9	-0.015	0.92	0.99

50	I_61.5	0.12	0.41	0.98
49	RC_10.9	0.106	0.47	0.99
50	RC_15.4	0.177	0.22	0.86
50	RC_31.25	-0.183	0.2	0.86
50	RC_46.5	0.048	0.74	1
50	RC_6.9	-0.118	0.41	0.98
50	RC_61.5	-0.073	0.61	1
49	V_10.9	-0.084	0.57	1
50	V_15.4	-0.081	0.58	1
50	V_31.25	0.024	0.87	1
50	V_46.5	-0.026	0.86	1
50	V_6.9	-0.066	0.65	0.99
50	V_61.5	0.008	0.96	0.96

Supplemental Table 5E. CTOPP Elision and ABR Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *CTOPP - Elision*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz).

N	Variable	r	p	MPT.exact.p
49	I_10.9	0.079	0.59	0.99
50	I_15.4	0.02	0.89	0.99
50	I_31.25	0.151	0.29	0.92
50	I_46.5	0.057	0.7	0.99
50	I_6.9	0.039	0.79	1
50	I_61.5	0.06	0.68	1
49	RC_10.9	0	1	1
50	RC_15.4	0.107	0.46	0.98
50	RC_31.25	-0.025	0.86	1
50	RC_46.5	**0.286**	**0.04**	0.33
50	RC_6.9	0.147	0.31	0.92
50	RC_61.5	-0.069	0.63	1
49	V_10.9	**0.328**	**0.02**	0.19
50	V_15.4	**0.301**	**0.03**	0.28
50	V_31.25	**0.428**	**0.001**	**0.03**
50	V_46.5	**0.326**	**0.02**	0.2
50	V_6.9	0.196	0.17	0.78
50	V_61.5	**0.291**	**0.04**	0.32

Supplemental Table 5F. CTOPP Nonword Repetition and ABR. Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *CTOPP – Nonword Repetition*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at

various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz). Significant relationships are bolded.

N	Variable	r	p	MPT.exact.p
49	I_10.9	-0.101	0.49	0.99
50	I_15.4	-0.109	0.45	0.98
50	I_31.25	0.059	0.68	0.99
50	I_46.5	-0.051	0.73	0.98
50	I_6.9	-0.092	0.53	0.99
50	I_61.5	0.062	0.67	1
49	RC_10.9	-0.005	0.98	0.98
50	RC_15.4	0.162	0.26	0.91
50	RC_31.25	-0.134	0.35	0.95
50	RC_46.5	0.17	0.24	0.91
50	RC_6.9	0.173	0.23	0.92
50	RC_61.5	0.021	0.88	0.98
49	V_10.9	0.056	0.7	0.99
50	V_15.4	0.079	0.59	0.99
50	V_31.25	0.135	0.35	0.95
50	V_46.5	0.067	0.65	1
50	V_6.9	0.14	0.33	0.95
50	V_61.5	0.136	0.35	0.96

Supplemental Table 5G. TOWRE Phonemic Decoding and ABR. Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *TOWRE – Phonemic Decoding*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz).

N	Variable	r	p	MPT.exact.p
49	I_10.9	0.168	0.25	0.89
50	I_15.4	0.059	0.69	1
50	I_31.25	0.152	0.29	0.93
50	I_46.5	0	1	1
50	I_6.9	-0.043	0.77	1
50	I_61.5	0.027	0.85	1
49	RC_10.9	-0.067	0.65	1
50	RC_15.4	-0.099	0.5	1
50	RC_31.25	0.006	0.97	1
50	RC_46.5	-0.02	0.89	1
50	RC_6.9	0.02	0.89	1
50	RC_61.5	0.013	0.93	1
49	V_10.9	0.083	0.57	1

50	V_15.4	0.095	0.51	1
50	V_31.25	0.131	0.37	0.97
50	V_46.5	0.024	0.87	1
50	V_6.9	0.092	0.52	1
50	V_61.5	0.013	0.93	1

Supplemental Table 5H. TOWRE Sight Word Efficiency and ABR. Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *TOWRE – Sightword Efficiency*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz).

N	Variable	r	p	MPT.exact.p
49	I_10.9	0.186	0.2	0.67
50	I_15.4	**0.311**	**0.03**	0.24
50	I_31.25	**0.344**	**0.01**	0.15
50	I_46.5	**0.35**	**0.01**	0.14
50	I_6.9	0.257	0.07	0.42
50	I_61.5	0.222	0.12	0.57
49	RC_10.9	-0.049	0.74	0.97
50	RC_15.4	-0.024	0.87	0.86
50	RC_31.25	**-0.292**	**0.04**	0.3
50	RC_46.5	-0.035	0.81	0.96
50	RC_6.9	-0.205	0.15	0.62
50	RC_61.5	-0.158	0.27	0.74
49	V_10.9	0.143	0.33	0.75
50	V_15.4	0.167	0.25	0.72
50	V_31.25	0.232	0.11	0.53
50	V_46.5	0.261	0.07	0.41
50	V_6.9	0.27	0.06	0.37
50	V_61.5	**0.308**	**0.03**	0.24

Supplemental Table 5I. WRMTIII Passage Comprehension and ABR. Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *WRMT – III Passage Comprehension*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz). Significant relationships are bolded.

N	Variable	r	p	MPT.exact.p
49	I_10.9	-0.034	0.82	1

50	I_15.4	-0.042	0.77	1
50	I_31.25	-0.045	0.76	1
50	I_46.5	0	1	1
50	I_6.9	-0.081	0.58	1
50	I_61.5	0.017	0.91	1
49	RC_10.9	-0.046	0.75	1
50	RC_15.4	0.024	0.87	1
50	RC_31.25	-0.122	0.4	0.99
50	RC_46.5	-0.045	0.76	1
50	RC_6.9	-0.024	0.87	1
50	RC_61.5	-0.261	0.07	0.49
49	V_10.9	0.091	0.53	1
50	V_15.4	0.083	0.56	1
50	V_31.25	0.169	0.24	0.91
50	V_46.5	0.172	0.23	0.9
50	V_6.9	-0.005	0.98	1
50	V_61.5	0.172	0.23	0.9

Supplemental Table 5J. WRMTIII Word Attack and ABR. Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *WRMT – III Word Attack*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz).

N	Variable	r	p	MPT.exact.p
49	I_10.9	-0.153	0.29	0.95
50	I_15.4	-0.085	0.56	0.99
50	I_31.25	0.03	0.84	0.98
50	I_46.5	0.05	0.73	0.96
50	I_6.9	-0.065	0.65	0.99
50	I_61.5	0.126	0.38	0.98
49	RC_10.9	-0.008	0.96	0.96
50	RC_15.4	0.124	0.39	0.97
50	RC_31.25	0.054	0.71	0.99
50	RC_46.5	0.067	0.64	1
50	RC_6.9	0.093	0.52	0.99
50	RC_61.5	-0.116	0.42	0.97
49	V_10.9	0.126	0.39	0.98
50	V_15.4	0.168	0.24	0.92
50	V_31.25	**0.277**	**0.05**	0.39
50	V_46.5	**0.312**	**0.03**	0.25
50	V_6.9	0.146	0.31	0.96
50	V_61.5	**0.315**	**0.03**	0.23

Supplemental Table 5K. WRMTIII Word ID and ABR. Pearson's R, probability values, and MPT exact probability values between ABR measures and the standard scores of *WRMT-III Word ID*. ABR measures included wave I & V latencies and the response consistency measure (RC) derived from recordings made at various stimulus presentation rates (6.9, 10.9, 15.4, 31.25, 46.5, 61.5 Hz). Significant relationships are bolded.

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Q3_Expanded Sample.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.001	0.99	0.99
78	Maxtotalyears	-0.06	0.6	0.91
84	Minage	0.013	0.9	0.99
57	YrsSinceTrain	0.063	0.64	0.96

Supplemental Table 6A. V_61.5 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V latencies (61.5 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	0.024	0.84	1
78	Maxtotalyears	-0.023	0.84	0.99
84	Minage	-0.005	0.97	0.97
57	YrsSinceTrain	-0.014	0.92	0.99

Supplemental Table 6B. V_46.5 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V latencies (46.5 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	0.102	0.4	0.8
78	Maxtotalyears	0.053	0.64	0.94
84	Minage	-0.017	0.88	0.88
57	YrsSinceTrain	-0.021	0.88	0.98

Supplemental Table 6C. V_31.25 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V latencies (31.25 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	0.043	0.73	0.99

78	Maxtotalyears	0.028	0.81	0.81
84	Minage	-0.034	0.76	0.98
57	YrsSinceTrain	0.031	0.82	0.96

Supplemental Table 6D. V_15.4 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V latencies (15.4 Hz)*.

N	Variable	r	p	MPT.exact.p
69	Maxprof	0.045	0.71	0.96
77	Maxtotalyears	0.007	0.95	0.96
83	Minage	0.029	0.8	0.95
56	YrsSinceTrain	-0.049	0.72	0.98

Supplemental Table 6E. V_10.9 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V latencies (10.9 Hz)*.

N	Variable	r	p	MPT.exact.ps
70	Maxprof	0.05	0.68	0.9
78	Maxtotalyears	-0.074	0.52	0.88
84	Minage	0.143	0.19	0.58
57	YrsSinceTrain	-0.047	0.73	0.73

Supplemental Table 6F. V_6.9 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-V latencies (6.9 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.087	0.47	0.87
78	Maxtotalyears	-0.072	0.53	0.87
84	Minage	0.038	0.73	0.73
57	YrsSinceTrain	-0.047	0.73	0.91

Supplemental Table 6G. I_61.5 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I latencies (61.5 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.208	0.08	0.25
78	Maxtotalyears	-0.203	0.07	0.22
84	Minage	0.132	0.23	0.49
57	YrsSinceTrain	0.118	0.38	0.39

Supplemental Table 6H. I_46.5 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I latencies (46.5 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.016	0.9	1
78	Maxtotalyears	-0.015	0.9	0.9
84	Minage	0.109	0.32	0.77
57	YrsSinceTrain	-0.015	0.91	0.99

Supplemental Table 6I. I_31.25 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I latencies (31.25 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.064	0.6	0.84
78	Maxtotalyears	-0.163	0.16	0.4
84	Minage	0.167	0.13	0.44
57	YrsSinceTrain	0.006	0.96	0.96

Supplemental Table 6J. I_15.4 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I latencies (15.4 Hz)*.

N	Variable	r	p	MPT.exact.p
69	Maxprof	-0.151	0.22	0.4
77	Maxtotalyears	-0.168	0.14	0.38
83	Minage	0.216	0.05	0.23
56	YrsSinceTrain	-0.094	0.49	0.49

Supplemental Table 6K. I_10.9 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I latencies (10.9 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.07	0.56	0.81
78	Maxtotalyears	-0.094	0.41	0.78
84	Minage	0.163	0.14	0.46
57	YrsSinceTrain	-0.039	0.77	0.77

Supplemental Table 6L. I_6.9 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *wave-I latencies (6.9 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.2	0.1	0.29
78	Maxtotalyears	-0.116	0.31	0.48
84	Minage	0.016	0.89	0.89
57	YrsSinceTrain	0.138	0.3	0.53

Supplemental Table 6M. RC_61.5 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *RC (61.5 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	0.119	0.33	0.51
78	Maxtotalyears	0.19	0.1	0.23
84	Minage	-0.099	0.37	0.38
57	YrsSinceTrain	**-0.268**	**0.04**	0.09

Supplemental Table 6N. RC_46.5 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *RC (46.5 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.206	0.09	0.26
78	Maxtotalyears	-0.102	0.38	0.63
84	Minage	0.12	0.28	0.62
57	YrsSinceTrain	-0.002	0.99	0.99

Supplemental Table 6O. RC_31.25 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *RC (31.25 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.052	0.67	0.66
78	Maxtotalyears	0.063	0.59	0.9
84	Minage	0.06	0.59	0.83
57	YrsSinceTrain	-0.224	0.09	0.19

Supplemental Table 6P. RC_15.4 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *RC (15.4 Hz)*.

N	Variable	r	p	MPT.exact.p
69	Maxprof	-0.141	0.25	0.46
77	Maxtotalyears	0.035	0.76	0.76

83	Minage	-0.052	0.64	0.86
56	YrsSinceTrain	-0.172	0.2	0.41

Supplemental Table 6Q. RC_10.9 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *RC (10.9 Hz)*.

N	Variable	r	p	MPT.exact.p
70	Maxprof	-0.09	0.46	0.86
78	Maxtotalyears	0.026	0.82	0.96
84	Minage	0.025	0.82	0.82
57	YrsSinceTrain	-0.088	0.51	0.8

Supplemental Table 6R. RC_6.9 and Music. Pearson's R, probability values, and MPT exact probability values between each music-training variable and the absolute latencies of the *RC (6.9 Hz)*.