Behavioral and Neurophysiological Effects of Treated and Untreated Hearing Loss in Older Adults

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Abstract

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The purpose of this dissertation work was to examine the impact of auditory deprivation in the form of age-related hearing loss (ARHL) and auditory stimulation in the form of hearing aid use, on the neural registration and abilities to use sound for higher level cognitive tasks, in older adults (aged 55-75). Three groups were examined: 1) NH: older adults with clinically normal hearing, 2) u-HL: peers with bilateral mild to moderate/moderately- severe sensory-neural hearing loss who have never worn hearing aids and 3) t-HL: peers with a similar amount of hearing loss, but who have been treated through binaural amplification (hearing aids). Participants completed two sessions: 1) Behavioral tests: Audiometry, cognitive screening, quality of life questionnaires, nonverbal IQ test, speech recognition in quiet and noise, and tests of verbal working memory function (both auditory and visual); 2) Electrophysiology: Evoked potentials (P1-N1-P2) recorded in response to a speech syllable presented at two different

sound levels (equal sound pressure level (SPL) and equal sensation level (SL)). All three groups performed similarly on tests of speech perception in noise, working memory and nonverbal IQ, but differed on self-report measures of hearing handicap. Both hearing loss groups indicated greater reported greater hearing handicap (HHIE) than NH groups. Additionally, individuals with untreated hearing loss showed a positive relationship between working memory performance and speech understanding in noise. Neural measures indicated significant morphological differences (latency and amplitude) between groups, but only when the stimuli were presented at equal SPL. Once audibility was accounted for (equal SL levels) these differences were not present, suggesting group differences were due to audibility, and not central changes secondary to auditory deprivation. Results highlight the importance of the audibility of sound, and suggest that early sound processing and later use of sound for processes involved in communication is not permanently affected by mild to moderate/moderately-severe ARHL.

Acknowledgements

This work would not have been possible, if not for the loving support of my amazing family and friends, guidance from my committee members, encouragement from the faculty and staff of the department of Speech and Hearing Sciences, camaraderie within the Brain and Behavior Lab, and the generosity of the participants involved in this study, who spent hours of their time in the basement with me, with the desire to improve the lives of individuals with hearing loss. From the bottom of my heart, I thank you.

Special thanks to Kelly Tremblay for her mentorship through this adventure and to all the members of the Brain and Behavior Lab, past and present.

Science is not only a disciple of reason, but, also, one of romance and passion.

-Stephen Hawking

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Chapter 1. General Introduction

There is a significant and timely interest in health disorders that emerge later in life. Age-related hearing loss (ARHL), a progressive primarily high frequency hearing loss that is partly due to cochlear hair cell degeneration, is becoming a considerable public health concern, given that by the age of 65, 1 out of every 3 adults will experience some degree of hearing loss. The prevalence increases to 1 in 2 by 70 years of age (Cruickshanks et al., 2003; Nash et al., 2011; NIDCD 77 2013). There is no known cure for ARHL, at this time, and treatment is limited to the use of hearing assistive technology (HAT), including amplification devices (e.g., hearing aids). HAT aims to provide individuals with greater access to speech information through increased sound levels. Even though the use of hearing aids has been shown to relate to decreased hearing handicap and improved quality of life (e.g. Chisolm et al., 2007), the majority of individuals with ARHL do not use amplification (Popelka et al., 1998; Kochkin, 2009; NIH-NIDCD statistics-National Health Interview Survey 2012). The National Institute on Deafness and Other Communication Disorders (NIDCD) estimates that of the older adults in the United States who could benefit from hearing aids, less than one third seek treatment (NIDCD statistics), indicating that tens of millions in the United States, and likely hundreds of millions worldwide, are living with a significant auditory sensory deficit. Consequences of ARHL include, but are not limited, to: social isolation (Weinstein & Ventry, 1982; Cherko, Hickson, & Bhutta, 2016; Solheim, Kværner, & Falkenberg, 2011), depression (Boi et al., 2012; Huang, Dong, Lu, Yue, & Liu, 2010; Mulrow et al., 1990) and, possibly, cognitive decline and dementia (Deal et

al., 2016; Lin, 2011; Lin et al., 2011; Lin et al., 2013; Lin & Albert, 2014; Panza, Solfrizzi, & Logroscino, 2015). The precise way in which hearing loss contributes to social and cognitive decline is not known; however, neuroimaging tools are being used to define the effects of aging and hearing loss on the brain as well as their functional correlates. What follows is a brief review of the literature on these topics.

Auditory peripheral damage, such as cochlear hair cell loss, not only reduces the level of sound arriving at the cortex, it can also cause permanent neural atrophy downstream; resulting in central effects of this peripheral pathology (CEPP). For example Willott (1996) and others have shown that animals who express an age-related related, or presbycusis-like hearing deficits at a young age (C57BL/J6 “black 6” mice) show multiple downstream consequences; including, synaptic and neuronal losses along the auditory pathway and at auditory cortex (Willott, Parham, & Hunter, 1991; Willott & Bross, 1996; Kazee et al., 1995), changes in auditory cortical frequency representation (Willott, Aitkin, & McFadden, 1993; Carlson & Willott, 1996), abnormal temporal processing (Zhong, Henry, & Heinz, 2014; Eggermont, 2016) and dysfunction of the excitatory and inhibitory neurotransmitter system (Alvarado, Fuentes-Santamaría, Gabaldón-Ull, Blanco, & Juiz, 2014; Profant et al., 2013). Central auditory system changes subsequent to ARHL, have additionally been reported in the human literature, using various neuroimaging techniques including EEG and fMRI; including, but not limited to auditory cortex atrophy and brain volume decline (Eckert, Cute, Vaden, Kuchinsky, & Dubno, 2012; Lin et al., 2014), altered functional connectivity between sensory cortices (Puschmann & Thiel, 2016), changes in glutamate and lactate levels in the auditory cortex (Profant et al., 2013) and a downregulation of neural activity during

speech processing (Peelle, Troiani, Grossman, & Wingfield, 2011). Thus, it can be surmised that the resulting poor quality of auditory input as sound is relayed to, and processed in, the brain, significantly contributes to communication difficulties.

Another contributing factor to the decline in auditory function among older adults is the aging process itself. Willott (1996) documented the central effects of biological aging (CEBA) by examining changes that occur in multiple ascending auditory nuclei, as well as in primary and secondary auditory cortical areas, of aging animals that retain good auditory sensitivity throughout their life span (e.g. CBA/CaJ mice and Fischer rats). They reported reductions in GABA enzyme producing neurons and GABAergic sensitivity critical for normal inhibitory function (Ling, Hughes, & Caspary, 2005; Burianova, Ouda, Profant, & Syka, 2009; Stebbings et al., 2016) as well as a reduction in the number of interneurons involved in stimulus detection and selectivity (de Villers-Sidani et al., 2010; Martin del Campo, Measor, & Razak, 2012) see (Willott, 1996; Bowl & Dawson, 2015, for review). In humans, neuroimaging tools reveal deleterious changes occurring in concert with the aging process; affecting the central auditory nervous system and beyond. Grady (2012) reported on research consistently showing age-related decline in cognitive processes involved in human communication, including executive functions of working memory and attention (Balota, Dolan, & Duchek, 2000; Connelly, Hasher, & Zacks, 1991; Zacks, Hasher, & Li, 2000; Allen & Crozier, 1992; Madden, 1990), the ability to inhibit irrelevant information (Hasher, Stoltzfus, Zacks, & Rypma, 1991) and task-switching (Kramer, Hahn, & Gopher, 1999). Theoretical explanations for these functional deficits include generalized slowing of central nervous system function (e.g. Salthouse, Hancock, Meinz, & Hambrick, 1996), compensatory

increases in brain activity (Cabeza, Anderson, Locantore, & McIntosh, 2002), dedifferentiation (Wilson, Segawa, Hizel, Boyle, & Bennett, 2012), and structural changes in the brain, including decreases in both grey and white matter, in areas important for speech and language understanding (Eckert et al., 2012; Peelle et al., 2011; Grady, 2012, for a comprehensive review). Collectively, these physiological changes might help to explain why older adults often describe having difficulty hearing in noise, even when there is no evidence of peripheral, cochlear, damage. Moreover, the typical person who experiences ARHL is presumed to be doubly disadvantage, because they have experienced the cumulative effects of both CEBA and CEPP.

There is tremendous interest in understanding the relationship between ARHL and cognitive decline. Decades of research in the psychological sciences has established a correlation between sensory and cognitive function (for review see Schneider & Pichora-Fuller, 2000; Deal et al., 2015; Deal et al., 2016; Lin, 2011; Lin et al., 2011; Lin, 2012; Lin et al., 2013; Lin et al., 2014; Lin & Albert, 2014). Even though a causal link has not been established, hearing aid amplification is being marketed as a protective treatment to reduce the risk of cognitive decline (http://www.hearingreview.com/2015/10/new-study-shows-hearing-aids-reduce-risk-of-cognitive-decline-in-older-adults/). What is more, recent publications propose using neuroimaging (e.g., EEG, MEG) tools in the clinic to determine those at risk for hearing loss related cognitive decline (Campbell & Sharma, 2013; Lister et al., 2016). This line of reasoning, however, is built on a literature base that is not without confounds: 1) tests of cognitive function require individuals to listen to and repeat words, and performance on such measures may reflect deficits in audibility rather than cognitive problems

(Dupuis et al., 2015; Jorgensen, Palmer, Pratt, Erickson, & Moncrieff, 2016), and 2) the physiological responses purported to indicate the presence of cognitive changes are influenced by the audibility of the stimulus used to evoked the response; a detail that is often overlooked.

Impact of ARHL or Decreased Audibility?

The inability to hear instructions and test items can hinder one's performance on any standard test measure. Notably, older individuals' performance on measures of cognitive function has been shown to decline with degraded sensory input, not only for those with known hearing deficits, but also listeners with no or only minimal hearing impairment (Dupuis et al., 2015; McCoy et al., 2005; Rabbitt, 1990; Uhlmann, Teri, Rees, Mozlowski, & Larson, 1989; Weinstein & Amsel, 1986). Therefore, performance on such tests may be further hindered by decreased audibility due to hearing loss. For example, Jorgensen et al (2016) examined the effects of audibility on a widely used cognitive screening test, called the Mini-Mental Status Exam (MMSE). They found, in a group of young normal hearing listeners, that performance worsened with decreased audibility of test instruction. Additionally, Dupuis et al (2016) found that older individuals with hearing loss consistently scored poorer on the Montreal Cognitive Assessment (MoCA) Test and were more negatively impacted by the presence of background noise in the test environment. These results suggest that estimates of cognitive decline might be inflated if hearing loss is not taken into account. It is therefore possible that the connection between auditory deprivation and changes in higher-level cognitive function is, at least partially, a result of poor audibility during cognitive testing/screening.

Neuroimaging tools, electro- (EEG) and magneto- (MEG) encephalograhpic measures, especially auditory evoked potentials/fields, are also affected by sound level (for a review, see: (Eggermont & Ponton, 2002). Sounds (e.g. tones, noise, speech) used to evoke responses are typically presented at one sound level for all participants; loud enough to ensure audibility regardless of hearing status. However, when only one presentation level is used, individuals with ARHL experience sounds at a reduced level. One way to account for differences in hearing status is to present sounds at an equal sensation level (SL), for instance 40 dB above a participant's pure-tone threshold, which, in part, accounts for differences in auditory sensitivity between groups of individuals with and without hearing loss. For example, in a study of the impact of age on interaural phase difference detection, Ross et al (2007) accounted for individual differences in hearing status by presenting each stimulus at 60 dB above each participant's threshold for the stimuli used in the study. Others have presented stimuli at a particular sensation level, relative to a participant's pure-tone average or detection threshold at a specific frequency (e.g. Bidelman, Villafuerte, Moreno, & Alain, 2014). An additional way to account for differences in hearing abilities is to simulate an equal amount of hearing loss for all participants. While this approach has been used in behavioral studies involving older adults (e.g. Humes, 2007), it has seldom been used to study the effects of ARHL on auditory evoked responses. Therefore, when there are dissimilarities in response timing or strength of evoked response measurements between older individuals with hearing loss and those with normal hearing, it is important to determine if the differences are rightly related to the research question (i.e.,

cognitive decline, speech perception in noise), or a confound related to decreased audibility.

Auditory Stimulation via Hearing Aid Amplification

The effects of stimulating the brain (brainstem and cortex) acoustically have been studied in different ways; such as, repeated sound exposure (Sheehan, McArthur, & Bishop, 2005; Tremblay, Inoue, McClannahan, & Ross, 2010), auditory training (Anderson & Kraus, 2013; Anderson, White-Schwoch, Parbery-Clark, & Kraus, 2013; Tremblay & Kraus, 2002; Tremblay, Shahin, Picton, & Ross, 2009; Tremblay, Ross, Inoue, McClannahan, & Collet, 2014; White-Schwoch, Carr, Anderson, Strait, & Kraus, 2013; Alain, Zendel, Hutka, & Bidelman, 2014) and lifelong musical learning (Seppänen, Hämäläinen, Pesonen, & Tervaniemi, 2012; Shahin, Bosnyak, Trainor, & Roberts, 2003). Collectively, results from these studies indicate that stimulating the brain with sound enhances the conduction speed and/or strength of the neural response to sound. Such enhanced sound processing may, in turn, positively contribute to performance in higher level cognitively demanding tasks such as understanding speech in noise. However, few studies have investigated the effects of auditory stimulation, through daily hearing aid use, on the brain (Bertoli, Probst, & Bodmer, 2011; Dawes, Munro, Kalluri, & Edwards, 2014b), and even less is known regarding neuroplastic changes in relation to auditory function in every day listening environments. Thus, there is insufficient research to determine if the use of amplification alters the way the brain responds to sound, or one's ability to use those new amplified sounds during higher level, more cognitively demanding processes (Bertoli et al., 2011; Contrera et al., 2016; Dawes et al., 2015b; Dawes et al., 2015a). Moreover, little is known about the relationship

between amplification related changes in neural activity in relation to specific perceptual measures known to be affected by age and hearing loss, and ultimately influence global communication abilities (e.g., speech recognition in noise or working memory function).

With these gaps in knowledge in mind, the current program of research was designed to characterize the behavioral and neurophysiological impact of auditory deprivation and auditory stimulation in older individuals with ARHL, in comparison to their normal hearing peers. In addition, we sought to control for the confounding factors of stimulus audibility, and screened all participants for mild cognitive impairment to ensure differences due to auditory deprivation or stimulation were not contaminated by pre-existing deficits in cognitive function. A cross-sectional design was used, as it is not possible to determine the onset of ARHL. Three groups of older adults with different hearing abilities were compared; normal hearing, untreated ARHL, and treated (via hearing aids) ARHL.

This dissertation includes two manuscript drafts that will be submitted for publication within the next few months. The first article addresses the effects of **auditory deprivation and auditory stimulation** on the **neural registration and use of sound** for speech perception in noise. The second article addresses the effects of **auditory deprivation and auditory stimulation** on **self-reported and behavioral measures of auditory function and the relationship between speech perception in noise and working memory function.** References for both manuscripts can be found at the end of this dissertation document.

Research Questions

1) What are the effects of auditory deprivation, in the form of ARHL, and auditory stimulation, in the form of binaural hearing aid use, on the neural registration and use of sound in older adults?

Hypothesis: Protracted auditory deprivation, in individuals with untreated ARHL (u-HL), leads to changes in the morphology and scalp distribution of early auditory cortical evoked responses. Auditory stimulation via daily use of amplification may ameliorate these changes, in individuals with treated ARHL (t-HL). Changes in the neural registration of sound impacts one's ability to use sound for higher level processes critical for speech communication, including understanding speech in noise, working memory function, and self perceived hearing abilities.

2) What is the relationship between working memory function and speech perception in noise abilities for individuals with normal hearing compared with treated and untreated hearing loss?

Hypothesis: Age-related hearing loss affects the sensory-cognitive relationship between speech perception and working memory due to the deleterious effects of protracted auditory deprivation on the central auditory nervous system. Stimulation of the auditory system through amplification may ameliorate these effects.

Chapter 2. The Effects of Untreated and Treated Hearing Loss on the Neural Registration and Use of Sound in Older Adults

A. Introduction

With the world's aging population increasing, age-related sensory-neural hearing loss (ARHL) will affect a growing number of individuals globally. Most concerning is that approximately two thirds of those with hearing loss do not pursue treatment with hearing aids (NIH-NIDCD-National Health Interview Survey 2012). When left untreated, progressive ARHL has been shown to correlate with decreased speech understanding, both in quiet and in noise (Akeroyd, 2008; Dubno et al., 2008), social withdrawal (Singh & Kathleen Pichora-Fuller, 2010), an increase in falls (Viljanen et al., 2009), depression (Huang et al., 2010) and cognitive decline, including decreased working memory function and dementia (Deal et al., 2015; Gurgel et al., 2014; Lin, 2011; Lin et al., 2011; Lin et al., 2013). Collectively, these findings suggest that the effects of sound deprivation may extend beyond sensory aspects of the auditory system, and that a large proportion of the population is at risk for experiencing such consequences. For these reasons, there is interest in understanding the link(s) between sensory deprivation and stimulation on the brain, as it relates to aging, hearing loss, and hearing aid use (Albers et al., 2015; Grady, 2012, for reviews).

In this study, we set out to characterize the effects of ARHL, as well as hearing aid use, on the neural detection and perception of sound and speech. Hearing loss related to auditory peripheral damage, such as cochlear hair cell loss, is known to

reduce the level of sound arriving at the cortex. It also causes permanent neural atrophy along the ascending auditory nervous system; resulting in central effects of this peripheral pathology (CEPP). For example, Willott (1996) and others have shown that animals who express presbycusis-like hearing deficits at a young age (C57BL/J6 “black 6” mice) show multiple central consequences; including, synaptic and neuronal losses along the auditory pathway and at auditory cortex (Willott et al., 1991; Willott & Bross, 1996; Kazee et al., 1995), changes in auditory cortical frequency representation (Willott et al., 1993; Carlson & Willott, 1996), abnormal temporal processing (Zhong et al., 2014; Eggermont, 2016) and dysfunction of the excitatory and inhibitory neurotransmitter system (Alvarado et al., 2014; Profant et al., 2013). Central auditory system changes subsequent to ARHL, have additionally been reported in the human literature, using various neuroimaging techniques including EEG and fMRI; including, but not limited to auditory cortex atrophy and brain volume decline (Eckert et al., 2012; Lin et al., 2014), altered functional connectivity between sensory cortices (Puschmann & Thiel, 2016), changes in glutamate and lactate levels in the auditory cortex (Profant et al., 2013) and a downregulation of neural activity during speech processing (Peelle et al., 2011). Thus, the resulting poor quality of auditory input, affecting the way sound is relayed to, and processed in, the brain, is believed to significantly contribute to auditory communication difficulties.

Another contributing factor to the decline in auditory function among older adults is the aging process itself. Willott (1996) documented the central effects of biological aging (CEBA) by examining changes that occur in multiple ascending auditory nuclei, as well as in primary and secondary auditory cortical areas, of aging animals that retain

good auditory sensitivity throughout their life span (e.g. CBA/CaJ mice and Fischer rats). They reported reductions in GABA enzyme producing neurons and GABAergic sensitivity critical for normal inhibitory function (Ling et al., 2005; Stebbings et al., 2016; Burianova et al., 2009) as well as a reduction in the number of interneurons involved in stimulus detection and selectivity (de Villers-Sidani et al., 2010; Martin del Campo et al., 2012) see (Willott, 1996; Bowl & Dawson, 2015). In humans, neuroimaging tools reveal deleterious changes occurring in concert with the aging process; affecting the central auditory nervous system and beyond. In Grady's (2012) review of the literature, there are consistent reports of age-related cognitive decline, including executive functions of working memory and attention (Balota et al., 2000; Hasher et al., 1991; Connelly et al., 1991; Allen & Crozier, 1992; Madden, 1990) the ability to inhibit irrelevant information (Hasher, Zacks, & Rahhal, 1999; Zacks et al., 2000) and task-switching (Kramer et al., 1999). Theoretical explanations for these functional deficits include generalized slowing of central nervous system function (e.g. Salthouse et al., 1996), compensatory increases in brain activity (Cabeza et al., 2002), dedifferentiation (Wilson et al., 2012), and structural changes in the brain, including decreases in both grey and white matter, in areas important for speech and language understanding (Eckert et al., 2012; Peelle et al., 2011). Collectively, these physiological changes might help to explain why older adults often describe having difficulty hearing in noise, even when there is no evidence of peripheral, cochlear, damage. In this respect, the typical person who experiences ARHL can be presumed to be doubly disadvantage, because they have experienced the cumulative effects of both CEBA and CEPP.

There is interest in defining how neural networks are affected by sound deprivation and/or stimulation, because the results could help to define the limits and benefits of clinical interventions. For this reason, we chose to characterize the effects of **auditory deprivation (ARHL) and auditory stimulation (treatment through hearing aid use)** on the **neural registration** of sound in older adults. More specifically, we set out to determine if and how the neural registration of sound relates to **speech understanding in noise;** an ability often compromised by advancing age and ARHL**.** We hypothesized that auditory deprivation, in the form of age-related hearing loss, would negatively impact the speed and strength of the neural registration of sound and correlate with diminished speech recognition in noise, in older cognitively intact adults, once differences in audibility were accounted for through the use of sensation level stimuli. To test this hypothesis, we used an EEG measure called the P1-N1-P2 complex, known to reflect signal detection at the level of the auditory cortex. These EEG responses, as well as performance on a speech in noise test were obtained from three groups of older adults; those with normal hearing (NH), untreated hearing loss (u-HL), and treated hearing loss (t-HL).

The auditory P1-N1-P2 complex is an EEG response commonly included in test protocols to assess various types of hearing losses. It also has a history of use in studies of the effects of auditory deprivation and, less commonly, auditory stimulation in older adults (for a review, see Picton, 2013; Picton & Durieux-Smith, 1988). The auditory P1-N1-P2 is an onset response thought to index the arrival and initial stages of sound processing at the level of the auditory cortex (Hillyard & Kutas, 1983). The response complex is a series of positive and negative deflections in the scalp recorded

EEG between 50-250 milliseconds (ms) following the presentation of sound, and is sensitive to the acoustic parameters of the evoking stimulus; with increases in stimulus intensity generally leading to increased response amplitude and decreased response latency (see Hyde, 1997, for a review). Historically, the P1-N1-P2 is one of the most studied and characterized EEG responses, dating back to 1939 (Davis, 1939). When used to examine the effects of aging on older adults with clinically defined normal hearing, converging evidence of delayed neural transmission of sound, demonstrated by prolonged P2 responses, was found (Bertoli, Smurzynski, & Probst, 2005; Tremblay, Piskosz, & Souza, 2002; Tremblay, Piskosz, & Souza, 2003; Welsh, Welsh, & Healy, 1985; Bidelman et al., 2014; Lister, Maxfield, Pitt, & Gonzalez, 2011; Ross, Fujioka, Tremblay, & Picton, 2007). Additional findings suggest that age may impact cortical sound processing through reduced inhibitory mechanisms, resulting in larger N1 amplitudes (Herrmann, Henry, Johnsrude, & Obleser, 2016; Tremblay et al., 2003; Amenedo & Díaz, 1998; Bidelman et al., 2014; Harkrider, Plyler, & Hedrick, 2005; Harkrider, Plyler, & Hedrick, 2006).

Less is known about the long-term effects of auditory deprivation due to peripheral hearing loss, on the neural registration of sound. Some studies have shown an increase in response amplitude, particularly of the P2, that is attributed to hearing loss (Amenedo & Díaz, 1998; Anderer, Semlitsch, & Saletu, 1996; Bertoli et al., 2005; Dushanova & Christov, 2013; Harkrider et al., 2005; Harkrider et al., 2006; Smith, Michalewski, Brent, & Thompson, 1980; Campbell & Sharma, 2013). Prolonged latencies of one or more components of the P1-N1-P2 response, thought to indicate slower neural conduction and deficits in auditory temporal processing, have also been

reported (Goodin, Squires, Henderson, & Starr, 1978; Iragui, Kutas, Mitchiner, & Hillyard, 1993; Tremblay et al., 2002; Ross & Tremblay, 2009; Kim et al., 2012; Pfefferbaum, Ford, Roth, & Kopell, 1980; Brown, Marsh, & LaRue, 1983; Harkrider et al., 2005; Harkrider et al., 2006). Other studies have found equivalent (Spink, Johannsen, & Pirsig, 1979; Papanicolaou, Loring, & Eisenberg, 1984; Vesco, Bone, Ryan, & Polich, 1993; Polich, 1997) or smaller amplitudes (Goodin et al., 1978; Harris, Wilson, Eckert, & Dubno, 2012; Picton, Stuss, Champagne, & Nelson, 1984). Thus, there lacks a consensus on the effects of auditory deprivation in aging adults on early cortical sound processing. Part of the reason likely relates to methodological differences in stimuli used to elicit responses; such as varied inter-stimulus intervals, and stimulus audibility.

Close attention to the methodological contributions to previously published results is critical, because it has been suggested that these auditory evoked responses, specifically the P2, could serve as early detectors of higher-level decline; including impaired speech perception in noise and even cognitive decline (Campbell & Sharma, 2013; Lister et al., 2016). For example, Campbell and Sharma (2013) recorded auditory P1-N1-P2 responses to a speech syllable (/ba/). They focused a portion of their analyses on a subset of fronto-central electrodes and found that individuals with hearing loss had longer latency and larger amplitude auditory P2 responses, when compared with their normal hearing peers. They also found that the latency of the P2 component was correlated with performance on a measure of speech understanding in noise, the Quick Speech in Noise test (QuickSIN); with longer latency related to poorer speech scores. They interpreted larger and later P2 potentials, along with decreased temporal

and increased frontal cortical activity measured using current density reconstruction, as representative of cortical reorganization, or resource re-allocation, resultant from auditory deprivation. One important limitation of Campbell and Sharma (2013), similar to many of the previously cited studies, was the use of one stimulus presentation level to elicit responses for individuals with and without ARHL. Decreased stimulus audibility is long known to generate P1-N1-P2 responses that are prolonged in latency and weaker in amplitude because age-related hearing loss attenuates parts of the signal to various degrees. This means, the prolonged P2 latencies reported by Campbell and Sharma (2013) and others, may reflect reduced audibility and not necessarily cortical resource re-allocation.

There are several ways audibility issues can be addressed when studying participants with and without hearing loss. One way is to present sounds at an equal sensation level (SL). For example, Ross et al (2007) accounted for individual differences in hearing status by presenting each stimulus 60 dB above each participant's threshold for the specific stimulus used in the study. Others have presented stimuli at a particular sensation level, relative to an individual's pure-tone average or threshold at a specific frequency (e.g. (Bidelman et al., 2014). An additional way to account for differences in auditory thresholds is to simulate an equal amount of hearing loss for all participants. While this latter approach has been used in behavioral studies involving older adults (see (Humes, 2007), it has seldom been used to study the effects of ARHL on auditory evoked responses. Therefore, when there are dissimilarities in response timing or strength of evoked response measurements between older individuals with hearing loss and those with normal hearing, it is unclear whether

differences are related to the research question (i.e., speech perception in noise or cognitive decline), or, rather, a confound related to decreased audibility.

Lastly, few studies involving ARHL report whether or not participants have been treated for hearing loss through daily use of binaural amplification. Characterizing the neurophysiological differences between those who do and do not utilize amplification is significant, as studies have shown that sound stimulation alters the morphology of the P1-N1-P2 complex (Shahin et al., 2003; Sheehan et al., 2005; Tremblay et al., 2010; Tremblay et al., 2014). These effects are robust, even when different forms of auditory stimulation were examined; such as, repeated sound exposure (Tremblay et al., 2010), auditory training (Anderson & Kraus, 2013; Anderson et al., 2013; Tremblay & Kraus, 2002; Tremblay et al., 2009; Tremblay et al., 2014; White-Schwoch et al., 2013) and lifelong musical learning (Seppänen et al., 2012; Shahin et al., 2003). Thus, there is evidence in the literature to substantiate claims that the neural registration of sound, as reflected by the P1-N1-P2 response, is affected by one's listening experience, which may, in turn, have subsequent effects on higher level, more cognitively demanding tasks that involve the use of sound.

Hearing aids can also be viewed as a tool for stimulating a formerly deprived auditory system, but there is a paucity of studies that approach amplification in this manner. A few studies have looked at possible neural correlates of hearing aid acclimatization (Dawes et al., 2014b; Bertoli et al., 2011), defined here as an improvement in auditory performance over time that is not due to practice or training, but instead associated with perceptual learning due to improved access to sound and speech (Arlinger et al., 1996). Dawes et al., (2014) measured auditory evoked P1-N1-

P2 responses in first time hearing aid users, prior to and following 12 weeks of monaural or binaural hearing aid use. Although they did not report any significant changes in P1-N1-P2 amplitudes or latencies; their analyses were limited to a single vertex electrode. Temporal electrodes have been shown to be more sensitive to morphological changes associated with auditory stimulation, such as repeated stimulus exposure (Tremblay et al., 2010). Bertoli et al (2011) examined P1-N1-P2 response properties across groups composed of experienced bilateral or unilateral hearing aid users and normal hearing controls. They found larger P2 amplitudes for individuals with unilaterally fit amplification, however, similar to previous studies, they focused analyses on central electrodes. Additionally, the authors reported that unilateral users were significantly older than bilateral hearing aid users or those with normal hearing, which may have contributed to group effects.

To better understand the effects of auditory deprivation (ARHL) and stimulation (hearing aid amplification) on the neural registration of sound, we compared auditory P1-N1-P2 latency and amplitude characteristics across three age-matched groups of older adults with different auditory experiences, which consisted of 10 older adults with normal hearing, 10 with a bilateral, mild sloping to moderate/moderately severe sensory neural hearing loss who have never worn hearing aids, and 10 with comparable hearing loss who have been using binaural amplification consistently for at least the past two years. This study controlled for stimulus audibility through the use of two stimulus levels: equal sound pressure level and equal sensation level, as well as used an objective, data driven analysis to determine where and when differences in brain responses occurred between groups.

B. Methods

All procedures were approved by the Institutional Review Board of the University of Washington. Participants were recruited from the University of Washington Speech and Hearing Clinic, the University of Washington Communication Studies Participant Pool (P30-DC04661), study fliers posted at Seattle area businesses, and word of mouth. All participants gave written, informed consent prior to participation and were paid for their time.

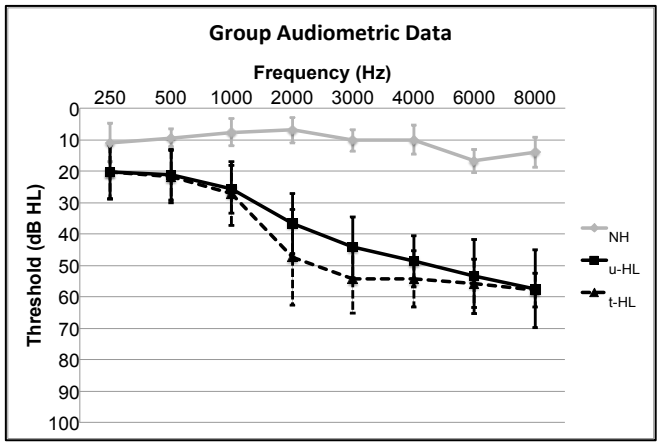

Figure 1. Audiometric data for each group. Thresholds were averaged between ears at each frequency. Error bars represent standard deviation.

Participants

Participants were monolingual English speaking non-musicians, aged 60-72 years, with no reported history of neurological disorders. Age matched groups included: Normal hearing (NH) adults (N=10, aged 63-70, M=66.3, SD=2, 9 female) with clinically normal hearing defined as pure tone thresholds 25 dB HL or better from 250-8000 Hz. Adults with untreated hearing loss (u-HL) (N=10, aged 60-72, M=67.4, SD=4, 9 female) with bilaterally symmetrical mild to moderate/moderately-severe sensory-neural hearing loss who have never worn hearing aids. Individuals with treated hearing loss (t-HL) (N=10, aged 62-72, M=67.7, SD=4, 3 female) bilaterally symmetrical mild to moderate/moderately-severe sensory-neural hearing loss who wear binaural amplification on a daily basis (6+ hours/day), and had done so for at least the past two

years. All individuals in the t-HL group wore binaural receiver-in-the-ear (RITE) style digital hearing aids with universal domes or custom earmolds; a variety of manufacturers was represented. See Figure 1 for group averaged audiometric data, averaged between ears, at octave frequencies from 250-8000 Hz.

Participants were screened for mild cognitive impairment using the Montreal Cognitive Assessment Test (MoCA) (Nasreddine et al., 2005). All participants enrolled in this study scored above 23 points; the cutoff score described as having 96% sensitivity and 95% specificity for mild cognitive impairment (Luis, Keegan, & Mullan, 2009).

Procedure

Prior to neurophysiology and speech in noise perception testing, all participants completed the following: bilateral pure-tone air and bone conduction audiometry (Madsen Astera, Otometrics: Taastrup, Denmark or 61 Grason-Stadler Inc. (GSI): Eden Prairie, USA) using the modified Hughson-Westlake procedure (Carhart & Jerger, 1959; Carhart & Jerger, 1959), bilateral word recognition testing in quiet (Auditec recordings of Northwestern University Auditory Test Number Six materials) at 40 dB sensation level (SL) re: 3 frequency pure-tone average (PTA) or louder (masking used when appropriate, to avoid crossover), and bilateral tympanometry to measure middle ear function (Tympstar, GSI: Eden Prairie, USA). Hearing aid response, across frequency, was assessed at 55, 65, and 70 dB SPL using the standard speech passage and maximum power output (MPO), using the Verifit I system (Audioscan, Etymonic Design Inc.: Dorchester, Ontario, Canada) in the on-ear mode via a probe tube microphone inserted into the participant's ear canal. Hearing aid response was compared to

National Acoustic Laboratory non-linear 2 (NAL-NL2) targets calculated by the Verifit I system. The devices of all participants were within 10 dB of NAL-NL2 targets from 250-2000 Hz with the exception of 1 participant (12 dB down from NAL-NL2 target at 2000 Hz only). Seven of the ten participant's devices were within 10 dB of NAL-NL2 targets at 3000 Hz and five out of ten at 4000 Hz. Devices were not adjusted under this protocol. Mean evaluation times approximated 60 minutes.

Electrophysiology (EEG)

Stimuli

Two stimuli were presented in a block design, one representing equal sound pressure level (SPL), the other representing equal sensation level (SL). The two stimulus presentation levels allowed us to study the effects of stimulus level on ERP responses.

Equal Sound Pressure Level (SPL): 180 ms Klatt synthesized /ba/ speech token, used in previous studies (Tremblay et al 1997 through 2014; see Figure 2). The 60 ms period of silence at the beginning of each stimulus was accounted for within this study's stimulus presentation program. SPL stimuli were presented at 71 dBC SPL binaurally through insert earphones (ER4B, Etymotic Research: Elk Grove, IL), for all study participants.

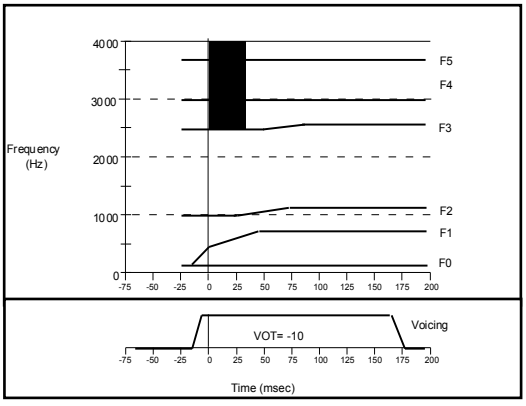

Figure 2. Klatt synthesized pre-voiced /ba/ stimulus. Duration 180 ms, -10 ms prevoicing. See (Tremblay, Kraus, Carrell, & McGee, 1997; Tremblay, Kraus, & McGee, 1998) **for further discussion and information regarding generation of this stimulus.**

Equal Sensation Level (SL): 180 ms Klatt synthesized /ba/ speech token (same as previously

described for SPL), filtered according to the following method to approximate a 40 dB sensation level (SL) stimulus for all participants. Filtering was executed through a custom MATLAB program. A target audiogram was created, representing a mild to severe hearing loss. Specifically, 40 dB HL from .25-1 kHz, 60 dB HL at 2 kHz, 65 dB HL at 3 kHz, 70 dB HL at 4 kHz, and 85 dB HL 5000 Hz (sampling rate of the /ba/ (10,000 Hz) resulted in no stimulus energy above the Nyquist frequency of 5000 Hz). Participant's audiometric thresholds averaged between ears at octave frequencies from 250-5000 Hz, (thresholds at 5000 Hz were approximated by averaging thresholds at 4000 and 6000 Hz, as all audiometric profiles were downward sloping at these frequencies) were subtracted from the target audiogram values. The difference values generated, in dB HL, were interpolated across frequency to create a spectral filter. The spectral filter was applied to the amplitude spectrum of the original /ba/ stimulus. The newly generated stimulus was reconstructed in the time domain via an inverse discrete fast Fourier transform with a 5 ms Hanning window added to both the onset and offset of the stimulus. This process resulted in an individualized stimulus for each participant.

Each participant's stimulus was calibrated to a 46.2 dBC SPL stimulus, representing 40 dB SL for an ideal listener with thresholds of 0 dB HL across all frequencies (Pure-tone average at 500 (8.5 dB SPL), 1000 (3.5 dB SPL) and 2000 (6.5 dB SPL) Hz; PTA = 6.2 dB SPL). Calibration was performed with a Larson Davis system 824 sound level meter and an occluded ear simulator (AEC204). Intensity level of SL stimuli averaged 56.4 dB C SPL (SD=4.0) for NH, 72.2 dB C SPL (SD=7.0) u-HL, and 76.6 dB C SPL (SD=8.2) t-HL.

Stimulus Presentation

Stimuli were presented using a custom MATLAB program (version R2013b, The Mathworks, Inc., Natick, MA) and System 2 Real Time Processor (TDT-RP2; Tucker Davis Technologies, Alachua FL). Stimuli were routed through a microphone amplifier (TDT-MA2) to a programmable sound attenuator (TDT-PA5) through a headphone buffer (TDT-HB6) and to bilateral insert earphones. Two blocks of 410 stimuli (1 block each: SL, SPL), approximately 15 minutes per block, were presented with a randomly jittered inter-stimulus interval (offset to onset) of 2-2.25 seconds to avoid anticipatory responses. Presentation order of the two blocks was balanced across groups.

Acquisition

EEG recordings were completed in a sound-attenuated booth. A passive EEG paradigm was used, meaning participants were instructed to watch a closed caption movie of their choice while staying still and alert, and were told to ignore the sounds being played through the earphones. Following the first block of stimuli, each participant was given a 3-5 minute break, at which time they could stand and stretch, if desired.

Continuous EEG signals were recorded with a custom 64-channel electrode cap (Electro-cap International), and Neuroscan system software (SCAN, version 4.5) with Synamps2 amplifier (Compumedics). The electrode montage followed an extended 10-20 system, including 4 ocular (EOG) channels to monitor horizontal and vertical eye movement, vertex (CZ) reference channel, and AFZ ground channel. Electrode impedance was kept below 5 kΩ. EEG signals were bandpass filtered from .1 to 100 Hz with 12 dB/octave roll off, amplified with a gain of 2010x and digitized at a sampling rate of 1000 Hz.

Analysis

Offline analysis was completed using a custom MATLAB program in combination with EEGLAB (version 12.0.2.5b; Delorme and Makeig (2004)). Continuous EEG files were imported and down-sampled to 250 Hz. EOG channels were removed, leaving 60 channels. The data were epoched into segments of -300 to 596 ms from stimulus onset. Independent components analysis (ICA) was used to remove ocular artifacts. ICA weights for each participant's data set were applied to the originally epoched data with 1-4 independent components (NH: M=2.2 SD=.43, u-HL: M=2.1 SD=.74, t-HL: M=2.4 SD=.70) removed from each participant's data. The data were re-referenced to a common reference, and CZ was reconstructed, resulting in 61 total channels. The data were baseline corrected to the interval -300 to 0 ms and threshold artifact rejection was applied using +/- 150 μV bounds. Epochs were then sorted according to stimulus level (SL, SPL). Sorted EEG data were low pass filtered with a 30 Hz cut-off frequency in MATLAB using a zero-phase finite impulse response least squares (FIRLS) filter. Auditory evoked potentials were generated by averaging across trials for each participant for each stimulus level (SL, SPL) at each electrode (1-61). Permutation tests (EEGLAB; statcond.m and custom MATLAB script) were conducted from stimulus onset (0ms) to 596 ms to identify electrodes and time points that differed between groups (NH vs. u-HL, NH vs. t-HL and u-HL vs. t-HL) for each stimulus level. For each group contrast, 5000 permutations were conducted with alpha levels of $p < .005$ and $p < .001$, as well as a False Discovery Rate (FDR) control ($p<.05$) for Type I error due to multiple comparisons.

Speech Perception in Noise

The Hearing in Noise Test (HINT) is a speech in noise assessment that consists of the presentation of a set of high-context sentences spoken by a male speaker in varying levels of steady state speech-weighted noise. The test was calibrated, administered and scored using a custom MATLAB program; with stimuli presented via an external sound card (MOTU, Cambridge, MA) and 4-channel compact headphone amplifier (PreSonus, Baton Rouge, LA). Participants were seated in a sound-attenuated booth. Both sentences and noise were presented binaurally through ER4-B insert earphones. Two, ten-sentence lists were presented, preceded by one ten-sentence practice list. Participants were asked to repeat all of the words they heard and to guess if they were unsure. A starting point signal to noise ratio (SNR) was determined by repeatedly playing the first sentence of the list at increasing intensity levels (4 dB step size) until all key words were correctly recalled. Thereafter, if 1 or more words were not correctly recalled, the level of the speech increased to provide a more favorable SNR; if all key words within the sentence were recalled correctly, the level of the speech decreased. Mean test times approximated 10 minutes. Scores were reported as the SNR at which the sentences were correctly recalled 50% of the time (SNR-50). A Kruskal-Wallis H test was performed to determine the presence of a significant difference between groups for sentence in noise recognition thresholds via the Statistical Package for Social Science (SPSS) version 23.0 and 24.0 (IBM Analytics, Armonk NY). SPSS was also used to investigate the relationship between P1-N1-P2 morphology and HINT scores through Pearson correlations.

C. Results

Electrophysiology

Permutation tests assisted in the determination of time points and electrodes of interest. Group differences are described in greater detail below for each stimulus level. For both the SPL and SL stimulus levels, group differences were present at several time points, for a number of electrodes across the scalp, at stringent significance levels of $p < .005$ and $p < .001$ uncorrected; however, no group differences passed through FDR control.

Equal Sound Pressure Level (SPL)

Figures 3, 4 and 5 display results for NH vs. u-HL, NH vs. t-HL and u-HL vs. t-HL, respectively; including raster plots for permutation test significance values for all electrodes and time points as well as time waveforms for selected channels and topographies at time points where significant differences were identified.

For the NH vs. u-HL group contrast, significant differences were found at several central and temporal scalp locations, at times consistent with P1 and P2 onset (Figure 3 A &B). Significant differences were also present later in the response epoch for right temporal electrodes. Examination of central and temporal waveforms (Figure 3 C) revealed a visible shift to later latencies of the entire response complex for the u-HL group. Waveforms, along with scalp topographies for each group (Figure 3 B) show that latency differences from approximately 300-360 ms, for temporal electrodes, may be due to the noted latency shift; with a later return to baseline for the u-HL group than for the NH group.

Differences were also seen between NH and t-HL across the scalp, at several time points (Figure 4 A). As seen in the previous group contrast, the P1-N1-P2 response complex appears delayed in latency for the group with hearing loss. This is most visible around P1 and P2 onset at temporal electrodes and fronto-central electrodes (Figure 4 B & C). Additionally, as with u-HL, differences are seen for latencies following the typical P1-N1-P2 epoch, which may indicate a later return to baseline for the t-HL group.

Differences between u-HL and t-HL groups were few, and almost exclusively at latencies near the response offset, or following the P2 response component (Figure 5 A & B). Examination of group averaged waveforms revealed somewhat larger and broader P2 response components for u-HL, with significant group differences between 236-288 ms (Figure 5 B). Subsequent differences, from 300-332 and 348-384 ms post stimulus onset are present at frontal and right temporal-parietal, and frontal scalp locations, respectively.

To summarize, EEG responses revealed physiological differences between those with hearing loss and those with normal hearing at time points consistent with P1 and P2 onset latencies, visible in a shift of the entire response to later latencies for both groups with hearing loss. These differences were most prominent at fronto-central and temporal scalp locations and may indicate a physiological impact of auditory deprivation. Differences between those with treated versus untreated hearing loss were less pronounced and mostly constrained to latencies approaching response offset; suggesting auditory stimulation may not have had an appreciable impact on the P1-N1-P2 response.

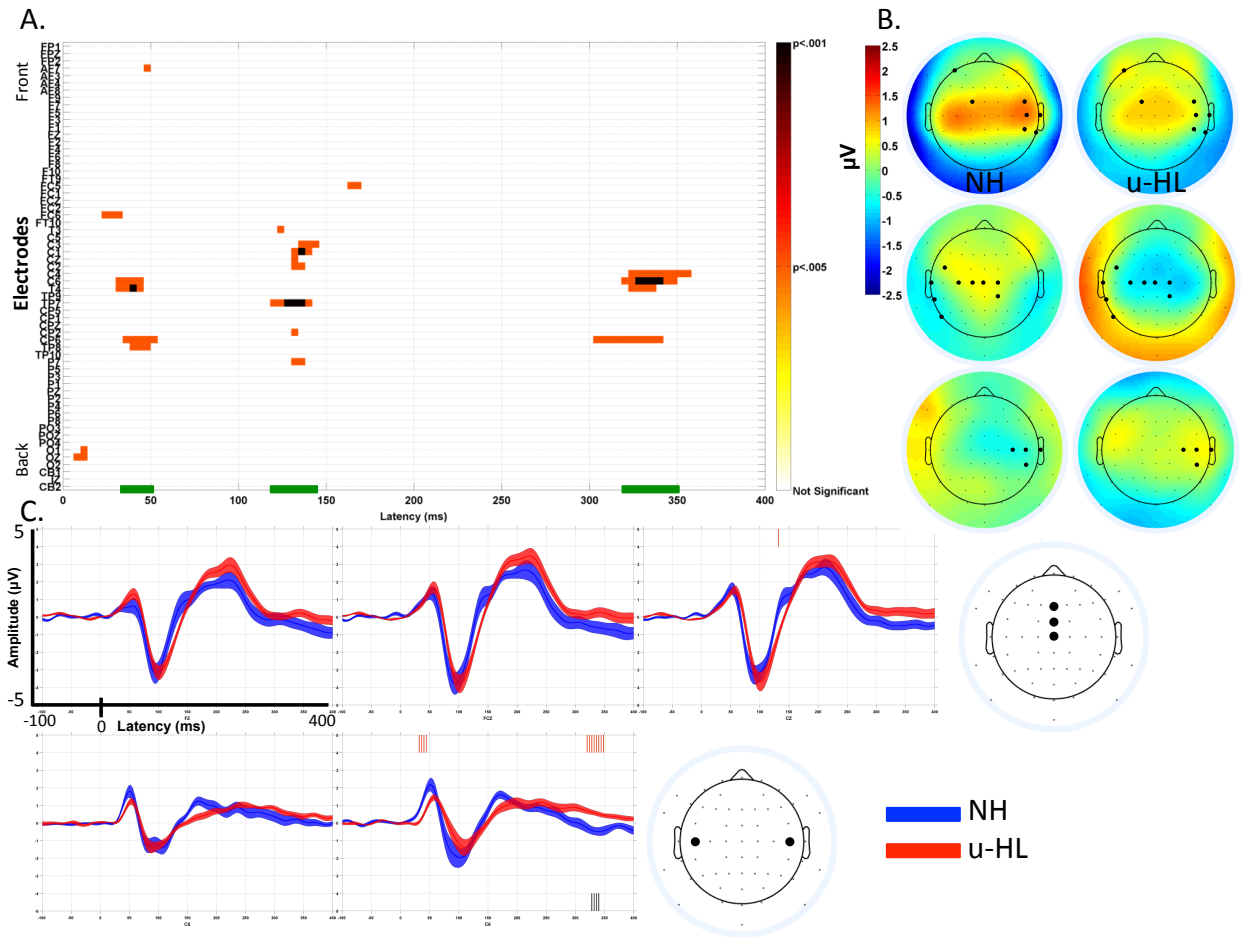

Figure 3. SPL: NH vs. u-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6) with ribbon height indicating the group mean amplitude +/- the standard error of the mean amplitude at each time point; time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

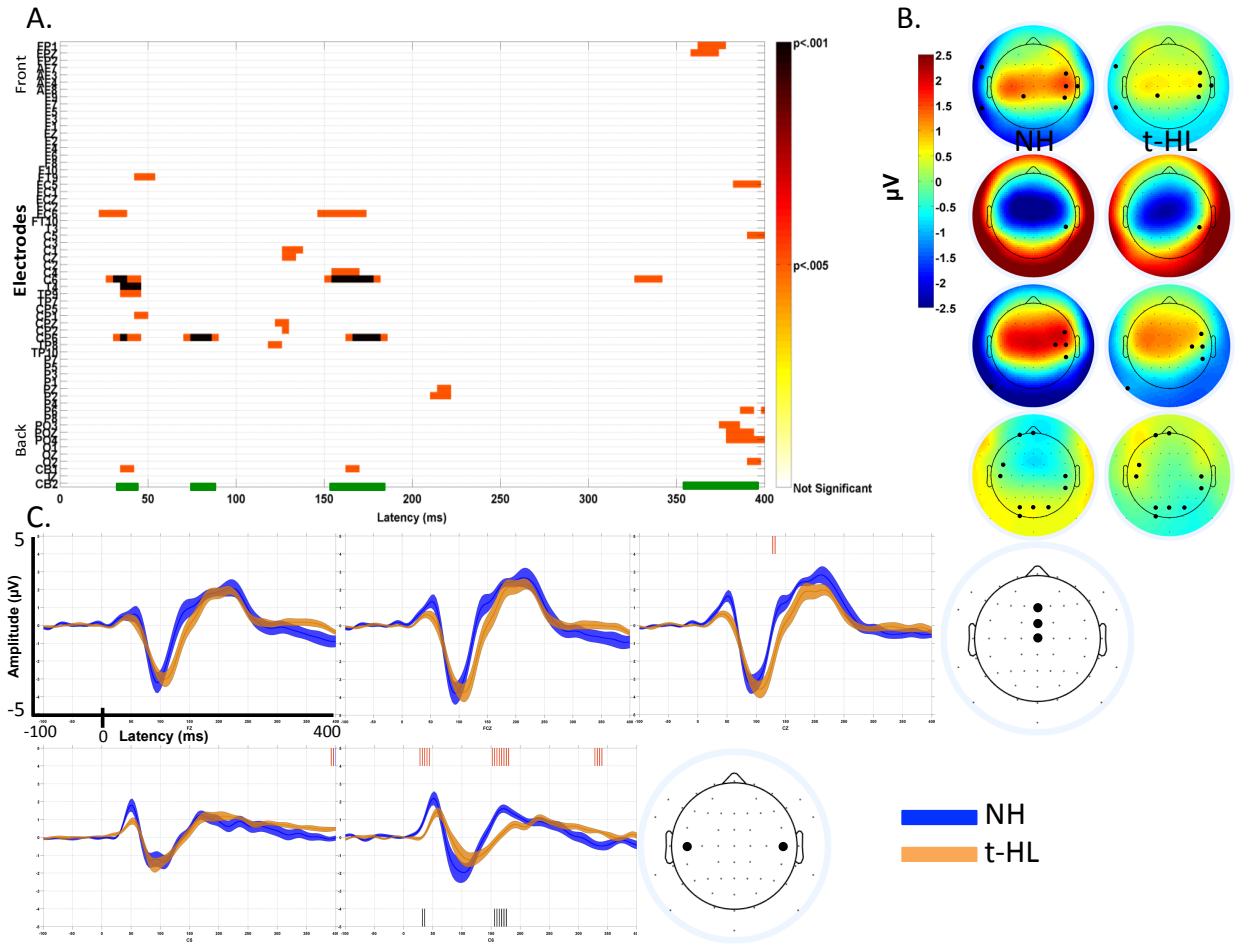

Figure 4. SPL: NH vs. t-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6) electrodes, with ribbon height indicating the group mean amplitude +/- the standard error of the mean amplitude at each time point; time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

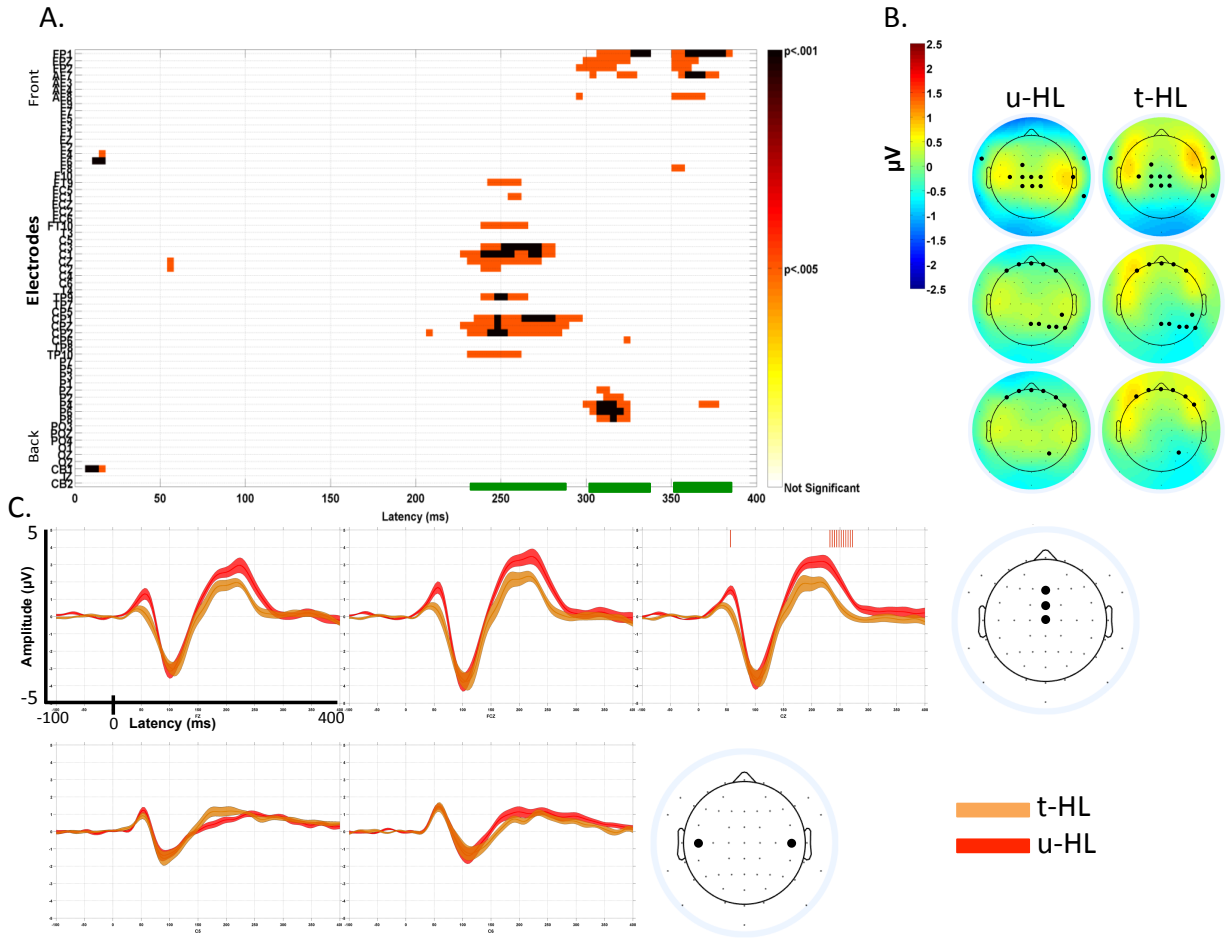

Figure 5. SPL: u-HL vs. t-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6) electrodes, with ribbon height indicating the group mean amplitude +/- the standard error of the mean amplitude at each time point; time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

Equal Sensation Level (SL)

Permutation tests revealed far fewer group differences at the SL stimulus level (Figures 6-8). However, activity at a large number of fronto-central and right temporal electrodes was significantly different from approximately 70 to 100 ms post stimulus onset when comparing the group with normal hearing to the treated hearing loss group. Inspection of time waveforms revealed earlier and larger N1 components for t-HL.

Because sounds were presented at equal sensation level, which was dependent on a participant's audiometric thresholds, stimuli for those with hearing loss were presented at a louder physical sound pressure level. On average, stimuli for those with t-HL were presented at 76 dBC SPL, compared to 56 dBC SPL for those with normal hearing. Given the N1 component increases more stereotypically to increased stimulus level than P1 and P2 components (Adler and Adler, 1989), overall stimulus sound pressure level may have resulted in differences in morphology.

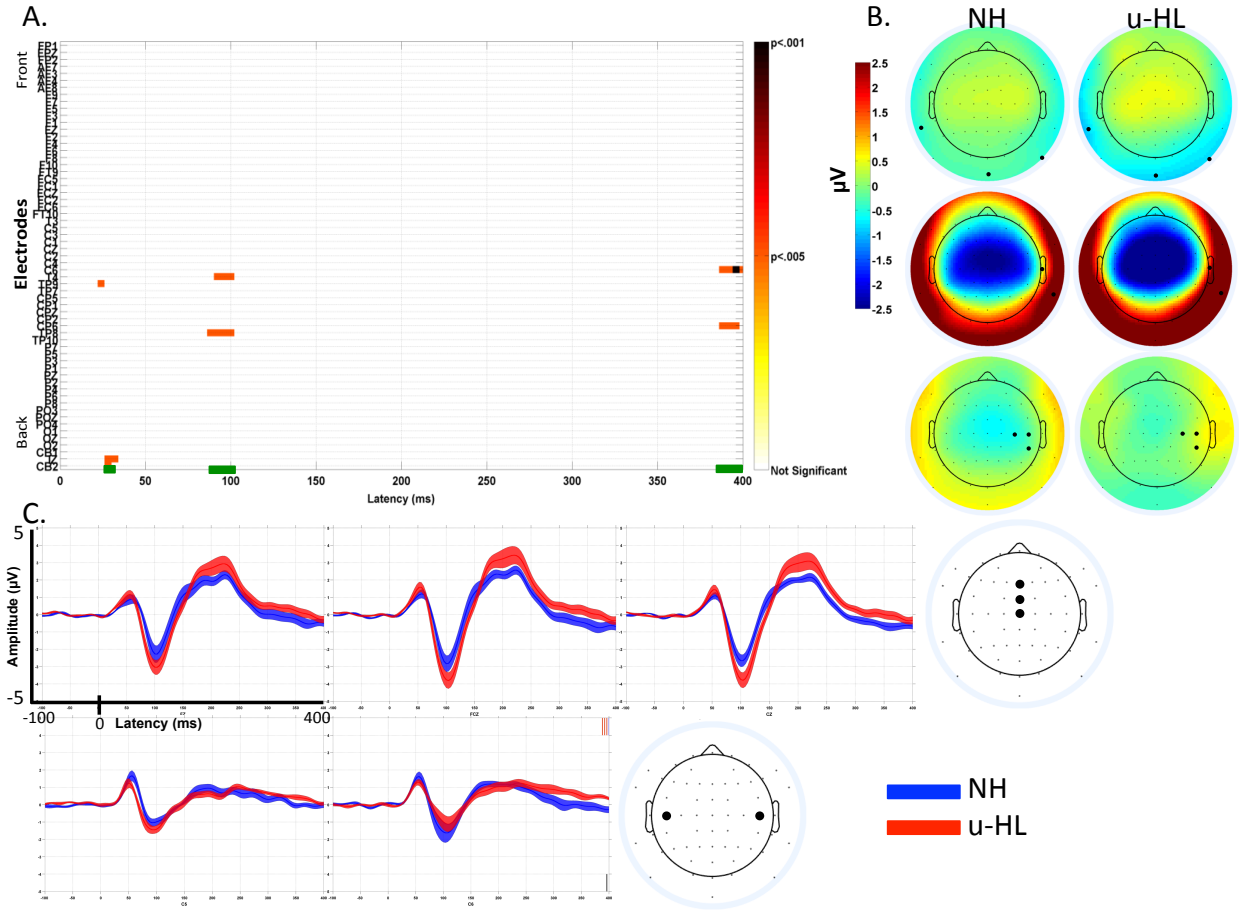

Figure 6. SL: NH vs. u-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6) electrodes, with ribbon height indicating the group mean amplitude +/- the standard error of the mean amplitude at each time point; time points that are

significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

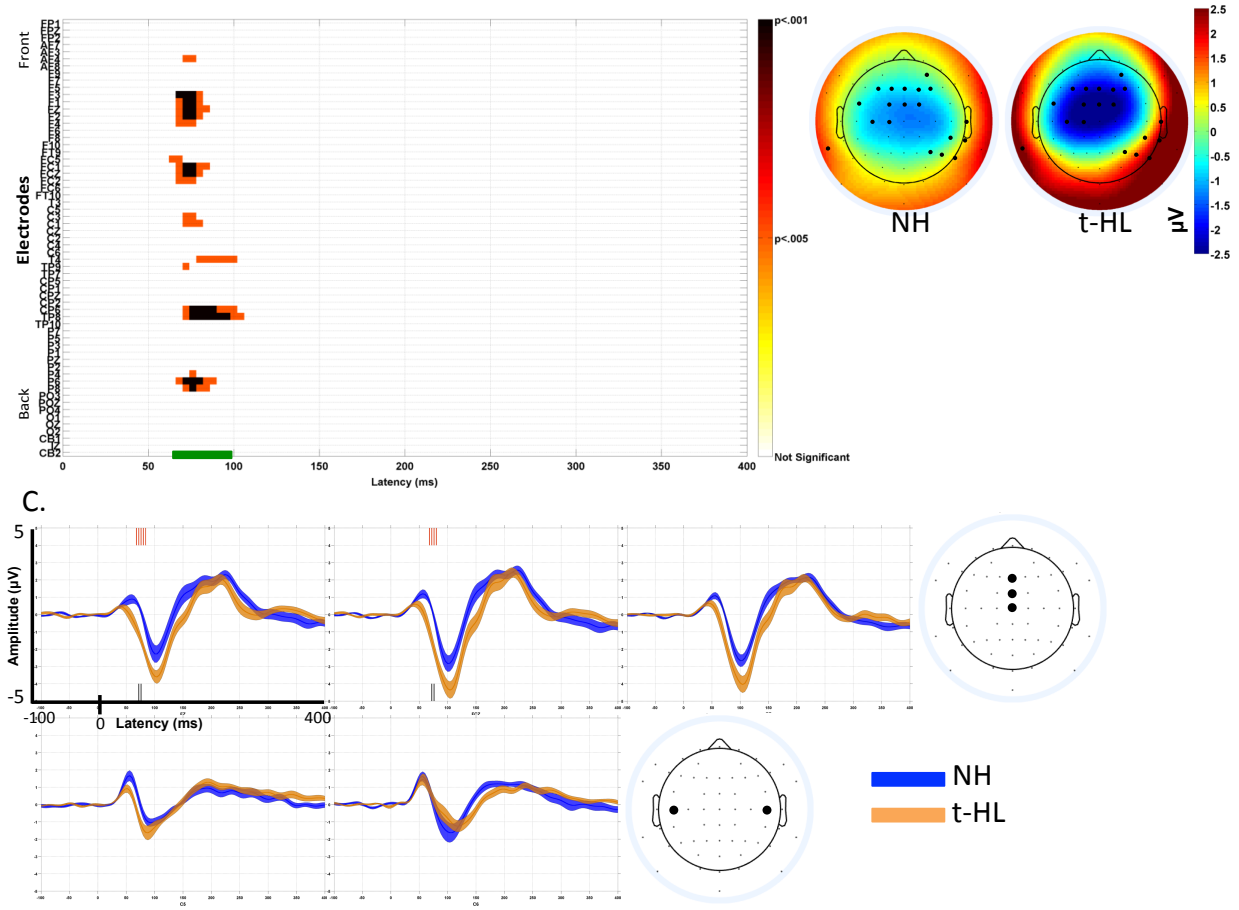

Figure 7. SL: NH vs. t-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6) electrodes, with ribbon height indicating the group mean amplitude +/- the standard error of the mean amplitude at each time point; time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

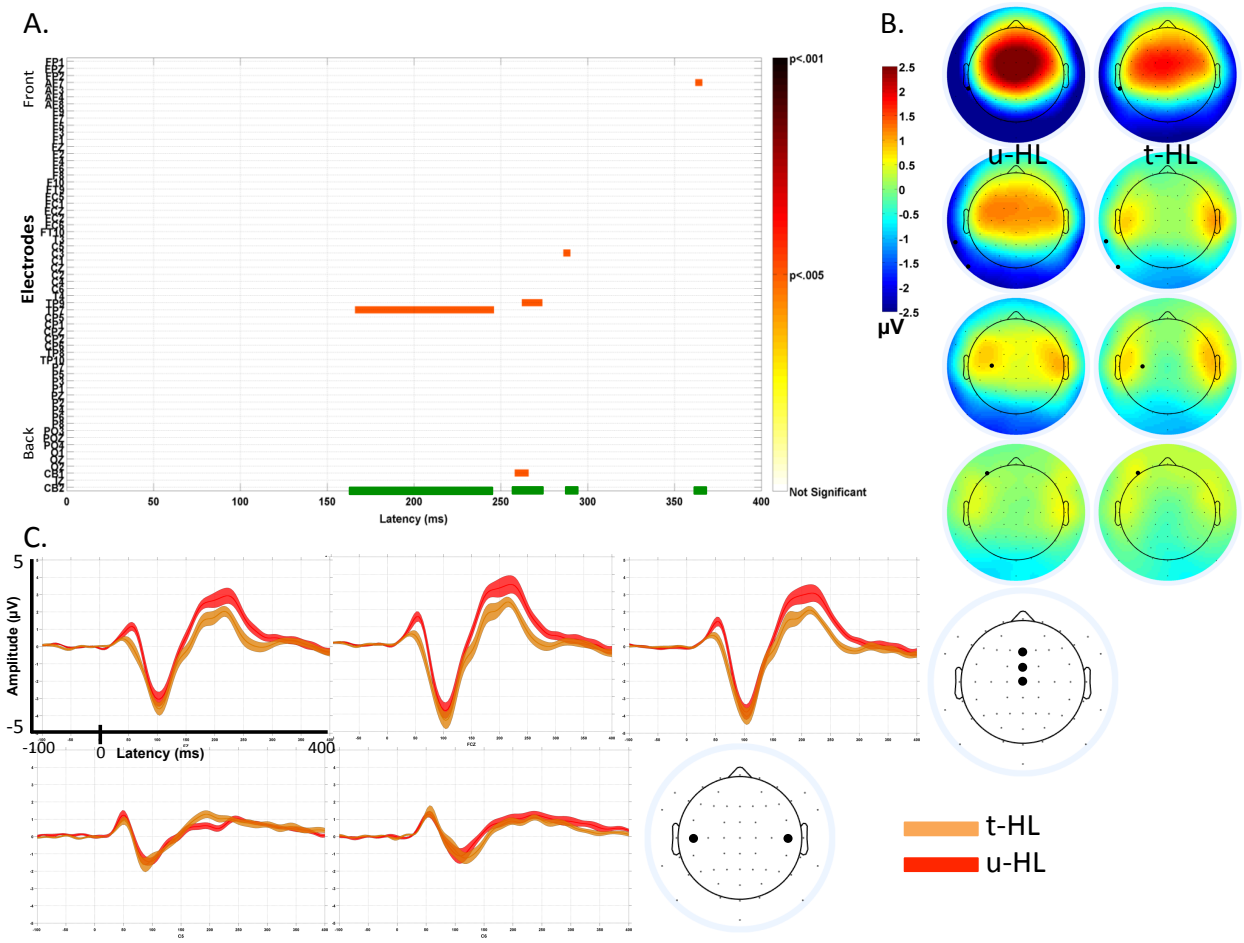

Figure 8. SL: u-HL vs. t-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6) electrodes, with ribbon height indicating the group mean amplitude +/- the standard error of the mean amplitude at each time point; time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

In summary, investigation of activity across the whole scalp revealed prolonged P1-N1-P2 latencies, for those with hearing loss, for the SPL stimulus. Latency delays were not, however, seen for the SL stimulus. Additionally, differences surrounding the N1 component, primarily between NH and t-HL, were identified for the SL stimulus; likely driven by the 20 dB increase in physical sound level for the hearing loss group.

Speech Perception in Noise

Due to the non-parametric distribution of the data, a Kruskal-Wallis H test was conducted to determine the presence of a significant effect of group on HINT scores. There was a statistically significant difference between HINT scores across groups ($H(2) = 7.844$, $p = .02$); with a mean rank of 9.50 for NH (M = -3.40, SD), 16.70 for u-HL (M SD) and 20.30 for t-HL (M SD). Post-hoc pairwise comparisons following Bonferroni correction for multiple tests revealed significantly poorer scores for those in the t-HL group compared to the NH group ($p = .02$). The remaining pairwise comparisons were not significant.

This analysis revealed significantly better speech perception in noise thresholds for the NH group, when compared with the t-HL group, but failed to reach significance for NH compared to u-HL ($p = .36$) or the u-HL and t-HL group contrast ($p = 1.00$).

N1 and P2 Morphology: Relationship to Speech Perception in Noise Performance

Several electrodes of interest were identified for correlation with HINT scores, including CZ, FCZ, and FZ; electrodes at which either N1 or P2 latencies or amplitudes were found to be predictive of, or correlate with, performance on tests of speech perception in noise in previous studies (Campbell & Sharma, 2013; Billings et al 2013). Additional electrodes showing significant differences following permutation tests at the $p < .001$ level were also selected (CP5, CP6, C5, C6, C1, C2, CPZ and CP2). Peak latency and amplitude for each component were identified using an automated procedure which selected the maxima and minima of individual waveforms within 20 ms windows around the peak amplitude found for each grand mean (all groups) waveform for each condition (SL, SPL), selected by the author. Latencies and amplitudes were

calculated relative to onset of the stimulus (0 ms) and to baseline, respectively. See Table 1 for correlation matrix.

Data inspection revealed two significant outliers that affected correlations. Outlier 1, in the normal hearing group, scored -9.57 dB SNR on the HINT, 2.5 standard deviations below (better than) the mean for the NH group (M = -3.40, SD = 2.45). Outlier 2, from the treated hearing loss group, scored 2.94 dB SNR on the HINT; 2.5 standard deviations above (worse than) the mean for the t-HL group (M = -1.34, SD = 1.74). These outliers were excluded from further analysis.

There were moderate positive relationships between HINT thresholds and N1 latency at electrodes FZ (r = .53, p = .004) and CPZ (r = .49, p = .008), and between HINT thresholds and P2 latency at electrodes CP1 (r = .38, p = .045) and CP5 (r = .44, p = .02) for the SPL stimulus level; indicating that higher (worse) speech perception in noise thresholds were related to delayed latency at these specific electrodes. However, no significant correlations were present between HINT thresholds and latency or amplitude at any additional electrodes for the SPL stimulus level or for any electrodes

for the SL stimulus level. Table 1 includes all measured correlations.

Table 1. Pearson Correlations for HINT scores and N1/P2 Peak Latency and Amplitude													
Equal Sensation Level (SL)													
Amplitude		FZ	FCZ	CZ	C1	C2	C5	C6	CPZ	CP1	CP2	CP5	CP6
N1	Pearson Correlation	-0.224	-0.235	-0.247	-0.244	-0.195	-0.205	0.064	-0.175	-0.206	0.165	-0.12	0.345
	Sig. (2-tailed)	0.251	0.229	0.205	0.212	0.319	0.296	0.747	0.372	0.294	0.402	0.543	0.072
P2	Pearson Correlation	0.075	0.014	-0.046	-0.096	-0.043	-0.265	0.041	-0.081	-0.203	0.309	-0.076	0.287
	Sig. (2-tailed)	0.704	0.945	0.815	0.626	0.829	0.174	0.836	0.683	0.301	0.11	0.701	0.139
Latency		FZ	FCZ	CZ	C1	C2	C5	C6	CPZ	CP1	CP2	CP5	CP6
N1	Pearson Correlation	0.301	0.28	0.279	0.19	0.296	-0.108	0.099	0.247	0.105	0.218	-0.198	0.316
	Sig. (2-tailed)	0.119	0.149	0.151	0.333	0.126	0.584	0.615	0.205	0.595	0.266	0.313	0.102
P2	Pearson Correlation	0.287	0.29	0.224	0.159	0.345	0.098	-0.001	0.374	0.36	0.338	0.252	-0.1
	Sig. (2-tailed)	0.138	0.135	0.253	0.418	0.072	0.62	0.995	0.05	0.06	0.078	0.196	0.628
Equal Soud Pressure Level (SPL)													
Amplitude		FZ	FCZ	CZ	C1	C2	C5	C6	CPZ	CP1	CP2	CP5	CP6
N1	Pearson Correlation	0.113	0.076	0.067	0.054	0.014	0.046	0.065	0.018	-0.035	-0.111	-0.017	0.371
	Sig. (2-tailed)	0.567	0.702	0.735	0.786	0.943	0.816	0.744	0.93	0.859	0.575	0.931	0.052
P2	Pearson Correlation	0.181	0.033	-0.189	-0.143	-0.146	-0.115	-0.026	-0.28	-0.283	-0.046	-0.159	0.146
	Sig. (2-tailed)	0.356	0.867	0.335	0.467	0.459	0.559	0.896	0.149	0.144	0.815	0.419	0.458
Latency		FZ	FCZ	CZ	C1	C2	C5	C6	CPZ	CP1	CP2	CP5	CP6
N1	Pearson Correlation	0.53	0.223	0.173	0.065	0.229	0.087	0.135	0.49	0.282	-0.014	0.129	0.067
	Sig. (2-tailed)	*0.004***	0.255	0.379	0.741	0.241	0.66	0.492	*0.008***	0.147	0.943	0.512	0.733
P2	Pearson Correlation	0.243	0.299	0.322	0.324	0.331	0.331	0.15	0.357	0.381	-0.299	0.437	-0
	Sig. (2-tailed)	0.212	0.122	0.095	0.093	0.085	0.085	0.445	0.062	*0.045**	0.122	*0.02**	0.998
*** p < .05, ** p < .01**													

D. Discussion

The goal of this study was to examine the effects of auditory stimulation and deprivation on the morphology of the P1-N1-P2 response in older adults with and without hearing loss. A secondary aim was to determine if evoked response patterns related to speech understanding in noise. To disentangle prior concerns regarding the contribution of stimulus presentation level to measures of evoked brain activity, two different stimulus presentation levels were used (SPL and SL). To eliminate the contribution of age as a variable, only older adults were included and groups were age-matched. Also, potential cognitive confounds were minimized by only including participants who passed the MoCA screening test.

Effects of Auditory Deprivation (Age-Related Hearing Loss)

Auditory deprivation, in the form of age-related hearing loss (ARHL), affected the way sound was encoded in the brain. Increased neural conduction time, evident through

longer response latency, was seen for individuals with mild to moderate/moderately severe sensory-neural hearing loss, when compared to their age-matched peers with normal hearing. One interpretation is that prolonged latencies were indicative of abnormal temporal processing resultant from protracted auditory deprivation involved in ARHL. Support for this interpretation includes studies showing prolonged latencies and altered amplitudes for those with hearing loss versus normal hearing peers (Goodin et al., 1978; Iragui et al., 1993; Tremblay et al., 2002; Ross & Tremblay, 2009; Kim et al., 2012; Pfefferbaum et al., 1980; Brown et al., 1983; Campbell & Sharma, 2013). Alternatively, differences between those with and without hearing loss may have been driven by the audibility of the stimulus; as the P1-N1-P2 complex has a monotonic relationship with stimulus intensity. When stimuli were presented at equal sensation level, or equal effective stimulus intensity, in the current study, a pronounced latency shift was not present. This suggests that stimulus audibility, rather than deprivation induced physiological changes, contributed to delayed response latency for those with hearing loss. This finding is significant, because prolonged response latency, specifically for the P2 component, in those with hearing loss has recently been suggested as a potential early marker of cortical resource re-allocation and a precursor to greater cognitive changes (Campbell & Sharma, 2013). Given the present results suggesting audibility effects, the relationship between response delays and higher level processing mechanisms may be confounded.

Effects of Auditory Stimulation (Hearing Aid Use)

There does not appear to be an effect of hearing aid use on the neural registration of sound, according to the P1-N1-P2 measure used here. One possible

explanation is that daily auditory stimulation through amplification did not alter the physiological representation of sound at the level of the auditory cortex. This interpretation is supported by Dawes et al (2014), who found no significant differences in response morphology prior to or following 12 weeks of hearing aid use, in a group of older individuals. Our study emphasizes that, while well-fit hearing aids, worn on a consistent basis, provide increased audibility of speech and sound; this increased audibility does not reverse the biological changes that have taken place following damage to the peripheral and ascending auditory system.

A limitation is that the heterogeneity of P1-N1-P2 timing characteristics both within each participant (on a trial by trial basis) and within each group, contributed to averaged group results. Consequently, averaging over multiple trials, as well as across individuals in the determination of group effects, may have resulted in temporal smearing and an insensitivity to stimulation related neuro-plastic effects present at an individual level. Therefore, further examination of individual differences and temporal response properties are warranted.

Relationship Between Evoked Response Patterns and Speech Perception in Noise.

A correlation between the latency of the auditory P2, as well as the N1, and speech perception in noise performance was found. However, this relationship was only present when stimuli were presented at the same sound pressure level for all participants. After hearing loss was accounted for through the creation of individual stimuli representing an equal sensation level, the relationship was no longer significant. These results indicate that the correlation between N1 and P2 response latency and

speech perception in noise performance was driven by stimulus audibility; with longer latency responses for those with hearing loss, due to decreased audibility of the stimulus, correlating with higher (worse) speech perception in noise thresholds. Additionally, these findings suggest that P1-N1-P2 latency and amplitude measures may not be reliably indicative of differences in higher level processing of auditory information due to hearing loss; an interpretation suggested in previous studies (Campbell & Sharma, 2013). To the author's knowledge, no previous studies have compared evoked P1-N1-P2 responses with performance on measures of speech perception in noise, while controlling for stimulus audibility.

In summary, the results of this study suggest that research showing decreased cortical auditory evoked response amplitudes or increased latencies for those with hearing loss may be due to differences in the audibility of the signal used to evoke the response; a methodologically, not physiologically driven effect. Furthermore, use of the P1-N1-P2 response for prediction of abilities to use sound for higher-level tasks, such as speech perception in noise, should be tempered, if stimulus audibility is not fully accounted for. Finally, the use of amplification does not appear to affect the neural detection of sound according to P1-N1-P2 response.

Chapter 3. Effects of Untreated and Treated Hearing Loss on Self-Report and Behavioral Measures of Auditory and Working Memory Function in Older Adults.

A. Introduction

Hearing loss is the third most prevalent chronic condition in older adults, impacting the lives of approximately one quarter to one third of those over 50 years of age, and, indirectly, their families and communication partners (Lethbridge-Cejku, Schiller, & Bernadel, 2004; Cruickshanks et al., 1998). Age-related hearing loss (ARHL), also called presbycusis, is characterized as a bilateral, progressive, high frequency sensory-neural hearing loss, typically occurring around the 5th decade of life. Coincident with decreased hearing thresholds are changes at the peripheral and central levels of the auditory nervous system (e.g. Gates & Mills, 2005; Willott et al., 1991; Willott, Hnath Chisolm, & Lister, 2001; Peelle et al., 2011; Harris, Dubno, Keren, Ahlstrom, & Eckert, 2009; Eckert et al., 2012; Campbell & Sharma, 2013; Tremblay et al., 2003)

Treatment of ARHL is limited to the use of compensatory listening strategies as well as hearing assistive technology (HAT); including amplification devices (e.g. hearing aids), which provide increased access to speech information through increased sound levels. Even though the use of amplification has been shown to relate to improvements in quality of life (e.g, Chisolm et al., 2007), the majority of individuals with ARHL do not seek treatment (Popelka et al., 1998; Kochkin, 2009; NIH-NIDCD-National Health Interview Survey 2012) suggesting that tens of millions of adults, in the United States alone, are living with a significant auditory sensory deficit and likely struggle with daily

communication. When left untreated, progressive ARHL has been shown to correlate with decreased speech understanding, both in quiet and in noise (Akeroyd, 2008; Dubno et al., 2008), social withdrawal (Davis et al., 2016; Weinstein & Ventry, 1982; Weinstein, Sirow, & Moser, 2016; Singh, Lau, & Pichora-Fuller, 2015), an increase in falls (Viljanen et al., 2009), depression (Huang et al., 2010) and cognitive decline, including decreased working memory function and dementia (Deal et al., 2015; Gurgel et al., 2014; Lin, 2011; Lin et al., 2011; Lin et al., 2013). Collectively, these findings suggest that the effects of ARHL may extend beyond the auditory system, and that a growing number of older individuals may be at risk of experiencing such consequences. For these reasons, there is interest in understanding the link(s) between sensory deprivation and stimulation and the functional consequences of age-related hearing loss and hearing aid use (see Albers et al., 2015; Grady, 2012, for reviews). Moreover, there is interest in defining these relationships in the earlier stages of progression; when the degree of hearing loss falls within the mild and moderate categories, given the current climate of hearing health care and the increasing number of opportunities available to patients for early intervention (Donahue, Dubno, & Beck, 2010).

Some of the known physiological consequences associated with aging and ARHL include: hearing loss related auditory cortex atrophy and brain volume decline (Eckert et al., 2012; Lin et al., 2014), altered functional connectivity between sensory cortices (Puschmann & Thiel, 2016), and a down regulation of neural activity during speech processing (Peelle et al., 2011). These types of neural consequences affect sound signal integrity and alter the way auditory information is transmitted along auditory and related neural networks. Our previous studies, for example, have shown

delayed sound conduction as well as modulations in the strength of the EEG amplitude, in adults with and without hearing loss (Tremblay et al., 2002; Tremblay et al., 2003; Tremblay et al., 2004; Campbell & Sharma, 2013) interpreted latency and amplitude differences as potential cortical markers of cognitive decline. Subsequent research, however, has shown that auditory deprivation related neural registration delays are neither permanent nor indicative of cognitive decline (McClannahan et al, in prep). For example, McClannahan et al., in prep, demonstrated typical, age appropriate, EEG responses when sound levels used to elicit responses were comparably audible for older adults with and without hearing loss. That is, typical neural registration of sound is possible when sound audibility is controlled for; so too is the functional use of that sound according to performance on tests of speech perception in noise. Most importantly, none of the participants in McClannahan et al were classified as having cognitive decline, according to their performance on measures of cognition (e.g., Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). Therefore, while there may be central effects related to sound deprivation, some of the literature may unintentionally be reporting the effects of decreased stimulus audibility and not long-term central consequences of sound deprivation.

Physiological studies aside, there is evidence to suggest that ARHL correlates with some aspects of cognitive performance. The cognitive domain frequently examined in populations with ARHL, is working memory (Lunner, 2003; Mishra, Stenfelt, Lunner, Rönnberg, & Rudner, 2014; Rudner, Foo, Rönnberg, & Lunner, 2009; Rönnberg, Rudner, Foo, & Lunner, 2008; Rönnberg et al., 2013). Working memory can be described as the system of temporary storage and handling of information, to be used in

cognitive tasks (Daneman & Merikle, 1996; Daneman & Carpenter, 1980). When the quality of a speech signal is degraded, there is a greater reliance on cognitive energy to compensate for impaired signal processing (for a review, see (Pichora-Fuller et al., 2016). One example is the contribution of working memory, and studies have shown a positive correlation between speech in noise performance and working memory function (Rönnberg et al., 2013; Smith & Pichora-Fuller, 2015; Souza & Arehart, 2015). However, as described by Füllgrabe and Rosen (Füllgrabe & Rosen, 2016a; Füllgrabe & Rosen, 2016b), the working memory-speech perception in noise relationship has been examined primarily in older populations with hearing loss; little is known about this sensory-cognitive relationship in older adults without audiometric hearing loss. What is more, when comparisons are made to normal hearing peers, stimulus audibility may again be a contributing factor to differences in performance, because tests of working memory and other cognitive abilities often require individuals to listen and follow auditory instructions. The inability to hear instructions and test items can hinder one's performance (Dupuis et al., 2015; McCoy et al., 2005; Rabbitt, 1990; Weinstein & Amsel, 1986; Humes, 2007) on such measures, resulting in scores that reflect audibility rather than cognitive performance. As described in Smith and Pichora-Fuller (2015) working memory function is often measured using the Reading Span Test (RST) (Daneman & Carpenter, 1980), a visual verbal working memory assessment, in order to avoid audibility issues. However, assessment of an auditory analog of a visual verbal working memory test, such as the Word Auditory Recognition and Recall Measure (WARRM) (Smith, Pichora-Fuller, & Alexander, 2016) may provide useful information when seeking to understand the impact of auditory sensory deficits on higher-level

cognitive function. Furthermore, behavioral measures of auditory function, such as speech perception in noise, rely heavily on audibility (Humes, 2007) and in turn involve the central processing of auditory information (Humes, Busey, Craig, & Kewley-Port, 2013) and higher-level cognitive abilities (Poeppel & Monahan, 2008). For example Anderson (Anderson, Parbery-Clark, Yi, & Kraus, 2011) reported that older adults with poor speech perception in noise abilities, measured using the Hearing in Noise Test (HINT), had abnormal neurophysiological representations of speech, when measured using the speech evoked auditory brainstem response. Therefore, it is important to consider the contribution of signal audibility when assessing all aspects of performance, both physiologically and perceptually, and when examining the consequences of ARHL on cognitive processing.

Much of the research thus far has included people with various degrees of hearing loss. Few have looked at the specific effects of bilateral mild-moderate/moderately-severe sloping hearing loss; perhaps the most common configuration of hearing loss among aging adults. What is more, there is a lack of consensus regarding whether or not treatment of hearing loss with amplification alters the auditory sensory-cognitive relationship. Some studies show positive effects of amplification on working memory function (e.g. Doherty & Desjardins, 2015), others do not (Tesch-Römer, 1997; van Hooren et al., 2005). There is neuroscience evidence to suggest that auditory stimulation, in the form of auditory training and cochlear implantation, alters the way sound is encoded in the auditory system (see Tremblay & Backer, 2016 for a review), however there is less evidence to indicate that hearing aid amplification leads to improvement in behavioral measures of auditory function, such as

speech perception in noise, following hearing aid fitting (Humes, Garner, Wilson, & Barlow, 2001; Humes, Wilson, Barlow, & Garner, 2002; Humes & Wilson, 2003; Dawes, Munro, Kalluri, & Edwards, 2014b). Self-reported abilities with sound and quality of life, however, have been shown to improve following fitting (Chisolm et al., 2007; Newman & Weinstein, 1988; Humes, Halling, & Coughlin, 1996; Mizutari et al., 2013). For example Newman et al (1988) showed a significant reduction in self-reported hearing handicap, measured using the Hearing Handicap Inventory for the Elderly (HHIE) extending to at least one year of hearing aid use. Similarly, Noble and Gatehouse (2006) found that following fitting with unilateral and/or bilateral amplification, individuals scored higher on several subscales of the Speech Spatial and Qualities of Hearing Questionnaire (SSQ); which probes a wide range of auditory functions and listening situations. It therefore follows that periods of auditory stimulation, through hearing aid use, may preserve an individual's capacity to make use of sound when compared to peers who have been untreated. Therefore, to better understand the consequences of ARHL, the current study included both behavioral measures of auditory abilities along with self-reported auditory function to establish a more comprehensive picture (Gopinath et al., 2012; Weinstein, 2015). It is this line of inquiry that will ultimately help us to understand how the tens of millions of adults, in the United States alone, are living with a significant auditory sensory deficit and if they are struggling with daily communication.

The purpose of this study was to define the functional effects of ARHL (**auditory deprivation),** as well as the use of hearing aid amplification (**auditory stimulation),** on a range of outcome measures, both self-report and perceptual assessments. We hypothesized that auditory deprivation would result in poorer self-reported and

behaviorally measured auditory and working memory function, in cognitively intact older adults; once age and audibility were accounted for. We also hypothesized that treatment of hearing loss through amplification would ameliorate deprivation induced deficits as evidenced by scores on par with normal hearing peers. Additionally, given the reported relationship between the sensory dependent measure of speech perception in noise and the cognitive domain of working memory, we also examined whether auditory deprivation or auditory stimulation altered this sensory-cognitive relationship. To test these hypotheses we examined ratings and performance across a battery of measures, which assay perceived and functional outcomes of hearing loss and higher-level function, in three groups of older adults; those with normal hearing (NH), untreated hearing loss (u-HL), and treated hearing loss (t-HL).

B. Methods

All procedures were approved by the Institutional Review Board of the University of Washington. Participants were recruited from the University of Washington Speech and Hearing Clinic, the University of Washington Communication Studies Participant Pool (P30-DC04661), study fliers posted at Seattle area businesses, and word of mouth. All participants gave written, informed consent prior to participation and were paid for their time.

Participants

Participants were aged 58-77 years, with no reported history of neurological disorders. Group 1: Normal Hearing (NH) consisted of 18 adults (aged 58-70, M=65, SD=3.3, 15 female, 3 male) with clinically normal hearing defined as pure tone thresholds 25 dB HL or better at octave frequencies from 250-8000 Hz. Group 2: Untreated Hearing Loss (u-HL) consisted of 18 adults (aged 60-77, M=70.2, SD=5.5, 11 female, 4 male) with bilaterally symmetrical mild to moderate/moderately-severe sensory-neural hearing loss who had **never worn hearing aids**. Group 3: Treated Hearing Loss (t-HL) consisted of 10 adults (aged 62-72, M=67.7, SD=3.6, 3 female, 7 male) with bilaterally symmetrical mild to moderate/moderately-severe sensory-neural hearing loss who had **worn binaural amplification on a daily basis (6+ hours/day) for at least the past two years**. All individuals in the t-HL group wore binaural receiver-in-the-ear (RITE) style digital hearing aids with universal domes or custom earmolds. See Figure 1 for averaged audiograms from each group. There was a significant difference in age between groups ($F(2,43) = 7.222$, $p = .002$). Post hoc tests revealed the u-HL group was, on average, 5 years older than the normal hearing group ($p = .002$) with no other significant group comparisons. For this reason linear regression analyses were used with age as a predictor.

All participants were screened for mild cognitive impairment using the Montreal Cognitive Assessment (MoCA) Test (Nasreddine et al., 2005). Participants enrolled in this study scored above 23 points; the cutoff score

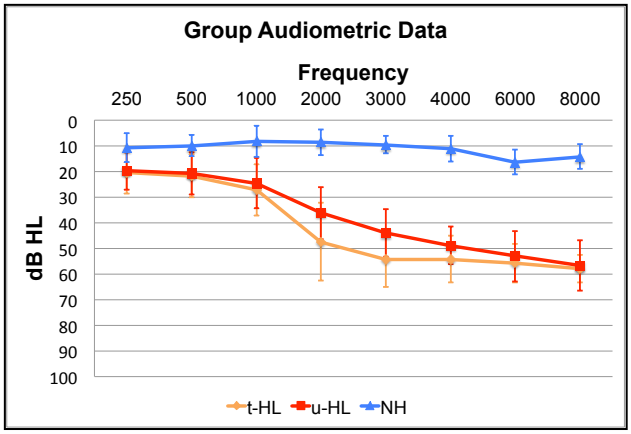

Figure 1. Group audiometric data. Thresholds were averaged between ears at each frequency. Error bars represent standard deviation.

described as having 96% sensitivity and 95% specificity for mild cognitive impairment (see Luis et al., 2009). Additionally, groups did not differ in non-verbal intelligence measured with the Culture Fair Intelligence Test (Cattell & Cattell, 1960) ($F(2,43) = 1.076$, $p = .350$).

Importantly, the audibility of test instructions and test items were maximized for all participants by providing pocket talkers or having the participants wear their personal hearing aids. Treated hearing loss was defined as fulltime (6 or more hours/day) use of binaural amplification for at least the past two years.

Procedure

All participants completed a full audiometric evaluation and, when appropriate, hearing aid assessment, as reported in McClannahan et al. (in prep). Briefly, the audiometric battery included: otoscopy, pure tone audiometry (air and bone conduction), supra-threshold word recognition testing (Madsen Astera, Otometrics: Taastrup, Denmark or Grason-Stadler Inc. (GSI): Eden Prairie, USA), tympanometry (Tympstar, GSI: Eden Praire, USA) and a hearing aid check (Verifit I, Audioscan, Etymonic Design Inc.: Dorchester, Ontario, Canada), including real ear measurements using the standard speech passage at 55, 65 and 70 dB SPL and maximum power output with swept tone.

Assessments/Measures

All measures were conducted in a quiet room or sound-attenuated booth. Individuals in the hearing loss groups wore their own personal amplification (t-HL), were provided with amplification in the form of a pocket talker (u-HL) and for several measures, instructions were presented through an audiometer at 40+ dB SL (all groups) to ensure audibility. Test order was randomized and balanced across groups.

Self-Reported Auditory Function

Two measures of self-reported auditory function were used to assess the impact of hearing loss on participants' daily lives. Both tests were administered in a quiet room, were self-paced and completed as written surveys to minimize interviewer bias. Perceived handicap is correlated with pursuance of treatment for hearing loss through amplification (hearing aids) (Chang, Ho, & Chou, 2009; Vestergaard Knudsen, Öberg, Nielsen, Naylor, & Kramer, 2010); therefore, we requested that individuals in the t-HL group consider their experiences and abilities currently, with their hearing aids on. This instruction was intended to result in an individual's description of current function, rather than motivation to obtain amplification.

The Hearing Handicap Inventory for the Elderly (HHIE) is a tool used to evaluate the situational and emotional impact of hearing loss in older individuals (Ventry & Weinstein, 1982). The survey is widely used both in clinical and research audiology, and is well validated (Ventry & Weinstein, 1982; Weinstein, Spitzer, & Ventry, 1986). The measure consists of 25 questions, with scores ranging from 0 to 100, with higher scores indicating greater perceived handicap. Mean test times approximated 10 minutes. The test was scored as the overall total score.

The Speech, Spatial and Qualities of Hearing Scale-abbreviated version (SSQ-12) is a self-assessment of experience and abilities with speech and sound in one's everyday life. Questions represent pragmatic subscales of speech in quiet, speech in noise, speech in speech contexts, multiple speech stream listening, localization, distance and movement, segregations, identification of sound, quality and naturalness, and listening effort (Gatehouse & Akeroyd, 2006). Participants were asked to rate their

experience and abilities on a scale of 0-10, with 0 being “Not at all” and 10 being “Perfectly” for 12 questions. Mean test times approximated 10 minutes. The test was scored as the average score across all 12 questions.

Speech Recognition in Noise

The Hearing in Noise Test (HINT) is a widely used clinical measure of speech recognition in noise. It is an adaptive measure, consisting of high-context sentences, spoken by a male speaker, embedded in varying levels of steady state speech-weighted noise (Nilsson, Soli, & Sullivan, 1994). Speech recognition thresholds are determined by the signal to noise ratio (SNR) at which sentences are correctly repeated 50% of the time. Lower (more negative) scores correspond to the ability to understand speech in higher levels of background noise, with higher scores indicative of poorer performance. The test was calibrated, administered and scored using a custom MATLAB program (version R2013b, The Mathworks, Inc., Natick, MA). Stimuli were played through an external sound card (MOTU, Cambridge, MA), 4-channel compact headphone amplifier (PreSonus, Baton Rouge, LA), to binaural insert earphones (ER4-B, Etymotic, Elk Grove, IL) (see McClannahan (in prep) for additional details). Two ten-sentence lists were presented, preceded by one ten-sentence practice list; with participant instructions to repeat all words that were heard. Mean test times approximated 10 minutes.

Working Memory

To accommodate group differences in hearing status, two measures (auditory and visual verbal) were utilized to assess working memory function. Both tests were conducted in a sound treated booth with instructions presented at an amplified level through insert earphones.

The Word Auditory Recognition and Recall Measure (WARRM) is an auditory only verbal working memory test that also assesses auditory word recognition (Smith et al., 2016). The WARRM was presented using the same custom MATLAB program, soundcard, and amplifier previously described. Participants were instructed to repeat/cite words aloud, and then to respond “First” or “Second” if the first letter of the word was in the first or second half of the alphabet, respectively. Following a series of words, participants heard a tone, after which they were told to recall all the words from the set, in serial order if possible. This procedure was repeated for five sets of two, three, four, five and six words, in ascending order, totaling 100 sentences. The test was presented binaurally via ER4B insert earphones at presentation levels of 70, 80 or 90 dB SPL for individuals with normal hearing, three-frequency PTA ≤ 40 dB HL, or three-frequency PTA > 40 dB HL, respectively, in accordance with the assessment’s authors’ recommendations. Mean test times approximated 15 minutes. The test was scored as the total number of correctly recalled words.

The Reading Span Test (RST) is an assessment of visual verbal working memory function designed to simultaneously stress memory storage and processing (Daneman & Carpenter, 1980). The test used in this study was a modification of Baddeley (Baddeley, Logie, Nimmo-Smith, & Brereton, 1985) RST (Rönnberg, Arlinger, Lyxell, & Kinnefors, 1989). The RST was administered using the same custom MATLAB program, soundcard, and amplifier previously described, with test instruction per (Lunner, 2003). Sentences were presented, one word at a time, on a computer screen; half made sense, half were nonsensical. Participants were instructed to judge whether the sentences made sense or not, and respond yes or no accordingly. After a number of

sentences, a dialog box instructed the participant to recall the first or last word in each sentence in that set, in serial order, if possible. Participants were given practice trials to ensure they were able to perform the task. To ensure scoring accuracy, the experimenter audio recorded recalled words and word order. This procedure was repeated for three sets of three, four, five and six sentences, in ascending order, totally 54 sentences. Mean test times approximated 15 minutes. The test was scored as the percent of words recalled correctly.

C. Results

Effects of Treated and Untreated Hearing Loss on Self-Report and Behavioral Scores

Age significantly differed across groups; therefore, linear regression analyses included age and group (NH, u-HL, t-HL) as predictors. More specifically, linear regression was used to determine if group or age were significant predictors of scores on each measure (HHIE, SSQ-12, HINT, WARRM, RST). For each regression, the normal hearing group was used as the reference group. See Table 1, at the end of this section, for model specifics. Interaction terms (u-HLxAge, t-HLxAge) were initially entered into the model for each measure, but did not reach significance and were subsequently excluded to increase power. Additional regressions were conducted, using the u-HL condition as the reference group, to examine the effects of treated versus untreated hearing loss; however, this analysis did not yield significant effects and will not be described in further detail.

Self-reported Auditory Function

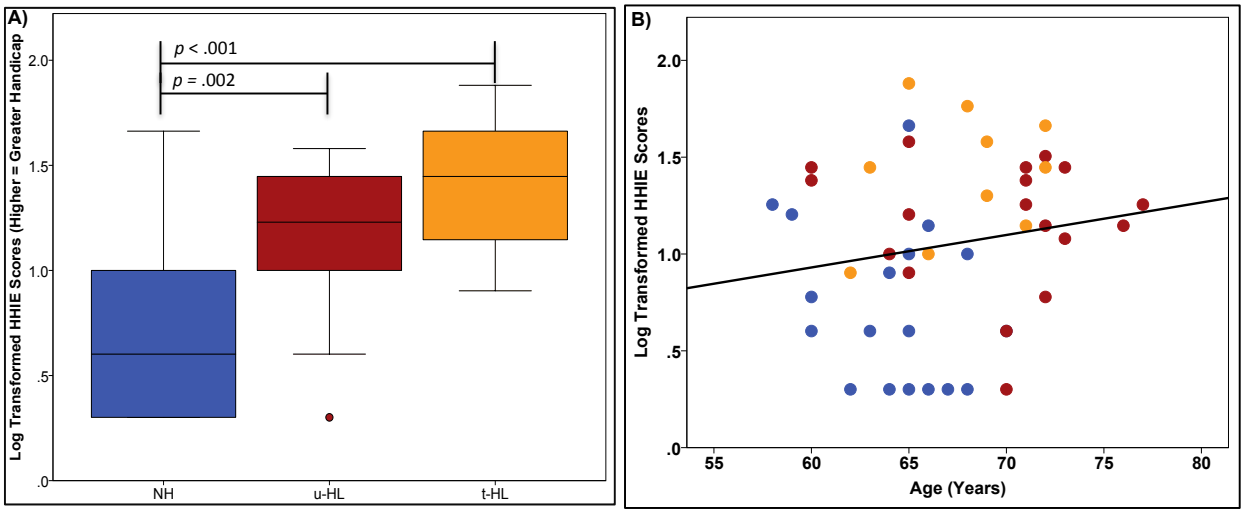

Figure 2. A) HHIE scores across groups: NH = Normal hearing, u-HL = untreated hearing loss, t-HL = treated hearing loss, presented in log transformed units. Out values are indicated by circles. B) HHIE scores as a function of age. Circles represent individual scores with NH in blue, u-HL in red and t-HL in gold.

HHIE - For people of the same age, both treated and untreated hearing loss predicted higher scores on the HHIE. Specifically, HHIE scores were significantly higher (worse) for those with treated hearing loss: (b = 0.716, SE = .153), t (42) = 4.667, p < .001, sr^2 = .32; and untreated hearing loss: (b = 0.477, SE = .142), t (42) = 3.369, p = .002, sr^2 = .17) than their normal hearing peers. Age did not significantly predict hearing handicap (b = -.010, SE = .014), t(42) = -.711, p = .481. **Prior to regression, scores were increased by one point to remove scores of zero, and log transformed to stabilize the variance.

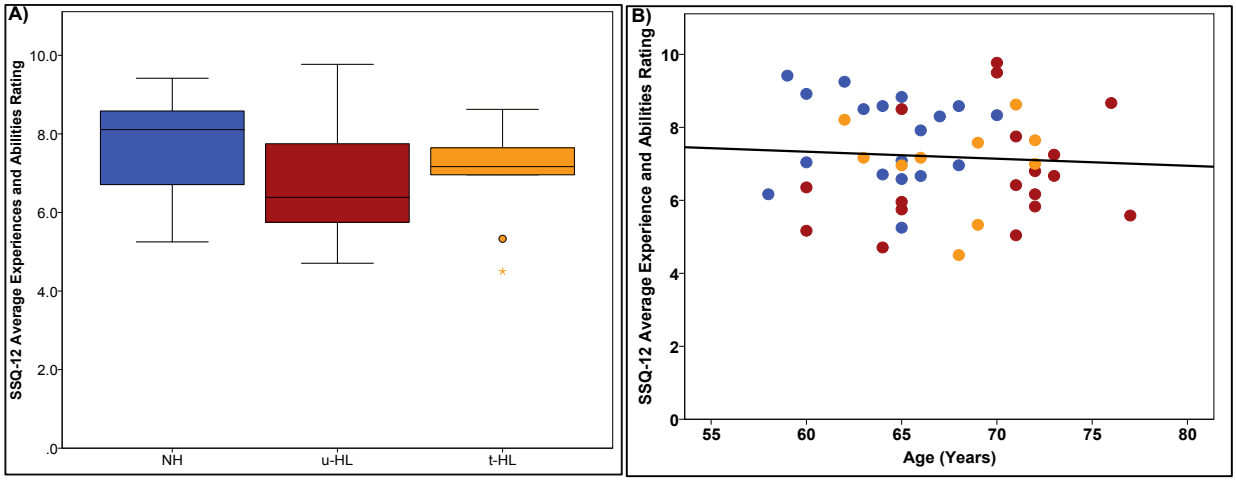

Figure 3. A) SSQ-12 scores across groups: NH = Normal hearing, u-HL = untreated hearing loss, t-HL = treated hearing loss. Out values are indicated by circles. B) SSQ-12 scores as a function of age. Circles represent individual scores with NH in blue, u-HL in red and t-HL in gold.

SSQ-12 - For people of the same age, the presence of hearing loss (both treated and untreated) did not account for a significant amount of the variance in SSQ-12 scores (R^2 = .113, F (3,42) = 1.787, p = .164, $R^2_{adjusted}$ = .050). These results indicate that older individuals with normal hearing, as well as treated and untreated hearing loss, rated experiences and abilities with sound similarly.

Speech Recognition in Noise

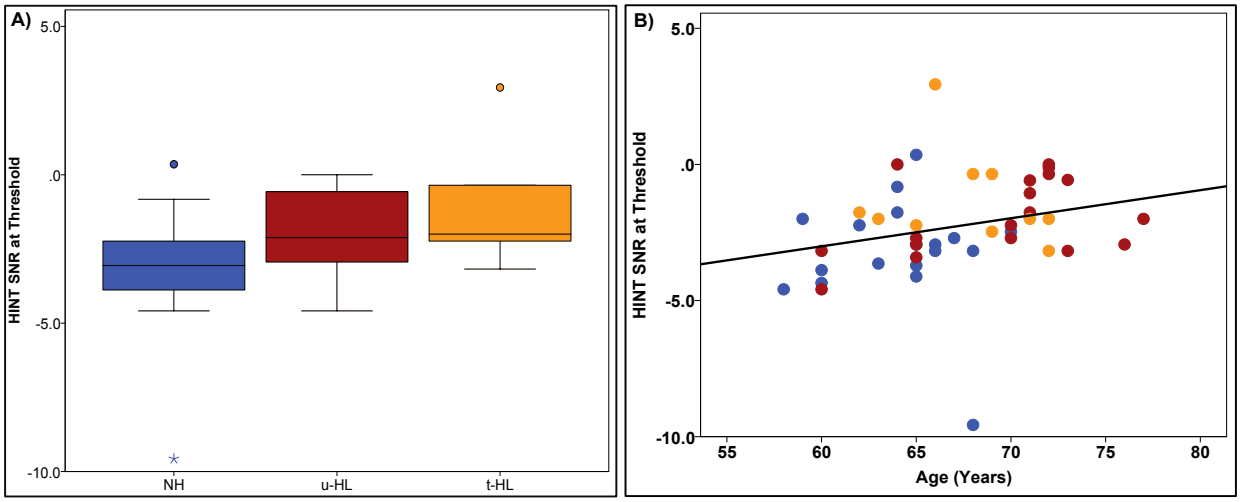

Figure 4. A) HINT signal to noise ratio (SNR) at threshold across group: NH = Normal hearing, u-HL = untreated hearing loss, t-HL = treated hearing loss. Out values indicated by circles. Far out value (blue star in (A) and blue circle at the bottom of (B)) for NH was excluded from analysis. B) HINT scores as a function of age. Circles represent individual scores with NH in blue, u-HL in red and t-HL in gold.

HINT - For people of the same age, neither treated (*b* = 1.194, *SE* = .600), *t*(41) = 1.991, *p* = .053) nor untreated (*b* = .502, *SE* = .558), *t*(41) = .900, *p* = .373) hearing loss, uniquely predicted speech perception in noise performance, when compared to normal hearing peers. That is, people with treated and untreated hearing loss had similar abilities to understand speech in background nose as their normal hearing peers. Additionally, age was not a significant predictor of HINT score (*b* = .80, *SE* = .053), *t*(41) = 1.491, *p* = .144). **Prior to analysis, one extreme outlier was identified in the NH group with a score greater than 3 standard deviations from the group mean (see Figure 4). To avoid contamination of the regression given the modest sample size and number of predictor values, this score was excluded from analysis.

Working memory

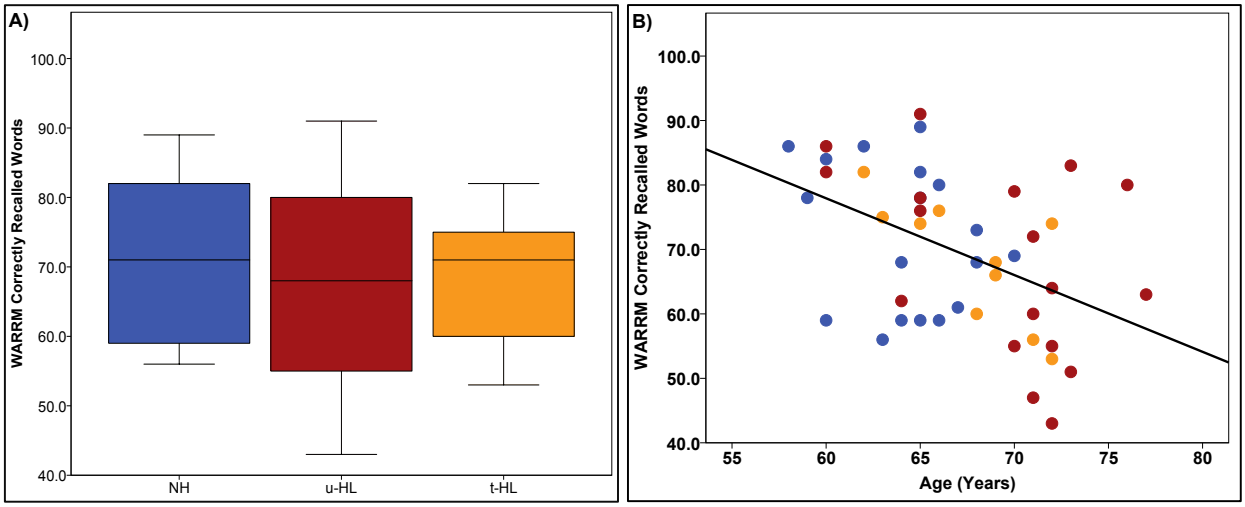

Figure 5. A) WARRM scores across group: NH = Normal hearing, u-HL = untreated hearing loss, t-HL = treated hearing loss. and as a function of age (right). B) WARRM scores as a function of age. Circles represent individual scores with NH in blue, u-HL in red and t-HL in gold.

WARRM- For people of the same age, neither treated (*b* = 1.234, *SE* = 4.641), *t*(42) =.266, *p* = .792) nor untreated (*b* = 3.109 *SE* = .4.284), *t*(42) = .726, *p* = .472) hearing loss significantly predicted WARRM scores, when compared to normal hearing peers. That is, when stimuli are presented at sufficiently audible levels, people with hearing loss did not perform more poorly on this auditory verbal working memory measure. Age, was uniquely predictive of WARRM scores, with advanced aging resulting in poorer scores (*b* = 1.337, *SE* = .415), *t*(42) = -3.218, *p* = .002, sr^2 = .19).

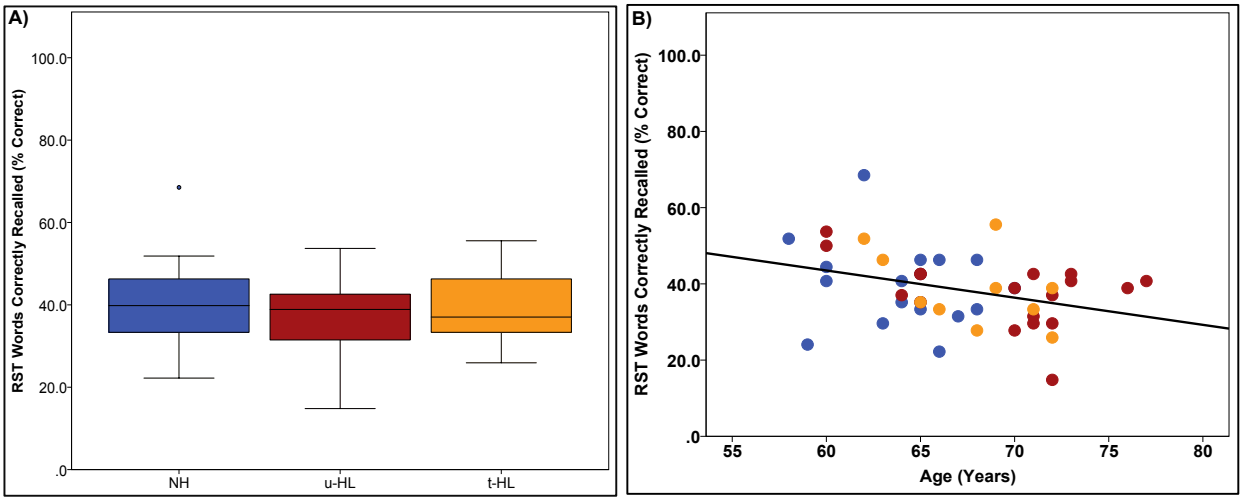

Figure 6. A) RST scores across group: NH = Normal hearing, u-HL = untreated hearing loss, t-HL = treated hearing loss, with out values indicated by circles. B) RST scores as a function of age. Circles represent individual scores with NH in blue, u-HL in red and t-HL in gold.

RST – Age and the presence of hearing loss (treated and untreated) did not account for a significant amount of the variance in RST scores (R^2 = .127, $F(3,42)$ = 2.028, p = .125, $R^2_{adjusted}$ = .064). In other words, people with hearing loss did not perform significantly different than their peers without hearing loss.

Summary

There were no significant differences between treated and untreated hearing loss groups on any of the measures used in this study (HHIE, SSQ-12, HINT, WARRM and RST). The presence of hearing loss had a significant effect on hearing handicap scores (HHIE); with greater ratings of hearing handicap for those with treated and untreated hearing loss compared with normal hearing peers.

Relationship Between Speech Perception in Noise and Working Memory Function

The relationship between speech perception in noise and working memory function showed that better working memory correlated with better speech understanding in higher levels of background noise; but that this relationship was only

present in the group with untreated hearing loss. Pearson correlations were assessed to examine the relationship between speech perception in noise, measured by the HINT and working memory function, measured by the WARRM and RST. Correlations were assessed with groups (NH, u-HL, t-HL) combined, as well as within each group separately. As described in the previous section, the extreme NH outlier was excluded from the analyses.

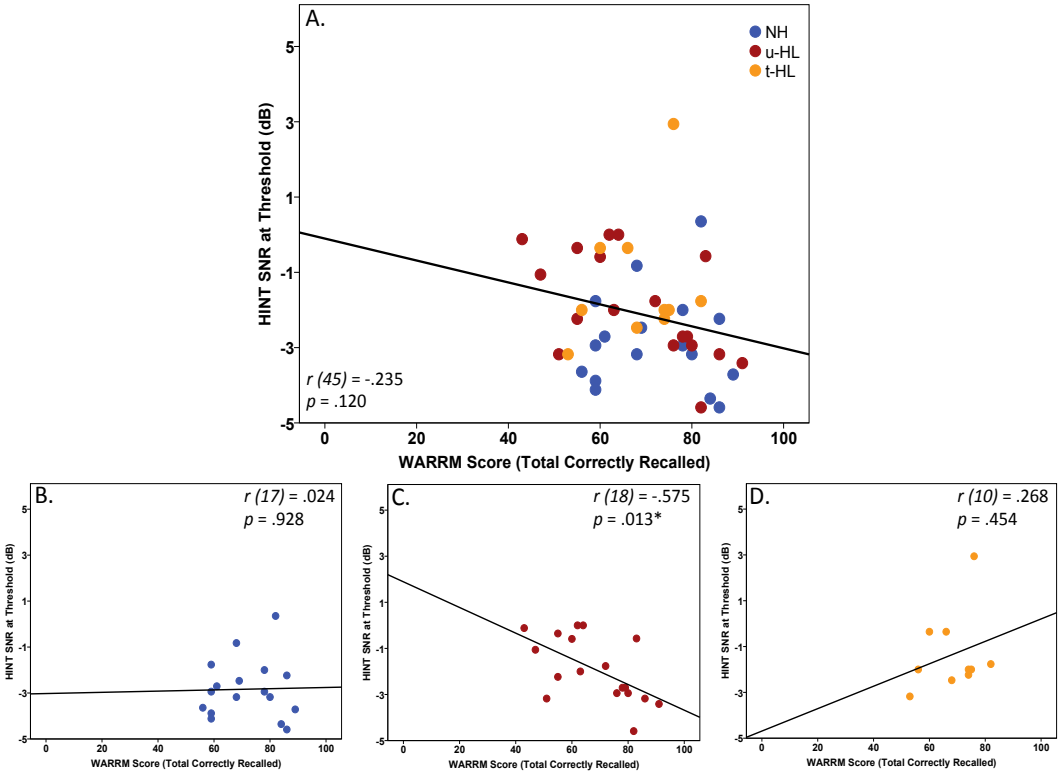

Figure 7. Across (A.) and within (B.-D.) group Pearson correlations for HINT and WARRM scores.

WARRM- For the untreated hearing loss group there was a moderate negative correlation, with higher (better) WARRM score correlating with lower (better) speech perception in noise scores (r (18) = -.575, p = .013; RST). No other correlations met significance. (Groups combined: r (45) = -.235, p = .120; NH: r (17) = .024, p = .928, t-HL: r (10) = .268, p = .454).

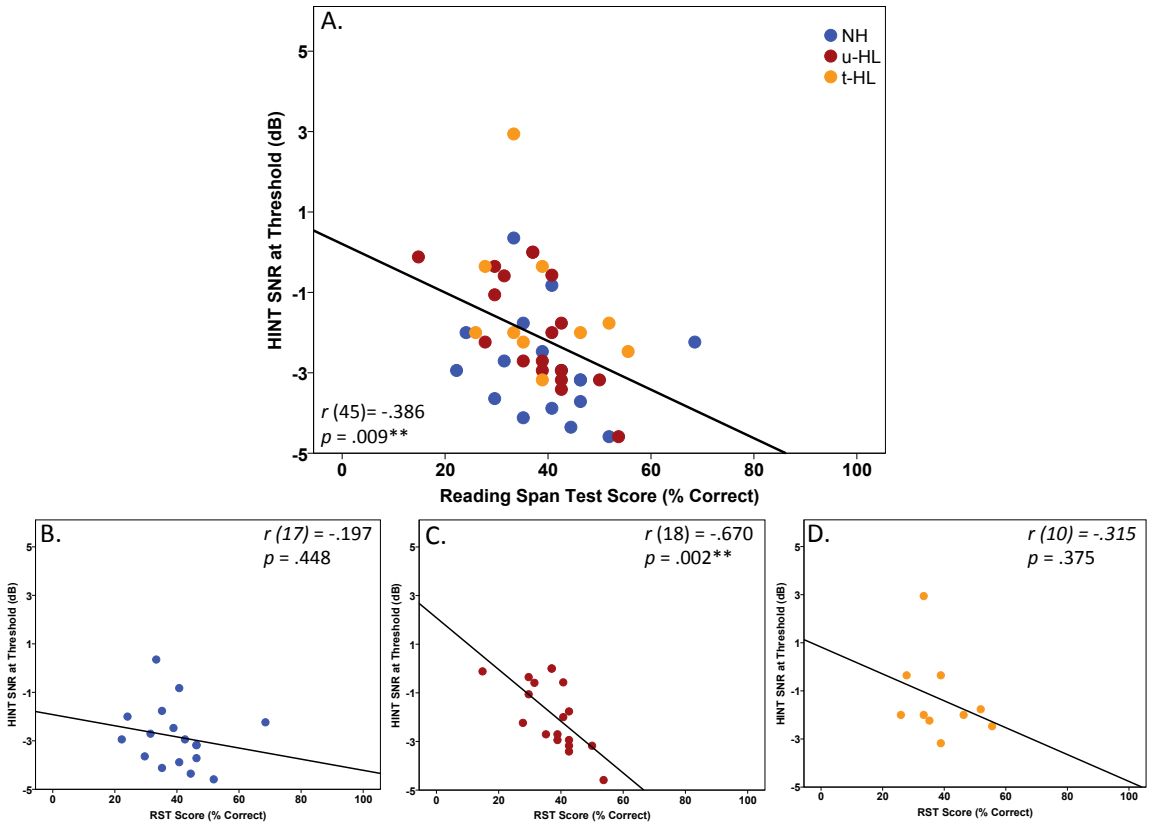

Figure 8. Across (A.) and within (B.-D.) group Pearson correlations for HINT and RST scores.

RST – With groups combined, there was a moderate negative correlation between HINT and RST scores (r (45) = -.386, p = .009). Additionally, there was a strong negative correlation between HINT and RST scores for the untreated hearing loss group (r (18) = -.670, p = .002). The remaining correlations were not significant (NH: r (17) = -.197, p = .448; t-HL: r (10) = -.315, p = .375).

Summary

Results of correlational analyses revealed that better speech perception in noise performance was correlated with better working memory function only for those with untreated hearing loss.

Table 1. Results for linear regression for each measure with age (continuous) and group (NH, u-HL, t-HL) as predictor values.

Measure	Predictors	Coefficient	95 % CI	*p*-value	Adjusted R^2
HHIE (+)					0.33
	Age	-0.01	(-.037, .018)	0.481	
	t-HL	0.716	(.407, 1.026)	< .001***	
	u-HL	0.477	(.191, .763)	0.002**	
SSQ-12 (x)					0.05
	Age	0.038	(-.063, .139)	0.455	
	t-HL	-0.842	(-1.969, .284)	0.139	
	u-HL	-1.149	(-2.189, -1.08)	.031*	
HINT					0.121
	Age	0.042	(-.089, .173)	0.552	
	t-HL	1.719	(.251, 3.186)	0.023*	
	u-HL	1.086	(-.269, 2.441)	0.113	
HINT (-)					0.136
	Age	0.08	(-.028, 187)	0.144	
	t-HL	1.194	(-.017, 2.405)	0.053	
	u-HL	0.502	(-.624, 1.629)	0.373	
WARRM					0.159
	Age	-1.337	(-2.175, -.498)	0.002**	
	t-HL	1.234	(-8.133, 10.600)	0.792	
	u-HL	3.109	(-5.537, 11.755)	0.472	
RST (x)					0.064
	Age	-0.83	(-1.532, -.128)	0.022*	
	t-HL	2.13	(-5.717, 9.978)	0.587	
	u-HL	2.287	(-4.957, 9.531)	0.527	
+ Log transformed, x F-test not significant, - outlier removed, * p < .05, ** p < .01					

D. Discussion

The aim of this study was to characterize the effects of auditory deprivation (ARHL) and stimulation (hearing aid use) on speech perception in noise, as well as working memory function, in people with mild to moderate/moderately-severe hearing loss. To better understand the functional experiences these groups might have in more real-world listening situations, self-reporting assessments were also included. What differs between our study and those previously reported in the literature is the

consideration of stimulus audibility across groups. To minimize potential confounds of reduced audibility, all test instructions were presented in quiet, and amplification was used for all people with hearing loss. Potential cognitive confounds were minimized by only including participants who passed the MoCA test.

Effects of Treated and Untreated Hearing Loss on Self-Reported Auditory Function

When compared to their normal hearing peers, those with treated and untreated hearing loss reported greater hearing handicap, as measured with the Hearing Handicap Inventory for the Elderly (HHIE). This result was expected. Previous studies have shown ARHL to have a significant impact on self-reported auditory function (Ventry & Weinstein, 1982; Weinstein & Ventry, 1983). However, when questions about specific listening conditions were examined with the Speech Spatial and Qualities of Hearing Scale (short form, SSQ-12), those with untreated and treated hearing loss rated their abilities similar to their normal hearing peers. One explanation for this finding is that all three groups consisted of older adults. It is well established that older adults with and without hearing loss describe difficulty following conversations when there is background noise and all participants, regardless of assigned group, were over the age of fifty-seven.

Also, the SSQ-12 evaluates self-assessed performance in multiple, often complex, listening situations, without mentioning hearing deficits (e.g. Q3: You are in conversation with one person in a room where there are many other people talking. Can you follow what the person you are talking to is saying?). In contrast, the HHIE probes how much hearing loss leads to negative outcomes or emotions during or avoidance of

certain situations (e.g. S-3: Does a hearing problem cause you to avoid groups?). While both self-report measures assess the nature of interactions with sound and abilities in everyday situations, our data suggests that all older people (with and without hearing loss) described listening to be challenging in complex situations and the addition of hearing loss compounded the problem resulting in greater handicap. When individuals with normal hearing were asked if hearing loss affected their ability to function in everyday life, the answers were often no.

There were no significant differences in HHIE or SSQ-12 scores, between those with treated and untreated hearing loss. These results suggest that having used hearing aids for a period of at least two years does not significantly alter a listener's experience in complex situations. Nor does it alter the perception of handicap, when compared with peers with similar hearing who have never worn hearing aids. These results were unexpected given that previous reports have shown decreased ratings of hearing handicap following hearing aid fitting, when compared to pre-fitting ratings (e.g. (Barbosa et al., 2015; Dawes et al., 2015a; Malinoff & Weinstein, 1989; Mulrow, Tuley, & Aguilar, 1992). One might have expected that self-assessed estimates of handicap would be lower among people who wear hearing aids. However, people who were experiencing greater handicap may have been more motivated to seek treatment, when compared to the untreated group. Humes et al (2003) reported that when compared to peer groups who elected not to use amplification, individuals who chose to use hearing aids had higher self-reported hearing handicap prior to hearing aid fitting. Similar findings of a positive relationship between hearing aid use and higher perceived

impairment using other measures of self-reported hearing handicap and limitations have been reported (see Vestergaard Knudsen et al 2010 for a review).

Effects of Treated and Untreated Hearing Loss on Speech Perception in Noise and Working Memory Function

Neither mild to moderate/moderately-severe age-related hearing loss, nor treatment of hearing loss, significantly affected speech perception in noise. All groups of individuals with hearing loss performed similarly. Once again this finding was unexpected. If left to speculate, participants might have used contextual information within the HINT to their benefit. This notion is supported by Wilson et al (2007) who showed performance on measures with a high level of context, such as the HINT, was less dependent on acoustic information when compared to measures with less contextual information. Another explanation might be the degree of hearing loss present in both hearing loss groups. Our participants had only a mild to moderate/moderately-severe hearing loss. Although this degree of hearing loss is significant enough to make people eligible for amplification, participants with this degree of loss still have audible low and mid frequency speech information at normal conversational levels involved in HINT testing. Therefore, it is unclear whether the severity of hearing loss or compensation through the use of contextual information led to the equivalent performance for those with normal hearing and ARHL, both treated and untreated. Future studies would benefit from assessment of speech perception in noise performance in older adults with and without ARHL, using multiple materials with varying levels of context.

Neither hearing loss nor treatment with amplification had a significant effect on auditory or visual verbal working memory function. This means all older participants performed similarly on tests of auditory and visual verbal working memory, when stimuli were sufficiently audible and visible. While some studies have shown improvement in working memory abilities following amplification (Doherty & Desjardins, 2015), others have not (Dawes et al., 2015a; Tesch-Römer, 1997; van Hooren et al., 2005). A few studies have reported minimal or no direct effects of the presence of hearing loss on working memory function (Desjardins & Doherty, 2013; Deal et al., 2016; Rönnberg et al., 2011). Therefore, these results suggest, 1) auditory deprivation associated with ARHL does not directly alter verbal working memory systems, and/or 2) auditory stimulation, through the use of hearing aid amplification, does not automatically lead to input driven changes in the way the brain is able to store and manipulate information for more complex cognitive processes involved in daily communication.

In contrast to many other studies, we controlled for audibility throughout the assessment (instruction delivery as well as the administration of cognitive measures) using amplified sound. This point is important, as several studies have reported negative effects of reduced audibility on cognitive test performance (Dupuis et al., 2015; McCoy et al., 2005; Rabbitt, 1990; Weinstein & Amsel, 1987). In our study, individuals with hearing aids were allowed to wear their personal devices, and individuals with untreated hearing loss received amplified instructions through binaural insert earphones.

Examination of the relationship between working memory function and speech perception in noise revealed that higher (better) working memory scores (for both

WARRM and RST) correlated with lower (better) thresholds for understanding speech in noise. However, this relationship was specific to **untreated** hearing loss. There was no significant relationship between working memory and speech perception in noise for those with normal hearing or treated hearing loss. These results question whether going without amplification, in the presence of even a mild-moderate hearing loss, may result in a greater need for cognitive compensation in order to process speech in noise.

The relationship between working memory and speech perception in noise has been studied extensively (Lunner, 2003; Smith & Pichora-Fuller, 2015). Several studies have found a positive correlation between speech perception in noise and working memory function in older adults with ARHL both treated and untreated (see Akeroyd, 2008 for a comprehensive review). Rönnberg et al (2003) explain this relationship through their Ease of Language Understanding (ELU) model of working memory, which proposes greater cognitive involvement in speech perception when demands are placed on the listener, such as increased complexity of the listening environment and/or presence of hearing loss (Rönnberg, 2003; Rönnberg et al., 2013; Rönnberg et al., 2008; Rönnberg, Rudner, Lunner, & Zekveld, 2010). Therefore, when speech perception is challenging and it is more difficult to reconcile incoming auditory information with representations for sounds stored in long-term memory due to auditory deprivation (Lyxell, Andersson, Borg, & Ohlsson, 2003), this can lead to an increased reliance on working memory. However, Füllgrabe and Rosen (2016) found that this relationship was not present for individuals with normal hearing, and Ng et al 2014 showed that while a relationship between working memory function and speech perception in noise was present at the initial fitting of amplification, the relationship

diminished over the course of six months of hearing aid use (Ng et al., 2014). Miller et al, in press also reported little effect of working memory function on speech perception in a variety of ecologically salient listening conditions in adults fit with binaural amplification (Miller et al., in press). One interpretation could be that for older adults with untreated hearing loss there is more reliance on working memory function in part due to degraded representations of speech in long-term memory; and that daily use of amplification improves or strengthens the connection between auditory input and phonological representations, resolving the compensatory reliance on working memory. The precise mechanism of this relationship, however, cannot be determined from the results of this study alone and warrant further investigation.

E. Conclusions

Results of this study suggest that while the presence of a mild to moderate/moderately-severe hearing loss contributes to greater self-reported hearing handicap in older adults, it may not have an appreciable affect on speech perception in noise or working memory function, skills involved in daily communication. Additionally, the use of hearing aids did not result in significantly better self-reported or behavioral measured auditory or cognitive function. This does not necessarily mean that hearing aids are not a beneficial treatment option for ARHL. Instead it might mean that even when controlling for audibility, there are still deficits present across all groups of older adults.

Finally, this study showed that for individuals with untreated hearing loss, better working memory performance correlated with improved speech perception in noise, indicative of more reliance on cognition for sensory processing in people with untreated

hearing loss than their normal hearing peers, or peers with similar hearing loss who were treated with binaural amplification. These results suggest an indirect effect of ARHL on the cognitive domain of working memory.

References

Akeroyd, M. A. (2008). Are individual differences in speech reception related to individual differences in cognitive ability? A survey of twenty experimental studies with normal and hearing-impaired adults. *Int J Audiol*, *47 Suppl 2*, S53-71.

Alain, C., Zendel, B. R., Hutka, S., & Bidelman, G. M. (2014). Turning down the noise: the benefit of musical training on the aging auditory brain. *Hear Res*, *308*, 162-173.

Albers, M. W., Gilmore, G. C., Kaye, J., Murphy, C., Wingfield, A., Bennett, D. A. et al. (2015). At the interface of sensory and motor dysfunctions and Alzheimer's disease. *Alzheimers Dement*, *11*(1), 70-98.

Allen, P. A., & Crozier, L. C. (1992). Age and ideal chunk size. *J Gerontol*, *47*(1), P47-51.

Alvarado, J. C., Fuentes-Santamaría, V., Gabaldón-Ull, M. C., Blanco, J. L., & Juiz, J. M. (2014). Wistar rats: a forgotten model of age-related hearing loss. *Front Aging Neurosci*, *6*, 29.

Amenedo, E., & Díaz, F. (1998). Aging-related changes in processing of non-target and target stimuli during an auditory oddball task. *Biol Psychol*, *48*(3), 235-267.

Anderer, P., Semlitsch, H. V., & Saletu, B. (1996). Multichannel auditory event-related brain potentials: effects of normal aging on the scalp distribution of N1, P2, N2 and P300 latencies and amplitudes. *Electroencephalogr Clin Neurophysiol*, *99*(5), 458-472.

Anderson, S., Parbery-Clark, A., Yi, H. G., & Kraus, N. (2011). A neural basis of speech-in-noise perception in older adults. *Ear Hear*, *32*(6), 750-757.

Anderson, S., & Kraus, N. (2013). Auditory training: evidence for neural plasticity in older adults. *SIG 6 Perspectives on Hearing and Hearing Disorders: Research and Diagnostics*, *17*(1), 37-57.

Anderson, S., White-Schwoch, T., Parbery-Clark, A., & Kraus, N. (2013). Reversal of age-related neural timing delays with training. *Proceedings of the National Academy of Sciences*, *110*(11), 4357-4362.

Arlinger, S., Gatehouse, S., Bentler, R. A., Byrne, D., Cox, R. M., Dirks, D. D. et al. (1996). Report of the Eriksholm Workshop on auditory deprivation and acclimatization. *Ear Hear*, *17*(3 Suppl), 87S-98S.

Baddeley, A., Logie, R., Nimmo-Smith, I., & Brereton, N. (1985). Components of fluent reading. *Journal of memory and language*, *24*(1), 119-131.

Balota, D., Dolan, P., & Duchek, J. (2000). Memory changes in healthy older adults. In E. Tulving & F. Craik (Eds.), *Oxford Handbook of Memory* (pp. 395-410). Oxford Universtiy Press.

Barbosa, M. R., Medeiros, D. S., Rossi-Barbosa, L. A., Silveira, M. F., de Barros Lima Martins, A. M., & Caldeira, A. P. (2015). Self-perception of the hearing-impaired elderly before and after hearing-aid fittings. *Geriatr Gerontol Int*, *15*(8), 977-982.

Ben-David, B. M., Campeanu, S., Tremblay, K. L., & Alain, C. (2011). Auditory evoked potentials dissociate rapid perceptual learning from task repetition without learning. *Psychophysiology*, *48*(6), 797-807.

Bertoli, S., Probst, R., & Bodmer, D. (2011). Late auditory evoked potentials in elderly long-term hearing-aid users with unilateral or bilateral fittings. *Hear Res*, *280*(1-2), 58-69.

Bertoli, S., Smurzynski, J., & Probst, R. (2005). Effects of age, age-related hearing loss, and contralateral cafeteria noise on the discrimination of small frequency changes: psychoacoustic and electrophysiological measures. *J Assoc Res Otolaryngol*, *6*(3), 207-222.

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

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.
(2016). Hearing Health Care for Adults: Priorities for Improving Access and Affordability.
Boi, R., Racca, L., Cavallero, A., Carpaneto, V., Racca, M., Dall' Acqua, F. et al. (2012). Hearing loss and depressive symptoms in elderly patients. *Geriatr Gerontol Int*, *12*(3), 440-445.
Bowl, M. R., & Dawson, S. J. (2015). The mouse as a model for age-related hearing loss - a mini-review. *Gerontology*, *61*(2), 149-157.
Brown, W. S., Marsh, J. T., & LaRue, A. (1983). Exponential electrophysiological aging: P3 latency. *Electroencephalogr Clin Neurophysiol*, *55*(3), 277-285.
Burianova, J., Ouda, L., Profant, O., & Syka, J. (2009). Age-related changes in GAD levels in the central auditory system of the rat. *Exp Gerontol*, *44*(3), 161-169.
Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging gracefully: compensatory brain activity in high-performing older adults. *Neuroimage*, *17*(3), 1394-1402.
Campbell, J., & Sharma, A. (2013). Compensatory changes in cortical resource allocation in adults with hearing loss. *Front Syst Neurosci*, *7*, 71.
Carhart, R., & Jerger, J. (1959). Preferred methods for clinical determination of pure-tone thresholds. *J Speech Hear Res*, *24*, 330-345.
Carlson, S., & Willott, J. F. (1996). The behavioral salience of tones as indicated by prepulse inhibition of the startle response: relationship to hearing loss and central neural plasticity in C57BL/6J mice. *Hear Res*, *99*(1-2), 168-175.
Cattell, R. B., & Cattell, A. K. S. (1960). Handbook for the individual or group Culture Fair intelligence test.
Chang, H. P., Ho, C. Y., & Chou, P. (2009). The factors associated with a self-perceived hearing handicap in elderly people with hearing impairment--results from a community-based study. *Ear Hear*, *30*(5), 576-583.
Cherko, M., Hickson, L., & Bhutta, M. (2016). Auditory deprivation and health in the elderly. *Maturitas*, *88*, 52-57.
Chisolm, T. H., Johnson, C. E., Danhauer, J. L., Portz, L. J., Abrams, H. B., Lesner, S. et al. (2007). A systematic review of health-related quality of life and hearing aids: final report of the American Academy of Audiology Task Force On the Health-Related Quality of Life Benefits of Amplification in Adults. *J Am Acad Audiol*, *18*(2), 151-183.
Connelly, S. L., Hasher, L., & Zacks, R. T. (1991). Age and reading: the impact of distraction. *Psychol Aging*, *6*(4), 533-541.
Contrera, K. J., Betz, J., Li, L., Blake, C. R., Sung, Y. K., Choi, J. S. et al. (2016). Quality of life after intervention with a cochlear implant or hearing aid. *Laryngoscope*, *126*(9), 2110-2115.
(2008). *The Handbook of Aging and Cognition*. New York: Psychology Press.
Cruickshanks, K. J., Tweed, T. S., Wiley, T. L., Klein, B. E., Klein, R., Chappell, R. et al. (2003). The 5-year incidence and progression of hearing loss: the epidemiology of hearing loss study. *Arch Otolaryngol Head Neck Surg*, *129*(10), 1041-1046.
Cruickshanks, K. J., Wiley, T. L., Tweed, T. S., Klein, B. E., Klein, R., Mares-Perlman, J. A. et al. (1998). Prevalence of hearing loss in older adults in Beaver Dam, Wisconsin. The Epidemiology of Hearing Loss Study. *Am J Epidemiol*, *148*(9), 879-886.
Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychon Bull Rev*, *3*(4), 422-433.
Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of verbal learning and verbal behavior*, *19*(4), 450-466.
Davis, A., McMahon, C. M., Pichora-Fuller, K. M., Russ, S., Lin, F., Olusanya, B. O. et al. (2016). Aging and Hearing Health: The Life-course Approach. *Gerontologist*, *56 Suppl 2*,

S256-67.
Davis, P. A. (1939). Effects of acoustic stimuli on the waking human brain. *Journal of Neurophysiology*.
Dawes, P., Cruickshanks, K. J., Fischer, M. E., Klein, B. E., Klein, R., & Nondahl, D. M. (2015a). Hearing-aid use and long-term health outcomes: Hearing handicap, mental health, social engagement, cognitive function, physical health, and mortality. *Int J Audiol*, *54*(11), 838-844.
Dawes, P., Emsley, R., Cruickshanks, K. J., Moore, D. R., Fortnum, H., Edmondson-Jones, M. et al. (2015b). Hearing loss and cognition: the role of hearing AIDS, social isolation and depression. *PLoS One*, *10*(3), e0119616.
Dawes, P., Munro, K. J., Kalluri, S., & Edwards, B. (2014b). Auditory acclimatization and hearing aids: late auditory evoked potentials and speech recognition following unilateral and bilateral amplification. *J Acoust Soc Am*, *135*(6), 3560-3569.
Dawes, P., Munro, K. J., Kalluri, S., & Edwards, B. (2014b). Acclimatization to hearing aids. *Ear Hear*, *35*(2), 203-212.
de Villers-Sidani, E., Alzghoul, L., Zhou, X., Simpson, K. L., Lin, R. C., & Merzenich, M. M. (2010). Recovery of functional and structural age-related changes in the rat primary auditory cortex with operant training. *Proc Natl Acad Sci U S A*, *107*(31), 13900-13905.
Deal, J. A., Betz, J., Yaffe, K., Harris, T., Purchase-Helzner, E., Satterfield, S. et al. (2016). Hearing Impairment and Incident Dementia and Cognitive Decline in Older Adults: The Health ABC Study. *J Gerontol A Biol Sci Med Sci*.
Deal, J. A., Sharrett, A. R., Albert, M. S., Coresh, J., Mosley, T. H., Knopman, D. et al. (2015). Hearing impairment and cognitive decline: a pilot study conducted within the atherosclerosis risk in communities neurocognitive study. *Am J Epidemiol*, *181*(9), 680-690.
Desjardins, J. L., & Doherty, K. A. (2013). Age-related changes in listening effort for various types of masker noises. *Ear Hear*, *34*(3), 261-272.
Doherty, K. A., & Desjardins, J. L. (2015). The benefit of amplification on auditory working memory function in middle-aged and young-older hearing impaired adults. *Front Psychol*, *6*, 721.
Donahue, A., Dubno, J. R., & Beck, L. (2010). Accessible and affordable hearing health care for adults with mild to moderate hearing loss. *Ear Hear*, *31*, 2-6.
Dubno, J. R., Lee, F. S., Matthews, L. J., Ahlstrom, J. B., Horwitz, A. R., & Mills, J. H. (2008). Longitudinal changes in speech recognition in older persons. *J Acoust Soc Am*, *123*(1), 462-475.
Dupuis, K., Pichora-Fuller, M. K., Chasteen, A. L., Marchuk, V., Singh, G., & Smith, S. L. (2015). Effects of hearing and vision impairments on the Montreal Cognitive Assessment. *Neuropsychol Dev Cogn B Aging Neuropsychol Cogn*, *22*(4), 413-437.
Dushanova, J., & Christov, M. (2013). Auditory event-related brain potentials for an early discrimination between normal and pathological brain aging. *Neural Regen Res*, *8*(15), 1390-1399.
Eckert, M. A., Cute, S. L., Vaden, K. I., Kuchinsky, S. E., & Dubno, J. R. (2012). Auditory cortex signs of age-related hearing loss. *J Assoc Res Otolaryngol*, *13*(5), 703-713.
Eggermont, J. J. (2016). Acquired hearing loss and brain plasticity. *Hear Res*.
Eggermont, J. J., & Ponton, C. W. (2002). The neurophysiology of auditory perception: from single units to evoked potentials. *Audiol Neurootol*, *7*(2), 71-99.
Füllgrabe, C., & Rosen, S. (2016a). Investigating the Role of Working Memory in Speech-in-noise Identification for Listeners with Normal Hearing. *Adv Exp Med Biol*, *894*, 29-36.
Füllgrabe, C., & Rosen, S. (2016b). On The (Un)importance of Working Memory in Speech-in-Noise Processing for Listeners with Normal Hearing Thresholds. *Front Psychol*, *7*, 1268.
Gatehouse, S., & Akeroyd, M. (2006). Two-eared listening in dynamic situations. *Int J Audiol*, *45*

Suppl 1, S120-4.
Gates, G. A., & Mills, J. H. (2005). Presbycusis. *Lancet*, *366*(9491), 1111-1120.
Goodin, D. S., Squires, K. C., Henderson, B. H., & Starr, A. (1978). Age-related variations in evoked potentials to auditory stimuli in normal human subjects. *Electroencephalogr Clin Neurophysiol*, *44*(4), 447-458.
Gopinath, B., Hickson, L., Schneider, J., McMahon, C. M., Burlutsky, G., Leeder, S. R. et al. (2012). Hearing-impaired adults are at increased risk of experiencing emotional distress and social engagement restrictions five years later. *Age Ageing*, *41*(5), 618-623.
Grady, C. (2012). The cognitive neuroscience of ageing. *Nat Rev Neurosci*, *13*(7), 491-505.
Gurgel, R. K., Ward, P. D., Schwartz, S., Norton, M. C., Foster, N. L., & Tschanz, J. T. (2014). Relationship of hearing loss and dementia: a prospective, population-based study. *Otol Neurotol*, *35*(5), 775-781.
Harkrider, A. W., Plyler, P. N., & Hedrick, M. S. (2005). Effects of age and spectral shaping on perception and neural representation of stop consonant stimuli. *Clin Neurophysiol*, *116*(9), 2153-2164.
Harkrider, A. W., Plyler, P. N., & Hedrick, M. S. (2006). Effects of hearing loss and spectral shaping on identification and neural response patterns of stop-consonant stimuli. *J Acoust Soc Am*, *120*(2), 915-925.
Harris, K. C., Dubno, J. R., Keren, N. I., Ahlstrom, J. B., & Eckert, M. A. (2009). Speech recognition in younger and older adults: a dependency on low-level auditory cortex. *J Neurosci*, *29*(19), 6078-6087.
Harris, K. C., Wilson, S., Eckert, M. A., & Dubno, J. R. (2012). Human evoked cortical activity to silent gaps in noise: effects of age, attention, and cortical processing speed. *Ear Hear*, *33*(3), 330-339.
Hasher, L., Stoltzfus, E. R., Zacks, R. T., & Rypma, B. (1991). Age and inhibition. *J Exp Psychol Learn Mem Cogn*, *17*(1), 163-169.
Hasher, L., Zacks, R. T., & Rahhal, T. A. (1999). Timing, instructions, and inhibitory control: some missing factors in the age and memory debate. *Gerontology*, *45*(6), 355-357.
Herrmann, B., Henry, M. J., Johnsrude, I. S., & Obleser, J. (2016). Altered temporal dynamics of neural adaptation in the aging human auditory cortex. *Neurobiol Aging*, *45*, 10-22.
Hillyard, S. A., & Kutas, M. (1983). Electrophysiology of cognitive processing. *Annu Rev Psychol*, *34*, 33-61.
Huang, C. Q., Dong, B. R., Lu, Z. C., Yue, J. R., & Liu, Q. X. (2010). Chronic diseases and risk for depression in old age: a meta-analysis of published literature. *Ageing Res Rev*, *9*(2), 131-141.
Humes, L. E. (2007). The contributions of audibility and cognitive factors to the benefit provided by amplified speech to older adults. *J Am Acad Audiol*, *18*(7), 590-603.
Humes, L. E., Busey, T. A., Craig, J., & Kewley-Port, D. (2013). Are age-related changes in cognitive function driven by age-related changes in sensory processing. *Atten Percept Psychophys*, *75*(3), 508-524.
Humes, L. E., Garner, C. B., Wilson, D. L., & Barlow, N. N. (2001). Hearing-aid outcome measured following one month of hearing aid use by the elderly. *J Speech Lang Hear Res*, *44*(3), 469-486.
Humes, L. E., Halling, D., & Coughlin, M. (1996). Reliability and stability of various hearing-aid outcome measures in a group of elderly hearing-aid wearers. *J Speech Hear Res*, *39*(5), 923-935.
Humes, L. E., & Wilson, D. L. (2003). An examination of changes in hearing-aid performance and benefit in the elderly over a 3-year period of hearing-aid use. *J Speech Lang Hear Res*, *46*(1), 137-145.
Humes, L. E., Wilson, D. L., Barlow, N. N., & Garner, C. (2002). Changes in hearing-aid benefit following 1 or 2 years of hearing-aid use by older adults. *J Speech Lang Hear Res*, *45*(4),

772-782.
Hyde, M. (1997). The N1 response and its applications. *Audiol Neurootol*, *2*(5), 281-307.
Iragui, V. J., Kutas, M., Mitchiner, M. R., & Hillyard, S. A. (1993). Effects of aging on event-related brain potentials and reaction times in an auditory oddball task. *Psychophysiology*, *30*(1), 10-22.
Jorgensen, L. E., Palmer, C. V., Pratt, S., Erickson, K. I., & Moncrieff, D. (2016). The Effect of Decreased Audibility on MMSE Performance: A Measure Commonly Used for Diagnosing Dementia. *J Am Acad Audiol*, *27*(4), 311-323.
Kayser, J., & Tenke, C. E. (2015). Issues and considerations for using the scalp surface Laplacian in EEG/ERP research: A tutorial review. *Int J Psychophysiol*, *97*(3), 189-209.
Kazee, A. M., Han, L. Y., Spongr, V. P., Walton, J. P., Salvi, R. J., & Flood, D. G. (1995). Synaptic loss in the central nucleus of the inferior colliculus correlates with sensorineural hearing loss in the C57BL/6 mouse model of presbycusis. *Hear Res*, *89*(1-2), 109-120.
Kim, J. R., Ahn, S. Y., Jeong, S. W., Kim, L. S., Park, J. S., Chung, S. H. et al. (2012). Cortical auditory evoked potential in aging: effects of stimulus intensity and noise. *Otol Neurotol*, *33*(7), 1105-1112.
Kochkin, S. (2009). MarkeTrak VIII: 25-year trends in the hearing health market. *Hearing Review*, *16*, 12-31.
Kramer, A. F., Hahn, S., & Gopher, D. (1999). Task coordination and aging: explorations of executive control processes in the task switching paradigm. *Acta Psychol (Amst)*, *101*(2-3), 339-378.
Lethbridge-Cejku, M., Schiller, J. S., & Bernadel, L. (2004). Summary health statistics for U.S. adults: National Health Interview Survey, 2002. *Vital Health Stat 10*, 222), 1-151.
Lin, F. R. (2011). Hearing loss and cognition among older adults in the United States. *J Gerontol A Biol Sci Med Sci*, *66*(10), 1131-1136.
Lin, F. R. (2012). Hearing loss in older adults: who's listening. *JAMA*, *307*(11), 1147-1148.
Lin, F. R., & Albert, M. (2014). Hearing loss and dementia - who is listening. *Aging Ment Health*, *18*(6), 671-673.
Lin, F. R., Ferrucci, L., An, Y., Goh, J. O., Doshi, J., Metter, E. J. et al. (2014). Association of hearing impairment with brain volume changes in older adults. *Neuroimage*, *90*, 84-92.
Lin, F. R., Ferrucci, L., Metter, E. J., An, Y., Zonderman, A. B., & Resnick, S. M. (2011). Hearing loss and cognition in the Baltimore Longitudinal Study of Aging. *Neuropsychology*, *25*(6), 763-770.
Lin, F. R., Yaffe, K., Xia, J., Xue, Q. L., Harris, T. B., Purchase-Helzner, E. et al. (2013). Hearing loss and cognitive decline in older adults. *JAMA Intern Med*, *173*(4), 293-299.
Ling, L. L., Hughes, L. F., & Caspary, D. M. (2005). Age-related loss of the GABA synthetic enzyme glutamic acid decarboxylase in rat primary auditory cortex. *Neuroscience*, *132*(4), 1103-1113.
Lister, J. J., Harrison Bush, A. L., Andel, R., Matthews, C., Morgan, D., & Edwards, J. D. (2016). Cortical auditory evoked responses of older adults with and without probable mild cognitive impairment. *Clin Neurophysiol*, *127*(2), 1279-1287.
Lister, J. J., Maxfield, N. D., Pitt, G. J., & Gonzalez, V. B. (2011). Auditory evoked response to gaps in noise: older adults. *Int J Audiol*, *50*(4), 211-225.
Luis, C. A., Keegan, A. P., & Mullan, M. (2009). Cross validation of the Montreal Cognitive Assessment in community dwelling older adults residing in the Southeastern US. *Int J Geriatr Psychiatry*, *24*(2), 197-201.
Lunner, T. (2003). Cognitive function in relation to hearing aid use. *Int J Audiol*, *42 Suppl 1*, S49-58.
Lyxell, B., Andersson, U., Borg, E., & Ohlsson, I. S. (2003). Working-memory capacity and phonological processing in deafened adults and individuals with a severe hearing impairment. *Int J Audiol*, *42 Suppl 1*, S86-9.

Madden, D. J. (1990). Adult age differences in attentional selectivity and capacity. *Eur J Cogn Psychol*, *2*, 229-252.

Malinoff, R. L., & Weinstein, B. E. (1989). Measurement of hearing aid benefit in the elderly. *Ear Hear*, *10*(6), 354-356.

Martin del Campo, H. N., Measor, K. R., & Razak, K. A. (2012). Parvalbumin immunoreactivity in the auditory cortex of a mouse model of presbycusis. *Hear Res*, *294*(1-2), 31-39.

McCoy, S. L., Tun, P. A., Cox, L. C., Colangelo, M., Stewart, R. A., & Wingfield, A. (2005). Hearing loss and perceptual effort: downstream effects on older adults' memory for speech. *Q J Exp Psychol A*, *58*(1), 22-33.

Miller, C., Stewart, E., Wu, Y.-H., Bishop, C., Bentler, R. A., & Tremblay, K. (in press). Working memory and speech recogntion in noise under ecologically relevant listening conditions: Effects of visual cues and noise type among adults with hearing loss. *Journal of Speech, Language, and Hearing Research*.

Mishra, S., Stenfelt, S., Lunner, T., Rönnberg, J., & Rudner, M. (2014). Cognitive spare capacity in older adults with hearing loss. *Front Aging Neurosci*, *6*, 96.

Mizutari, K., Michikawa, T., Saito, H., Okamoto, Y., Enomoto, C., Takebayashi, T. et al. (2013). Age-related hearing loss and the factors determining continued usage of hearing aids among elderly community-dwelling residents. *PLoS One*, *8*(9), e73622.

Mulrow, C. D., Aguilar, C., Endicott, J. E., Velez, R., Tuley, M. R., Charlip, W. S. et al. (1990). Association between hearing impairment and the quality of life of elderly individuals. *J Am Geriatr Soc*, *38*(1), 45-50.

Mulrow, C. D., Tuley, M. R., & Aguilar, C. (1992). Sustained benefits of hearing aids. *J Speech Hear Res*, *35*(6), 1402-1405.

Nash, S. D., Cruickshanks, K. J., Klein, R., Klein, B. E., Nieto, F. J., Huang, G. H. et al. (2011). The prevalence of hearing impairment and associated risk factors: the Beaver Dam Offspring Study. *Arch Otolaryngol Head Neck Surg*, *137*(5), 432-439.

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I. et al. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *J Am Geriatr Soc*, *53*(4), 695-699.

Newman, C. W., & Weinstein, B. E. (1988). The Hearing Handicap Inventory for the Elderly as a measure of hearing aid benefit. *Ear Hear*, *9*(2), 81-85.

Ng, E. H., Classon, E., Larsby, B., Arlinger, S., Lunner, T., Rudner, M. et al. (2014). Dynamic relation between working memory capacity and speech recognition in noise during the first 6 months of hearing aid use. *Trends Hear*, *18*.

Nilsson, M., Soli, S. D., & Sullivan, J. A. (1994). Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *J Acoust Soc Am*, *95*(2), 1085-1099.

Noble, W., & Gatehouse, S. (2006). Effects of bilateral versus unilateral hearing aid fitting on abilities measured by the Speech, Spatial, and Qualities of Hearing Scale (SSQ). *Int J Audiol*, *45*(3), 172-181.

Nunez, P. L., & Srinivasan, R. (2006). *Electric Fields of the Brain* (2nd ed.). New York: Oxford University Press.

Panza, F., Solfrizzi, V., & Logroscino, G. (2015). Age-related hearing impairment-a risk factor and frailty marker for dementia and AD. *Nat Rev Neurol*, *11*(3), 166-175.

Papanicolaou, A. C., Loring, D. W., & Eisenberg, H. M. (1984). Age-related differences in recovery cycle of auditory evoked potentials. *Neurobiol Aging*, *5*(4), 291-295.

Peelle, J. E., Troiani, V., Grossman, M., & Wingfield, A. (2011). Hearing loss in older adults affects neural systems supporting speech comprehension. *J Neurosci*, *31*(35), 12638-12643.

Pfefferbaum, A., Ford, J. M., Roth, W. T., & Kopell, B. S. (1980). Age-related changes in auditory event-related potentials. *Electroencephalogr Clin Neurophysiol*, *49*(3-4), 266-276.

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W., Humes, L. E. et al. (2016). Hearing Impairment and Cognitive Energy: The Framework for Understanding Effortful Listening (FUEL). *Ear Hear*, *37 Suppl 1*, 5S-27S.

Picton, T. (2013). Hearing in time: evoked potential studies of temporal processing. *Ear Hear*, *34*(4), 385-401.

Picton, T. W., & Durieux-Smith, A. (1988). Auditory evoked potentials in the assessment of hearing. *Neurol Clin*, *6*(4), 791-808.

Picton, T. W., Stuss, D. T., Champagne, S. C., & Nelson, R. F. (1984). The effects of age on human event-related potentials. *Psychophysiology*, *21*(3), 312-325.

Poeppel, D., & Monahan, P. J. (2008). Speech perception: Cognitive foundations and cortical implementation. *Current Directions in Psychological Science*, *17*, 80-85.

Polich, J. (1997). EEG and ERP assessment of normal aging. *Electroencephalogr Clin Neurophysiol*, *104*(3), 244-256.

Popelka, M. M., Cruickshanks, K. J., Wiley, T. L., Tweed, T. S., Klein, B. E., & Klein, R. (1998). Low prevalence of hearing aid use among older adults with hearing loss: the Epidemiology of Hearing Loss Study. *J Am Geriatr Soc*, *46*(9), 1075-1078.

Profant, O., Balogová, Z., Dezortová, M., Wagnerová, D., Hájek, M., & Syka, J. (2013). Metabolic changes in the auditory cortex in presbycusis demonstrated by MR spectroscopy. *Exp Gerontol*, *48*(8), 795-800.

Puschmann, S., & Thiel, C. M. (2016). Changed crossmodal functional connectivity in older adults with hearing loss. *Cortex*, *86*, 109-122.

Rabbitt, P. (1990). Mild hearing loss can cause apparent memory failures which increase with age and reduce with IQ. *Acta Otolaryngol Suppl*, *476*, 167-75; discussion 176.

Rönnberg, J. (2003). Cognition in the hearing impaired and deaf as a bridge between signal and dialogue: a framework and a model. *Int J Audiol*, *42 Suppl 1*, S68-76.

Rönnberg, J., Arlinger, S., Lyxell, B., & Kinnefors, C. (1989). Visual evoked potentials: relation to adult speechreading and cognitive function. *J Speech Hear Res*, *32*(4), 725-735.

Rönnberg, J., Danielsson, H., Rudner, M., Arlinger, S., Sternäng, O., Wahlin, A. et al. (2011). Hearing loss is negatively related to episodic and semantic long-term memory but not to short-term memory. *J Speech Lang Hear Res*, *54*(2), 705-726.

Rönnberg, J., Lunner, T., Zekveld, A., Sörqvist, P., Danielsson, H., Lyxell, B. et al. (2013). The Ease of Language Understanding (ELU) model: theoretical, empirical, and clinical advances. *Front Syst Neurosci*, *7*, 31.

Rönnberg, J., Rudner, M., Foo, C., & Lunner, T. (2008). Cognition counts: a working memory system for ease of language understanding (ELU). *Int J Audiol*, *47 Suppl 2*, S99-105.

Rönnberg, J., Rudner, M., Lunner, T., & Zekveld, A. A. (2010). When cognition kicks in: working memory and speech understanding in noise. *Noise Health*, *12*(49), 263-269.

Ross, B., Fujioka, T., Tremblay, K. L., & Picton, T. W. (2007). Aging in binaural hearing begins in mid-life: evidence from cortical auditory-evoked responses to changes in interaural phase. *J Neurosci*, *27*(42), 11172-11178.

Ross, B., & Tremblay, K. (2009). Stimulus experience modifies auditory neuromagnetic responses in young and older listeners. *Hear Res*, *248*(1-2), 48-59.

Rudner, M., Foo, C., Rönnberg, J., & Lunner, T. (2009). Cognition and aided speech recognition in noise: specific role for cognitive factors following nine-week experience with adjusted compression settings in hearing aids. *Scand J Psychol*, *50*(5), 405-418.

Salthouse, T. A., Hancock, H. E., Meinz, E. J., & Hambrick, D. Z. (1996). Interrelations of age, visual acuity, and cognitive functioning. *J Gerontol B Psychol Sci Soc Sci*, *51*(6), P317-30.

Schneider, B., & Pichora-Fuller, M. K. (2000). Implications of Perceptual Deterioration for Cognitive Aging Research. In F. Craik & S. T (Eds.), *Handbook of Aging and Cognition* (2nd ed.). Mahwah, NJ: Lawrence Erlbaum Associates.

Seppänen, M., Hämäläinen, J., Pesonen, A. K., & Tervaniemi, M. (2012). Music training

enhances rapid neural plasticity of n1 and p2 source activation for unattended sounds. *Front Hum Neurosci*, *6*, 43.
Shahin, A., Bosnyak, D. J., Trainor, L. J., & Roberts, L. E. (2003). Enhancement of neuroplastic P2 and N1c auditory evoked potentials in musicians. *J Neurosci*, *23*(13), 5545-5552.
Sheehan, K. A., McArthur, G. M., & Bishop, D. V. M. (2005). Is discrimination training necessary to cause changes in the P2 auditory event-related brain potential to speech sounds. *Cognitive Brain Research*, *25*(2), 547-553.
Singh, G., & Kathleen Pichora-Fuller, M. (2010). Older adults' performance on the speech, spatial, and qualities of hearing scale (SSQ): Test-retest reliability and a comparison of interview and self-administration methods. *Int J Audiol*, *49*(10), 733-740.
Singh, G., Lau, S. T., & Pichora-Fuller, M. K. (2015). Social Support Predicts Hearing Aid Satisfaction. *Ear Hear*, *36*(6), 664-676.
Smith, D. B., Michalewski, H. J., Brent, G. A., & Thompson, L. W. (1980). Auditory averaged evoked potentials and aging: factors of stimulus, task and topography. *Biol Psychol*, *11*(2), 135-151.
Smith, S. L., & Pichora-Fuller, M. K. (2015). Associations between speech understanding and auditory and visual tests of verbal working memory: effects of linguistic complexity, task, age, and hearing loss. *Front Psychol*, *6*, 1394.
Smith, S. L., Pichora-Fuller, M. K., & Alexander, G. (2016). Development of the Word Auditory Recognition and Recall Measure: A Working Memory Test for Use in Rehabilitative Audiology. *Ear Hear*, *37*(6), e360-e376.
Solheim, J., Kværner, K. J., & Falkenberg, E. S. (2011). Daily life consequences of hearing loss in the elderly. *Disabil Rehabil*, *33*(23-24), 2179-2185.
Souza, P., & Arehart, K. (2015). Robust relationship between reading span and speech recognition in noise. *Int J Audiol*, *54*(10), 705-713.
Spink, U., Johannsen, H. S., & Pirsig, W. (1979). Acoustically evoked potential: dependence upon age. *Scand Audiol*, *8*(1), 11-14.
Stebbings, K. A., Choi, H. W., Ravindra, A., Caspary, D. M., Turner, J. G., & Llano, D. A. (2016). Ageing-related changes in GABAergic inhibition in mouse auditory cortex, measured using in vitro flavoprotein autofluorescence imaging. *J Physiol*, *594*(1), 207-221.
Tesch-Römer, C. (1997). Psychological effects of hearing aid use in older adults. *J Gerontol B Psychol Sci Soc Sci*, *52*(3), P127-38.
Tremblay, K., Kraus, N., Carrell, T. D., & McGee, T. (1997). Central auditory system plasticity: generalization to novel stimuli following listening training. *J Acoust Soc Am*, *102*(6), 3762-3773.
Tremblay, K., Kraus, N., & McGee, T. (1998). The time course of auditory perceptual learning: neurophysiological changes during speech-sound training. *Neuroreport*, *9*(16), 3557-3560.
Tremblay, K., Kraus, N., McGee, T., Ponton, C., & Otis, B. (2001). Central auditory plasticity: changes in the N1-P2 complex after speech-sound training. *Ear Hear*, *22*(2), 79-90.
Tremblay, K. L., & Backer, K. C. (2016). Listening and Learning: Cognitive Contributions to the Rehabilitation of Older Adults With and Without Audiometrically Defined Hearing Loss. *Ear Hear*, *37 Suppl 1*, 155S-62S.
Tremblay, K. L., Billings, C., & Rohila, N. (2004). Speech evoked cortical potentials: effects of age and stimulus presentation rate. *J Am Acad Audiol*, *15*(3), 226-37; quiz 264.
Tremblay, K. L., Inoue, K., McClannahan, K., & Ross, B. (2010). Repeated stimulus exposure alters the way sound is encoded in the human brain. *PLoS One*, *5*(4), e10283.
Tremblay, K. L., & Kraus, N. (2002). Auditory training induces asymmetrical changes in cortical neural activity. *J Speech Lang Hear Res*, *45*(3), 564-572.
Tremblay, K. L., Piskosz, M., & Souza, P. (2002). Aging alters the neural representation of speech cues. *Neuroreport*, *13*(15), 1865-1870.
Tremblay, K. L., Piskosz, M., & Souza, P. (2003). Effects of age and age-related hearing loss on

the neural representation of speech cues. *Clin Neurophysiol*, *114*(7), 1332-1343.
Tremblay, K. L., Ross, B., Inoue, K., McClannahan, K., & Collet, G. (2014). Is the auditory evoked P2 response a biomarker of learning. *Front Syst Neurosci*, *8*, 28.
Tremblay, K. L., Shahin, A. J., Picton, T., & Ross, B. (2009). Auditory training alters the physiological detection of stimulus-specific cues in humans. *Clin Neurophysiol*, *120*(1), 128-135.
Uhlmann, R. F., Teri, L., Rees, T. S., Mozlowski, K. J., & Larson, E. B. (1989). Impact of mild to moderate hearing loss on mental status testing. Comparability of standard and written Mini-Mental State Examinations. *J Am Geriatr Soc*, *37*(3), 223-228.
van Hooren, S. A., Anteunis, L. J., Valentijn, S. A., Bosma, H., Ponds, R. W., Jolles, J. et al. (2005). Does cognitive function in older adults with hearing impairment improve by hearing aid use. *Int J Audiol*, *44*(5), 265-271.
Ventry, I. M., & Weinstein, B. E. (1982). The hearing handicap inventory for the elderly: a new tool. *Ear Hear*, *3*, 128-134.
Vesco, K. K., Bone, R. C., Ryan, J. C., & Polich, J. (1993). P300 in young and elderly subjects: auditory frequency and intensity effects. *Electroencephalogr Clin Neurophysiol*, *88*(4), 302-308.
Vestergaard Knudsen, L., Öberg, M., Nielsen, C., Naylor, G., & Kramer, S. E. (2010). Factors influencing help seeking, hearing aid uptake, hearing aid use and satisfaction with hearing aids: A review of the literature. *Trends Amplif*, *14*, 127-154.
Viljanen, A., Kaprio, J., Pyykkö, I., Sorri, M., Pajala, S., Kauppinen, M. et al. (2009). Hearing as a predictor of falls and postural balance in older female twins. *J Gerontol A Biol Sci Med Sci*, *64*(2), 312-317.
Weinstein, B. E. (2015). What hearing impairment measures do not tell us-but self-report measures do. *The Hearing Journal*, *68*, 26-32.
Weinstein, B. E., & Amsel, L. (1987). Hearing impairment and cognitive function in Alzheimer's disease. *J Am Geriatr Soc*, *35*(3), 273-275.
Weinstein, B. E., & Amsel, L. (1986). Hearing loss and senile dementia in the institutionalized elderly. *Clinical Gerontologist*, *4*, 3-15.
Weinstein, B. E., Sirow, L. W., & Moser, S. (2016). Relating Hearing Aid Use to Social and Emotional Loneliness in Older Adults. *Am J Audiol*, *25*(1), 54-61.
Weinstein, B. E., Spitzer, J. B., & Ventry, I. M. (1986). Test-retest reliability of the Hearing Handicap Inventory for the Elderly. *Ear Hear*, *7*(5), 295-299.
Weinstein, B. E., & Ventry, I. M. (1982). Hearing impairment and social isolation in the elderly. *J Speech Hear Res*, *25*(4), 593-599.
Weinstein, B. E., & Ventry, I. M. (1983). Audiometric correlates of the Hearing Handicap Inventory for the elderly. *J Speech Hear Disord*, *48*(4), 379-384.
Welsh, L. W., Welsh, J. J., & Healy, M. P. (1985). Central presbycusis. *Laryngoscope*, *95*(2), 128-136.
White-Schwoch, T., Carr, K. W., Anderson, S., Strait, D. L., & Kraus, N. (2013). Older adults benefit from music training early in life: biological evidence for long-term training-driven plasticity. *The Journal of Neuroscience*, *33*(45), 17667-17674.
Willott, J. F. (1996). Anatomic and physiologic aging: a behavioral neuroscience perspective. *J Am Acad Audiol*, *7*(3), 141-151.
Willott, J. F., Aitkin, L. M., & McFadden, S. L. (1993). Plasticity of auditory cortex associated with sensorineural hearing loss in adult C57BL/6J mice. *J Comp Neurol*, *329*(3), 402-411.
Willott, J. F., & Bross, L. S. (1996). Morphological changes in the anteroventral cochlear nucleus that accompany sensorineural hearing loss in DBA/2J and C57BL/6J mice. *Brain Res Dev Brain Res*, *91*(2), 218-226.
Willott, J. F., Hnath Chisolm, T., & Lister, J. J. (2001). Modulation of presbycusis: current status and future directions. *Audiol Neurootol*, *6*(5), 231-249.

Willott, J. F., Parham, K., & Hunter, K. P. (1991). Comparison of the auditory sensitivity of neurons in the cochlear nucleus and inferior colliculus of young and aging C57BL/6J and CBA/J mice. *Hear Res*, *53*(1), 78-94.

Wilson, R. S., Segawa, E., Hizel, L. P., Boyle, P. A., & Bennett, D. A. (2012). Terminal dedifferentiation of cognitive abilities. *Neurology*, *78*(15), 1116-1122.

Zacks, R., Hasher, L., & Li, K. (2000). Human memory. In F. Craik & S. T (Eds.), *Handbook of Aging and Cogntion* (2nd ed., pp. 293-357). Mahwah: Lawrence Erlbaum Associates.

Zendel, B. R., & Alain, C. (2012). Musicians experience less age-related decline in central auditory processing. *Psychol Aging*, *27*(2), 410-417.

Zendel, B. R., & Alain, C. (2013). The influence of lifelong musicianship on neurophysiological measures of concurrent sound segregation. *J Cogn Neurosci*, *25*(4), 503-516.

Zendel, B. R., & Alain, C. (2014). Enhanced attention-dependent activity in the auditory cortex of older musicians. *Neurobiol Aging*, *35*(1), 55-63.

Zhong, Z., Henry, K. S., & Heinz, M. G. (2014). Sensorineural hearing loss amplifies neural coding of envelope information in the central auditory system of chinchillas. *Hear Res*, *309*, 55-62.

Appendix: Additional Analyses

Peak analysis for fronto-central electrodes

Grand averaged responses for each stimulus level (SPL, SL) at electrodes CZ, FCZ, and FZ along with topographies at component peaks are presented in Figures 3 (Equal Sound Pressure Level) and 4 (Equal Sensation Level). Mean values and standard deviations for peak amplitude and latency are located in Appendix I. Visual inspection of time waveforms revealed robust P1-N1-P2 responses for all groups at each selected electrode and for both SPL and SL stimulus levels.

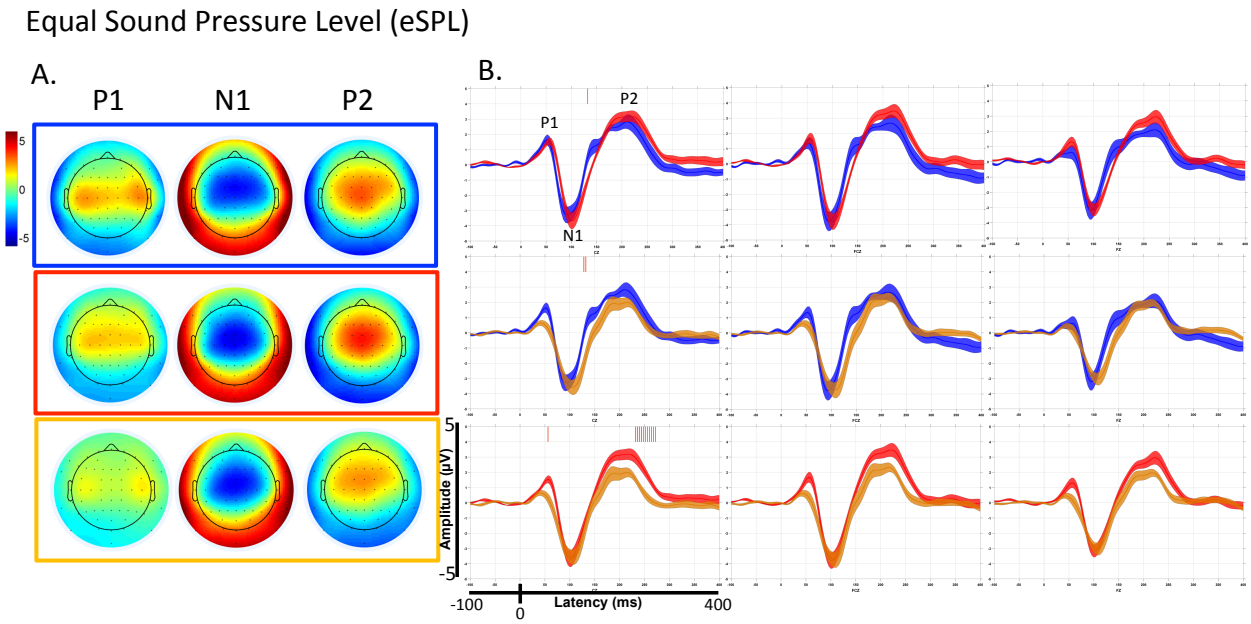

Figure 1. A. P1, N1 and P2 peak topographies for NH, u-HL and t-HL (from top to bottom). B. Group averaged time waveforms at electrodes CZ, FCZ and FZ (from left to right). The width of the ribbon represents the mean value ± the group standard error at each time point. Significant differences revealed through permutations tests indicated by red bars (p<.005) at the top of each waveform. Row 1: NH (blue) and u-HL (red), Row 2: NH and t-HL (gold), Row 3: u-HL and t-HL.

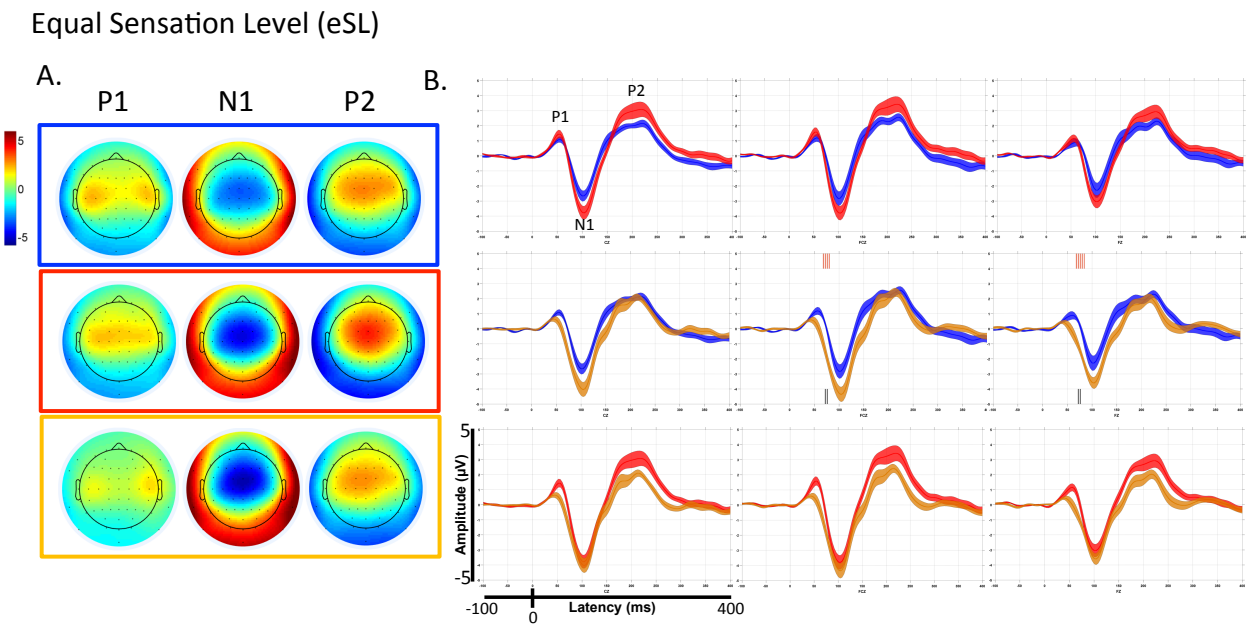

Figure 2. A. P1, N1 and P2 peak topographies for NH, u-HL and t-HL (from top to bottom). B. Group averaged time waveforms at electrodes CZ, FCZ and FZ (from left to right). The width of the ribbon represents the mean value ± the group standard error at each time point. Significant differences revealed through permutations tests indicated by red (*p*<.005) and black (*p*<.001) bars at the top and bottom of each waveform. Row 1: NH (blue) and u-HL (red), Row 2: NH and t-HL (gold), Row 3: u-HL and t-HL.

Peak Amplitudes

Equal Sound Pressure Level (SPL)

Analyses of variance revealed no main effects of group for P1, N1 or P2 peak or peak-to-peak amplitudes. It should be noted that mean P1 and P2 amplitude differences approached significance for electrode CZ (see Table 1). P1 mean peak amplitude at CZ was largest for u-HL(1.79) followed by NH (1.69) and t-HL (.88) and P2 mean peak amplitude largest for u-HL (3.49) followed by NH (3.24) and t-HL (2.35); however these differences did not reach significance.

Table 1. ANOVA results for peak amplitude at CZ, FCZ, and FZ.

Amplitude		eSPL			eSL		
		F (2,27)	*p*-value	η^2	F (2,27)	*p*-value	η^2
CZ	P1	3.085	0.062	0.186	2.273	0.122	0.144
	N1	0.002	0.998	0.000	3.155	0.059	0.189
	P2	3.136	0.060	0.188	2.752	0.082	0.169
	P1-N1	0.759	0.478	0.053	3.329	0.051	0.198
	N1-P2	1.223	0.310	0.083	5.591	0.009**	0.293
FCZ	P1	2.296	0.120	0.145	2.716	0.084	0.168
	N1	0.015	0.985	0.001	2.883	0.073	0.176
	P2	3.048	0.110	0.151	2.457	0.105	0.154
	P1-N1	0.707	0.502	0.050	2.131	0.138	0.136
	N1-P2	0.980	0.388	0.068	4.249	0.025*	0.239
FZ	P1	1.812	0.183	0.118	2.931	0.070	0.111
	N1	0.001	0.999	0.000	2.667	0.088	0.165
	P2	2.289	0.121	0.145	2.322	0.117	0.147
	P1-N1	0.570	0.572	0.040	1.510	0.239	0.101
	N1-P2	1.031	0.370	0.071	3.459	0.046*	0.204

** p<.05, ** p<.01*

Equal Sensation Level (SL)

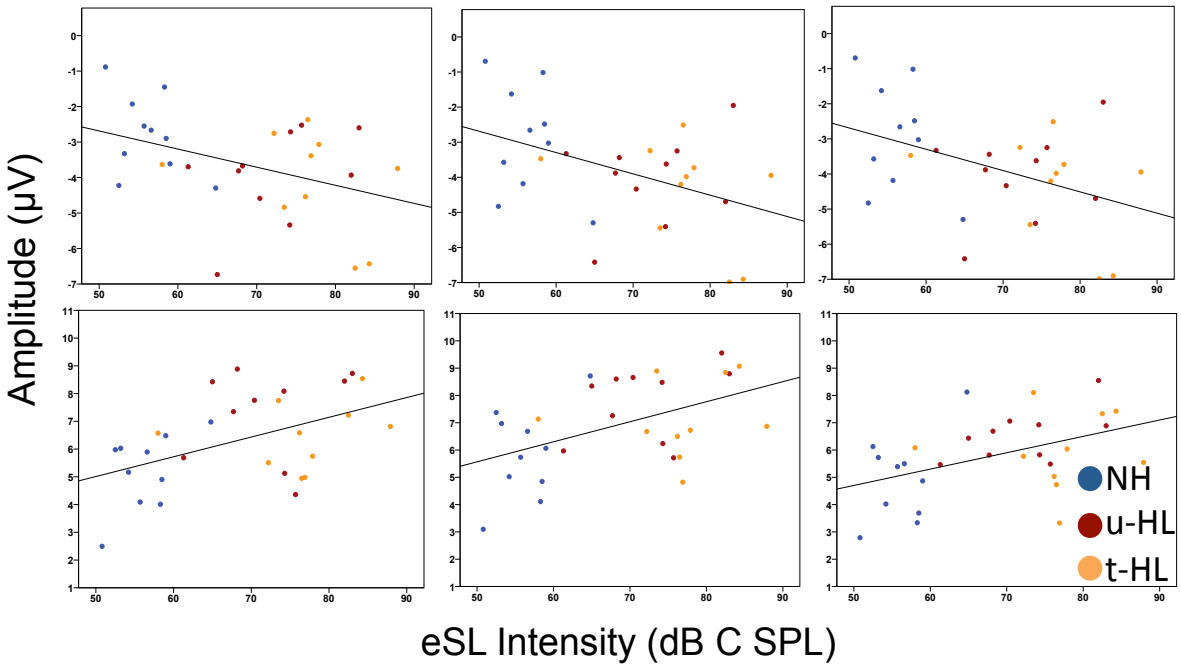

Figure 3. N1 (row 1) and N1-P2 (row 2) amplitude as a function of SL stimulus intensity for electrodes CZ (column 1), FCZ (column 2), and FZ (column 3).

ANOVAs revealed no main effects of group on P1, N1 and P2 peak amplitudes across selected electrodes. Several peak amplitudes approached significance (see Table 1). P1 mean peak amplitude at CZ was largest for u-HL(1.54) followed by NH(1.12) and t-HL(.84), N1 amplitudes were larger for the t-HL(-4.13) and u-HL(-3.96) compared to NH(-2.78), and P2 peak amplitudes appeared largest for u-HL(3.32) group, with NH(2.42) and t-HL(2.33) having smaller P2 amplitudes.

However, there was a significant main effect of group on N1-P2 peak-to-peak amplitude for all three electrodes (Table 1). Post-hoc tests revealed significantly larger N1-P2 peak-to-peak amplitude for u-HL in comparison to NH (CZ p=.007; FCZ p=.021), with other group comparisons not reaching significance. Pearson product-moment correlation coefficients were computed to assess the relationship between N1 and N1-P2 amplitude and stimulus sound pressure level. Analyses revealed moderate correlations between both N1 and N1-P2 amplitudes and SL stimulus level; with louder stimuli correlating with larger response amplitudes for N1 (CZ: r(28)=-.40, p=.03; FCZ:

r(28)=-.43, *p*=.02; FZ: r(28)=-.43, *p*=.02), and N1-P2 (CZ: r(28)=.482, *p*=.007, FCZ: r(28)=.448, *p*=.006, FZ: r(28)=.452, *p*=.006. See Figure 5). These results indicate that the difference in overall stimulus intensity was at least partially responsible for larger N1 and N1-P2 amplitudes for those in the hearing loss groups.

Peak Latencies

Table 2. ANOVA results for peak latency for electrodes CZ, FCZ and FZ.

Latency		eSPL			eSL		
		F (2,27)	*p*-value	η_p^2	F (2,27)	*p*-value	η_p^2
CZ	P1	2.759	0.081	0.170	5.424	0.01*	0.287
	N1	4.172	0.026*	0.236	0.040	0.961	0.003
	P2	0.699	0.520	0.047	0.019	0.981	0.001
FCZ	P1	3.433	0.047*	0.203	5.414	0.011*	0.286
	N1	4.296	0.024*	0.241	0.316	0.732	0.023
	P2	1.094	0.349	0.075	0.294	0.748	0.021
FZ	P1	1.070	0.357	0.073	2.931	0.070	0.178
	N1	7.716	.002**	0.364	0.171	0.844	0.012
	P2	0.645	0.533	0.046	0.196	0.823	0.014
** p<.05, ** p<.01*							

SPL

Group had a significant main effect on peak P1 (FCZ) and N1 (CZ, FCZ and FZ), but not P2, latency (see Table 3). Post-hoc tests revealed significantly shorter peak N1 latencies for the normal hearing group, when compared with the treated hearing loss group (CZ:*p*=.046, FCZ:*p*=.024, FZ:*p*=.002) and shorter P1 peak latency for the treated versus untreated hearing loss group (p=.037); with the remaining group comparisons not reaching significance.

SL

Analysis for the SL stimulus level revealed a significant main effect of group for P1 latency at electrodes CZ and FCZ and approaching significance for FZ (Table 2), but not for N1 or P2 peak latencies. Post-hoc analyses indicated that the treated hearing loss group had significantly shorter peak P1 latency at FCZ than u-HL (*p*=.022) and NH (*p*=.022), and when compared with u-HL at CZ (*p*=.048). The remaining group comparisons did not reach significance.

To summarize, P1 response latencies were earliest for the t-HL group regardless of stimulus level and N1 peak latencies were earliest for the group with normal hearing, but only when the same stimulus level was presented to all participants. Importantly, there were no significant differences in peak latency for the P2 component across groups for either stimulus level.

Table 3. Peak latency and amplitudes for EPs at Cz, FCz and Fz.

Auditory Evoked Potentials: Equal Sound Pressure Level (eSPL)							
Electrode	Group	P1		N1		P2	
		Latency M(SD)	Amplitude M(SD)	Latency M(SD)	Amplitude M(SD)	Latency M(SD)	Amplitude M(SD)
CZ	NH	53.60 (5.10)	1.79 (1.11)	98.80 (11.78)	-3.79 (1.57)	201.60 (20.59)	3.24 (1.17)
	u-HL	55.20 (9.76)	1.67 (.67)	103.60 (7.17)	-3.84 (1.65)	211.60 (18.90)	3.49 (1.12)
	t-HL	47.20 (8.60)	.88 (.83)	110.40 (7.35)	-3.81 (1.45)	208.80 (20.29)	2.35 (.91)
FCZ	NH	52.40 (9.88)	1.71 (1.21)	99.20 (11.12)	-4.09 (1.61)	201.60 (21.43)	3.24 (1.26)
	u-HL	57.60 (7.59)	1.83 (1.02)	104.40 (7.41)	-3.96 (1.57)	212.40 (18.52)	3.73 (1.18)
	t-HL	47.20 (9.00)	.88 (1.01)	110.80 (7.55)	-4.00 (1.52)	212.80 (17.47)	2.63 (.91)
FZ	NH	53.60 (12.96)	1.33 (1.05)	99.20 (5.27)	-3.33 (1.89)	208.00 (20.31)	2.44 (1.20)
	u-HL	57.60 (8.68)	1.49 (.97)	105.20 (7.07)	-3.31 (1.22)	216.80 (16.84)	3.16 (1.11)
	t-HL	50.40 (11.03)	.71 (.86)	112.00 (9.04)	-3.30 (1.25)	215.20 (18.07)	2.20 (.80)
Group mean peak amplitude (μV) and latency (ms) values. M=mean, SD=standard deviation							

Auditory Evoked Potentials: Equal Sensation Level (eSL)							
Electrode	Group	P1		N1		P2	
		Latency M(SD)	Amplitude M(SD)	Latency M(SD)	Amplitude M(SD)	Latency M(SD)	Amplitude M(SD)
CZ	NH	57.20 (4.24)	1.12 (.60)	105.20 (5.01)	-2.78 (1.13)	211.20 (19.76)	2.42 (.64)
	u-HL	58.80 (4.64)	1.54 (.89)	104.80 (7.50)	-3.96 (1.32)	212.80 (18.26)	3.32 (1.52)
	t-HL	49.20 (10.34)	.84 (.68)	105.20 (6.14)	-4.13 (1.45)	211.60 (19.64)	2.33 (.75)
FCZ	NH	58.80 (9.99)	1.31 (.86)	105.60 (4.30)	-2.94 (1.56)	208.00 (22.39)	2.92 (.71)
	u-HL	58.50 (5.01)	1.73 (.99)	106.00 (8.27)	-4.03 (1.25)	214.80 (18.86)	3.72 (1.53)
	t-HL	47.20 (11.12)	.88 (.75)	107.60 (4.40)	-4.44 (1.52)	212.00 (18.28)	2.68 (.89)
FZ	NH	59.20 (10.29)	1.13 (.63)	106.00 (3.89)	-2.36 (1.63)	210.80 (23.02)	2.60 (.74)
	u-HL	56.00 (10.50)	1.34 (.88)	105.60 (9.08)	-3.30 (1.11)	216.40 (18.23)	3.22 (1.28)
	t-HL	48.00 (11.16)	.76 (.60)	107.20 (4.92)	-3.69 (1.17)	213.60 (18.40)	2.25 (.94)
Group mean peak amplitude (μV) and latency (ms) values. M=mean, SD=standard deviation							

Surface Laplacian Analysis

The scalp recorded EEG was transformed into estimates of radial current flow at the level of the scalp, the surface Laplacian, using the Current Source Density (CSD) Toolbox (Jürgen Kayser, 2009, Columbia University) and custom Matlab script. The surface Laplacian is an estimate of the current sources (positive; current flowing from the scalp) and the sinks (negative; current flowing into the scalp) distributed across the scalp (Nunez & Srinivasan, 2006). Surface Laplacian estimation does not rely on assumptions regarding volume conduction, functional anatomy or independence of

generator sources, as is the case with inverse solution methods (e.g. current density reconstruction via standardized low-resolution brain electromagnetic tomography (s-LORETA), Brain Electrical Source Analysis (BESA). While this measure does not result in information regarding the underlying source(s) of activity, it does provide enhanced spatial specificity and greater detail regarding differences in activity between closely spaced electrodes (Kayser & Tenke, 2015); which may provide additional information regarding subtle changes in the neural registration of sound due to auditory deprivation and/or stimulation. Permutation tests were conducted from stimulus onset (0ms) to 596 ms to identify electrodes and time points that differed between groups for each stimulus level. For each contrast, 5000 permutations were conducted with alpha levels of p=.005, p=.001, as well as a False Discovery Rate (FDR) control for Type I error due to multiple comparisons

Results

Because differences in scalp topography may indicate deprivation and/or stimulation related changes in the neural registration of sound, the surface Laplacian was applied to the EEG data to provide enhanced spatial resolution (Kayser & Tenke, 2015). Similar to the results of permutation tests for the evoked potentials (EPs) included in Paper 1, tests of the transformed data for both the SPL and SL stimulus levels revealed group differences at multiple time points around P1, N1 and P2 latency windows and at several scalp locations, at stringent uncorrected alpha levels of p=.005 and p=.001. Differences did not pass through FDR control for Type I error.

Some differences with EP measures, however, were noted. Whereas evoked potential topographies showed a large fronto-central area of maximum activity, the

Laplacian transformed data showed greatest activity, or greatest rate of change in voltage, over more restricted and well-defined bilateral temporal areas. This was an expected topography for the Laplacian transformation of activity from an auditory source, as the surface Laplacian has greatest sensitivity to the radial auditory sources and filters out commonalities across electrodes.

SPL

When comparing those with normal hearing to peers with hearing loss groups (Figures 4 & 5), several fronto-central electrodes revealed significant differences near P1 and P2 onsets for the normal hearing group. Examination of response waveforms revealed visibly earlier (P1 and P1) and larger (P2 for temporal electrodes) response components for the NH group. Additional differences were identified between 300-400 ms, likely due to delayed response offset for each hearing loss group, as described previously for non-transformed data, and evident in the topographies which continue to show changes in scalp voltage for the hearing loss groups, when compared to the normal hearing group (Figures 13 and 14 C). As seen in the evoked potential data, there were visible delays in the response latencies as well as significant differences that may indicate reduced component amplitudes for u-HL and t-HL in comparison to NH. Significant differences between hearing loss groups (Figure 6) were generally restricted to time points near or following P2 offset, with larger amplitudes visualized for the u-HL group in comparison with the t-HL group. This amplitude difference may be resultant from slightly poorer hearing for the t-HL group, particularly at 2000 Hz (see audiometric data in Figure 1), a frequency at which the stimulus has significant energy. In summary, results of Laplacian transformed waveforms when sounds were presented at the same

level for all pariticpants (SPL) revealed significant differences surrounding P1 and P2 onset latencies which can be described as larger and earlier response components for those with normal hearing, in comparison to those with hearing loss, either treated or untreated. It is important to note, that while differences are significant at $p<.005$ and $p<.001$, no differences were significant once passed through FDR to control for Type I error rate, therefore, type I errors cannot be ruled out and results should not be over interpreted. However, results are consistent with ANOVA results previously reported. Additionally, differences between groups with treated versus untreated hearing loss were minimal, even with increased spatial resolution provided by surface Laplacian transformation. An additional observation, that is not as pronounced for the non-transformed data, is the presence of response asymmetry, with larger N1 amplitudes at right temporal electrodes (see C5 and C6 waveforms for Figures 4-6) for NH, but no or less visible differences between left and right temporal electrodes for the hearing loss groups.

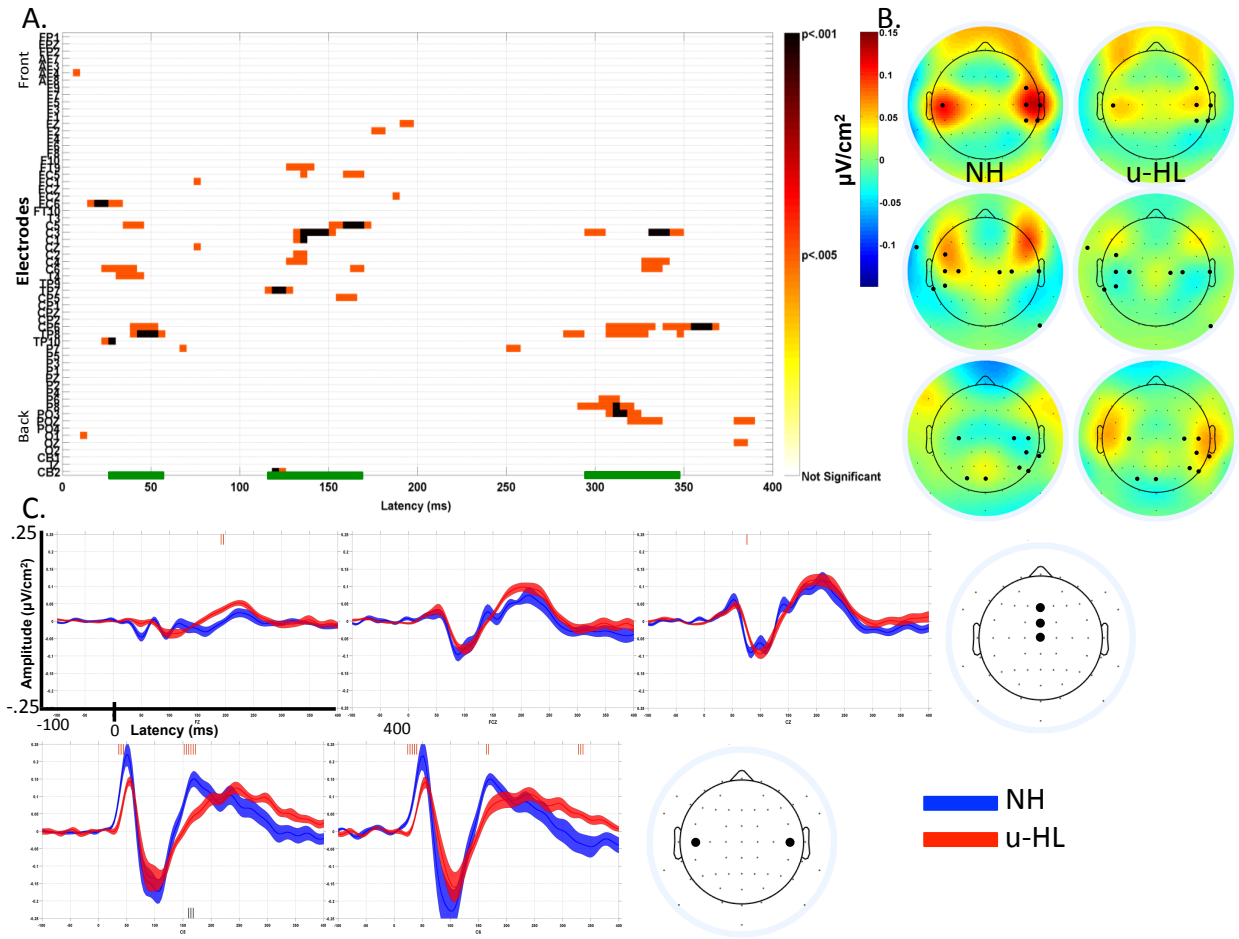

Figure 4. Laplacian SPL: NH vs. u-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6); time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

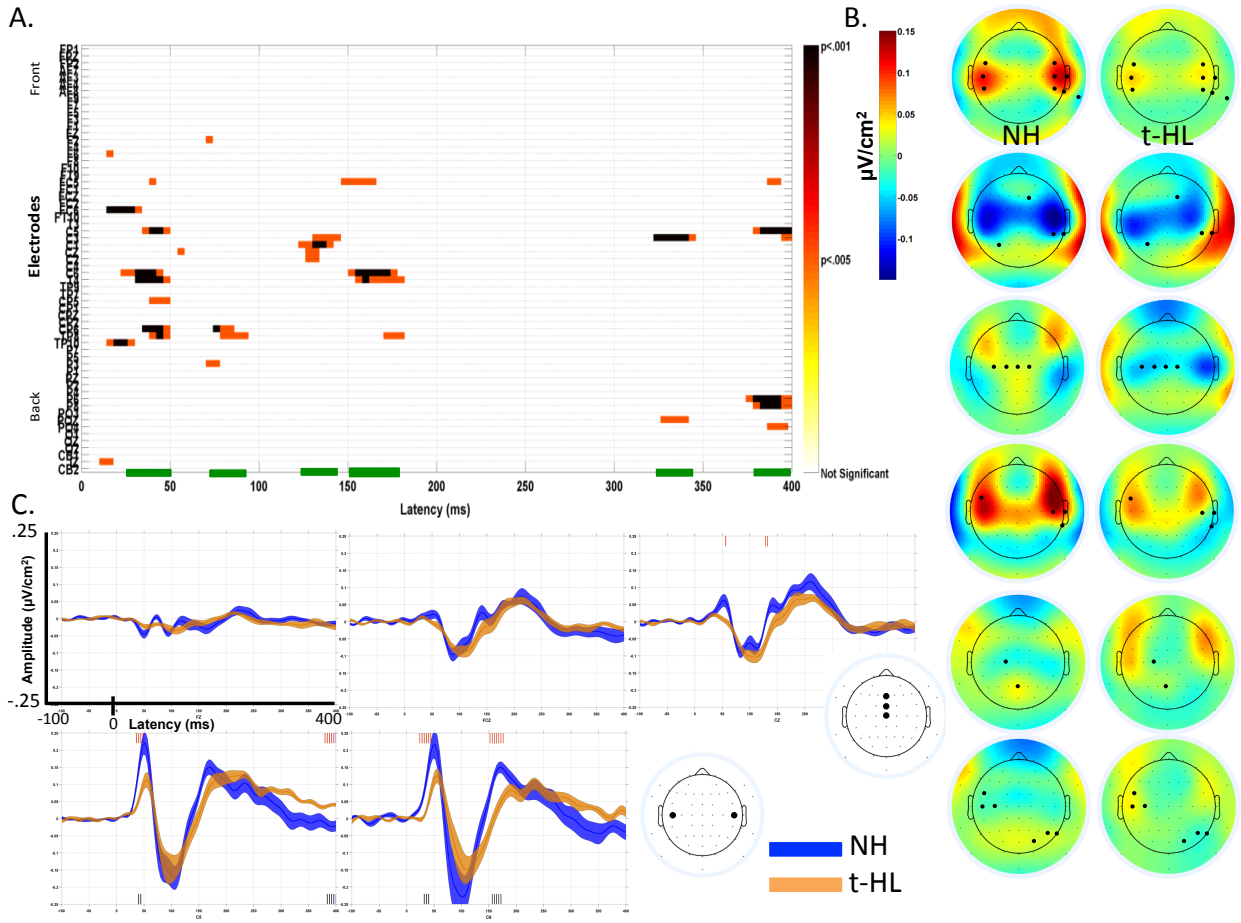

Figure 5. Laplacian SPL: NH vs. t-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6); time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

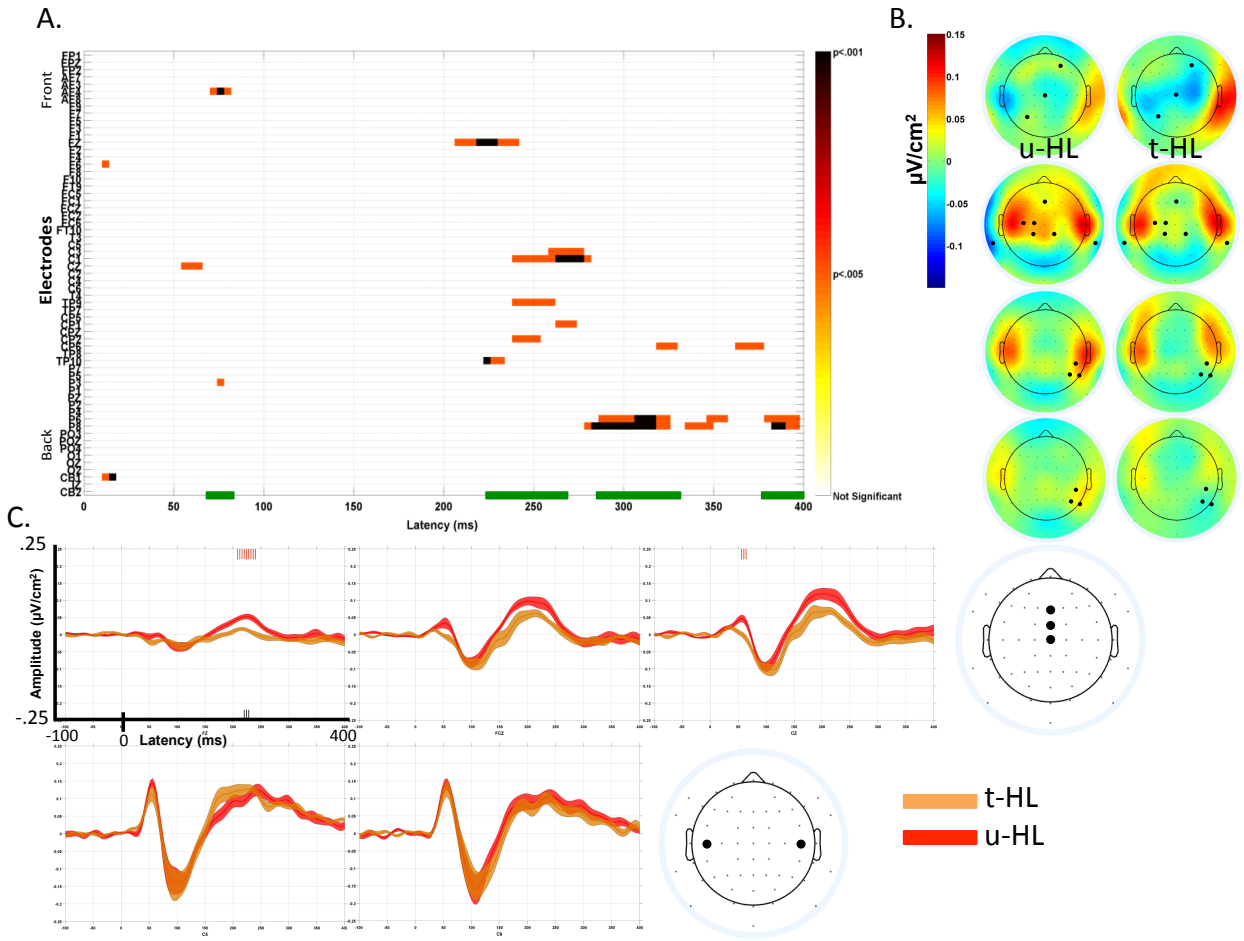

Figure 6. Laplacian SPL: t-HL vs. u-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6); time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

SL

Results of group contrasts for the equal sensation level (SL) stimulus also revealed group differences, however, to a lesser extent that for the SPL stimulus, consistent with non-transformed data. Additionally, differences did not appear at latencies consistent with P1 or P2 onset, but were focused around the N1 component latency window (see Figures 7-9); with larger and broader responses for those with hearing loss for vertex and fronto-central electrodes, but not over temporal electrodes.

Overall, results of Laplacian transformed waveforms for the SL stimulus level revealed several fronto-central electrodes and fewer temporal electrodes showing differences between groups, primarily surrounding the N1 component. Once again, an asymmetry was noted for the N1 response, right larger than left, for the NH group only.

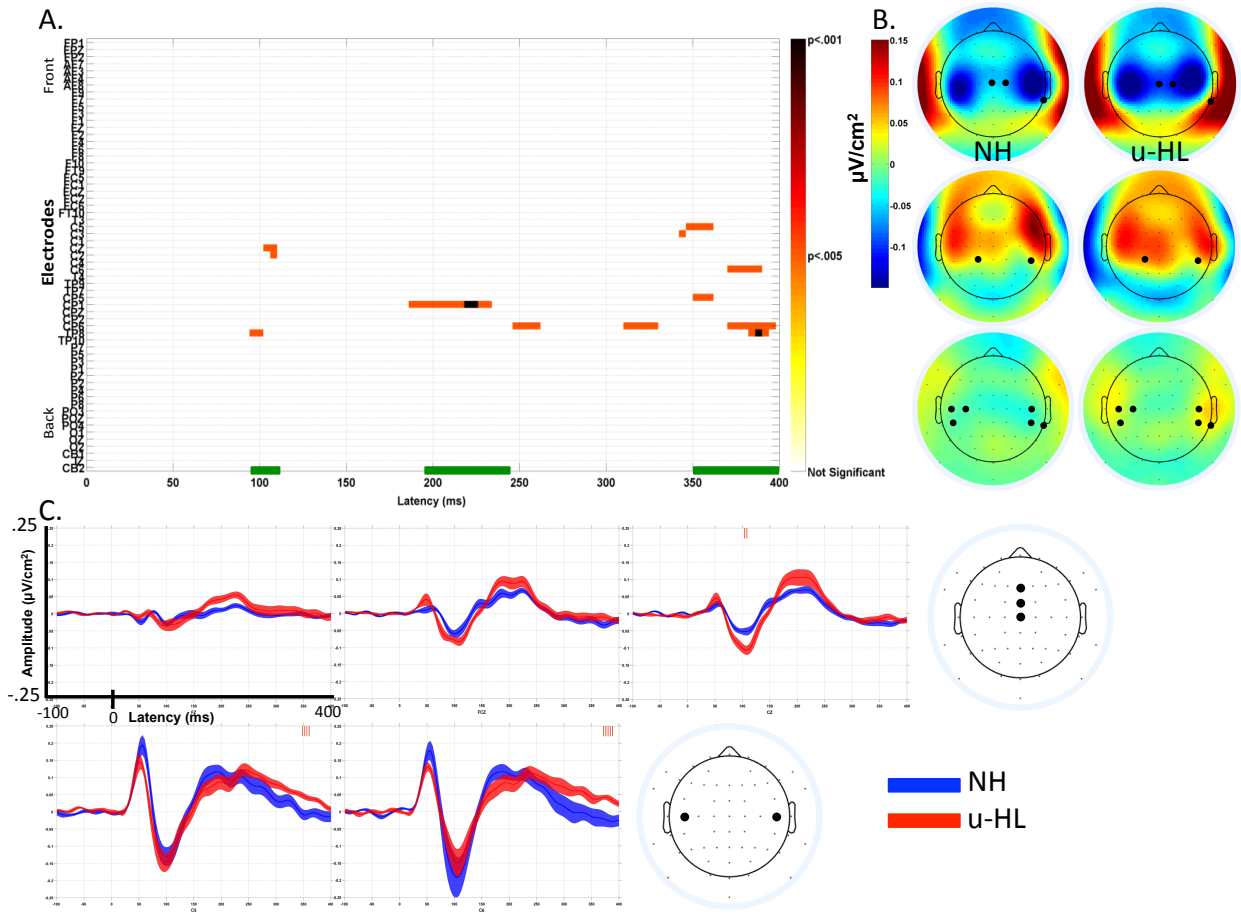

Figure 7. Laplacian SL: NH vs. u-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6); time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

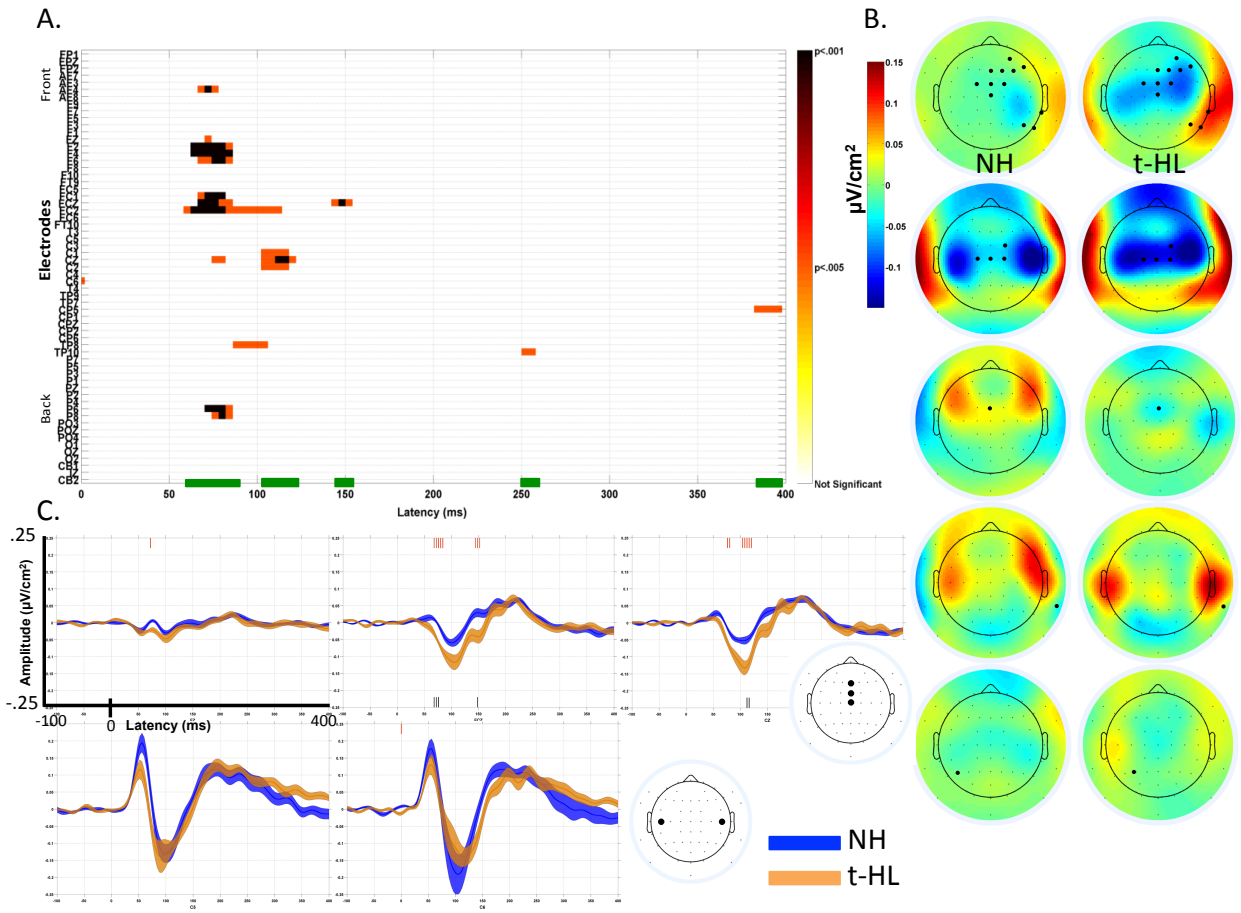

Figure 8. Laplacian SL: NH vs. t-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6); time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

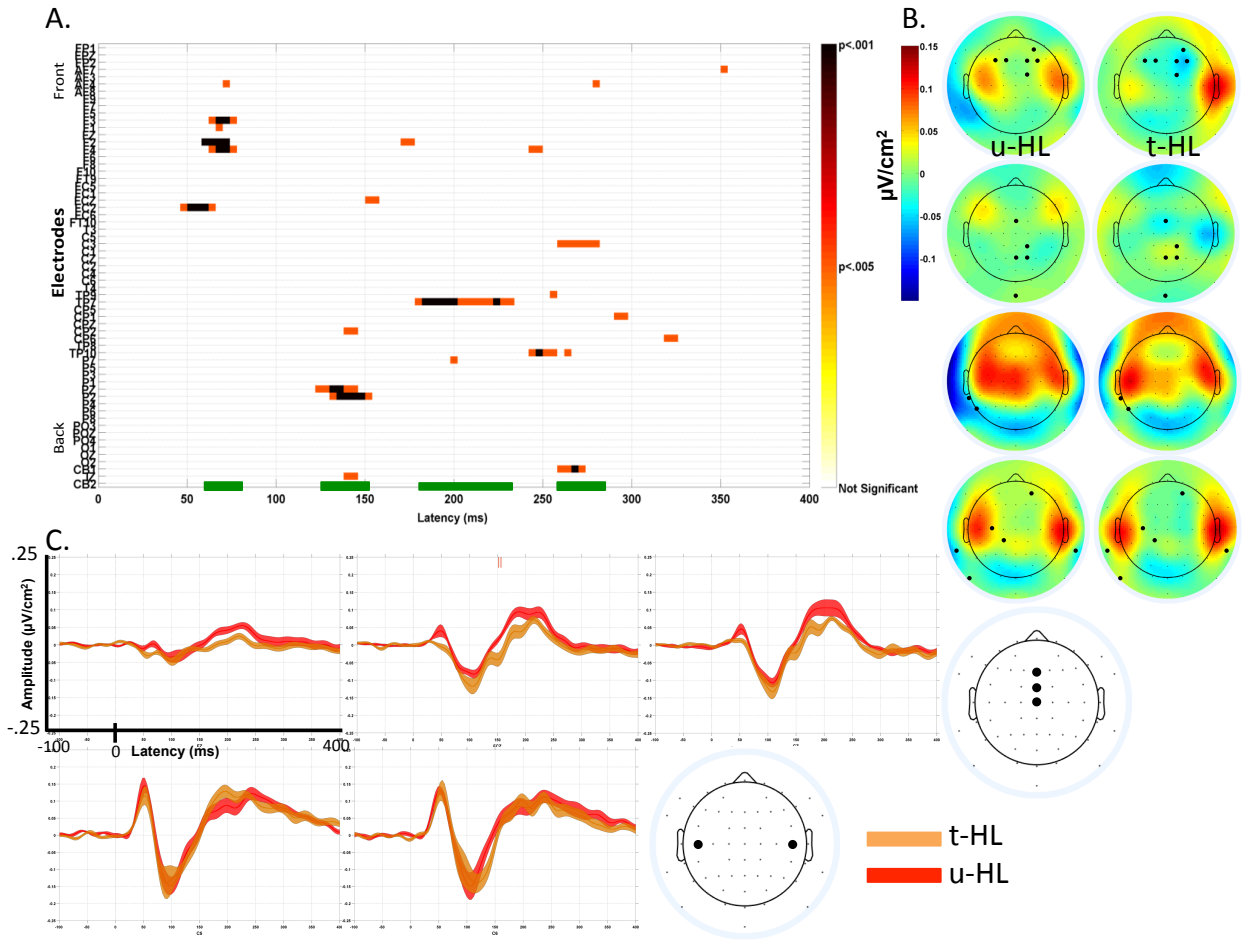

Figure 9. Laplacian SL: t-HL vs. u-HL. A) Raster plot of permutation test p-values (white = not significant, red = *p* < .005, black = p < .001) at all 61 electrodes (y-axis, top of the graph is the front of the head, down to the back of the head at the bottom) across the P1-N1-P2 response window (x-axis). B) Topographies at time points showing group differences identified in raster plot (green bars; electrodes with significant *p*-values marked in bold). C) Representative waveforms from frontal (FZ, FCZ, and CZ) and temporal (C5, C6); time points that are significantly different between groups identified with red bars (*p* < .005) at the top and/or black bars (*p* < .001) at the bottom of each figure.

Overall, permutation tests for the surface Laplacian transformed data were consistent with non-transformed data. However, temporal electrode locations revealed the largest response amplitudes, particularly for the N1 component, and revealed that an asymmetry present for the NH group, was not present for either group with hearing loss.