Auditory Evoked Potentials and Speech-in-Noise Perception: Effects of Aging and Hearing Loss

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DEDICATION

I dedicate my dissertation work to my family. My family made my success both possible and rewarding. This work is especially dedicated to my father, Tae Man Park and my mother, Ok Soon Choi. They have been a constant source of support and encouragement during the challenges of graduate school and life.

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Abstract

Purpose: This study was designed to investigate (1) the effects of age and hearing loss on auditory neural coding, (2) interrelationships between auditory evoked potentials (AEP) taking place at early and later stage of auditory processing, and (3) electrophysiological correlates of age-related declines in speech-in-noise perception.

Methods: 30 young normal-hearing adults (YNH, M=21 years), 26 older adults with near-normal hearing (ONH, M=63.9 years) and 26 older adults with hearing loss (OHL, M=72.8 years) participated in the study. AMLR Pa and N1, P2 and N2 of ALLRs were recorded using two-channel electrode system. 500 Hz tone burst and syllable /ba/ were presented in quiet and in babble at the level of 90 Leq (dBA), accompanied by babble at the level of 65 Leq (dBA). Revised Speech Perception in Noise (R-SPIN) test was conducted to measure speech-in-noise perception.

Results: ONH listeners demonstrated significantly enhanced Pa and N1 amplitudes and significantly prolonged Pa, P2 and N2 latencies compared with YNH listeners, indicating the effects of aging. OHI group demonstrated significantly prolonged N2 latencies compared with ONH group, indicating the effects of hearing loss. OHI listeners demonstrated significantly enhanced amplitudes and significantly prolonged latencies across all AEP components compared with YNH listeners, indicating that the combined effects may have stronger impacts on age-related changes in AEP morphology. Significant correlations between the amplitudes of Pa and each component of ALLRs were found in ONH and OHI groups, indicating that enhanced Pa amplitudes correspond with enhanced amplitudes of cortical responses in older listeners. Significant correlations between latencies of Pa and each component of ALLRs were found in all

groups, indicating that prolonged Pa latencies correspond with prolonged latencies of cortical responses in all listeners. In both ONH and OHI groups, lower R-SPIN-LP scores are significantly correlated with enhanced Pa, P2, and N2 amplitudes and prolonged N2 latencies, particularly for syllable /ba/.

Discussion and Conclusions: Interplay between effects of aging and hearing loss may have stronger impacts on morphological changes in the AEP waveforms. Amplitude-based interrelationships reflect age-related changes in a transfer of neural information between subcortical and cortical auditory network. Latency-based interrelationships indicate the association between neural timings at subcortical and cortical levels. Age-related enhancements of Pa, P2 and N2 amplitudes and age-related prolongations of N2 latencies may serve as electrophysiological correlates of age-related declines in SIN perception.

Chapter 1:

Introduction

Aging can be defined as a progressive loss of physiological function with age (Lopez-Otin et al., 2013). One of the most common effects of aging process involves hearing loss. Age-related hearing loss, also known as presbycusis, is a multifactorial process that affects elderly individuals in varying degrees of hearing loss ranging from mild to profound (Gate, 2005). It is conceptually understood that presbycusis is a mixture of acquired auditory stresses, trauma, and otologic diseases that affect hearing over time, superimposed upon an intrinsic, genetically controlled, aging process (CHABA, 1988). Pathologically, presbycusis involves the degeneration of both peripheral and central auditory pathways. Cochlear dysfunction possibly leads to the functional changes in central auditory system. Practically, presbycusis is symptomized by the mixture of peripheral and central hearing loss (for a review, see Gate, 2005; 2012).

Overall, 10% of the population has a hearing loss great enough to impair communication, and this rate increases to 40% in the population over 65 years (Ries, 1994; Yueh et al., 2003; Frisina, 2006). The prevalence of presbycusis rises with age, ranging from 40% to 66% in people over the age of 75, and more than 80% in people over the age of 85 (Yueh et al, 2006).

The most common complaint in presbycusis is not that people cannot hear, but rather that they cannot understand what is being said, particularly in the presence of any background or interfering noise (Marshall, 1981; Jerger et al., 1989, 1990; Humes, 1996). The poor speech understanding in noise, competing speech, or distorted speech (e.g., compressed speech) with aging is the hallmark of age-related central auditory processing disorders, which is also labelled

as central presbycusis (Gates, 2012). Central presbycusis is usually superimposed on varying degrees of peripheral hearing loss, indicating that it is not easy to isolate peripheral components from multifactorial central presbycusis (Gates & Mills, 2005).

In addition to age-related peripheral changes, the auditory system undergoes age-related central changes. Reduced sensory input resulting from age-related structural and functional changes in the auditor periphery may result in compensatory down-regulation of inhibitory process, interfering with neural coding. Age-related pre- and postsynaptic changes in the inhibitory neurotransmission, such as significant age-related reductions in the level of glycine receptors in the dorsal cochlear nucleus, γ-Aminobutyric acid (GABA) in the inferior colliculus, and glutamic acid decarboxylase (GAD) in the primary auditory cortex (Caspary et al., 1995; 2005), cause an excitatory-inhibitory imbalance (i.e., an increase in excitation and/or a lack of inhibition) in central auditory system, leading to functional reorganization of central neural network. Such compensatory alterations of inhibitory synaptic circuits involve a mechanism of GABAergic homeostatic plasticity (Turrigiano, 1999, 2007). The homeostatic process, which aims to stabilize the input/output neuronal activity in higher auditory circuits by scaling the strength of excitatory and inhibitory synapse (Turrigiano, 1999, 2007), leads to compensatory gain enhancement for the recovery of sensitivity to diminished afferent inputs, resulting in the central neuronal hyperexcitability. The neuronal changes associated with homeostatic plasticity, such as increased spontaneous firing rates (i.e., discharge rates), disruption of neural synchrony, and cortical tonotopic map reorganization, induce the degradation in spectrotemporal coding of acoustic signals, impairing the ability to integrate and segregate speech signals from an acoustic mixture that is critical to perceptual discrimination of speech sounds in noise.

A series of electrophysiological studies have suggested that age-related morphological changes in event-related potentials may be associated with the neurochemical changes related to GABAergic inhibitory neurotransmission. Neural coding of acoustic signals occurs at all levels of the central auditory pathway. The firing of auditory neurons generates measurable bioelectrical brain responses, a pattern of voltage fluctuations, which are termed auditory evoked potentials (AEPs). AEPs consist of positive and negative deflections that begin about 1 ms after the onset of auditory signal and generally lasts about 500ms, reflecting neural activation involved in the auditory processing from auditory nerve to the cortex. Theoretically, as the time after sound onset increases, the neural generator becomes more central. In far field recordings from humans, AEPs are universally classified on the basis of response latency as: (1) early (the first 10 ms); (2) middle (10 to 50 ms); and (3) late (50 to 500+ ms) responses. The early latency response includes receptor potentials from the cochlea, known as electrocochleography (EGochG) and neurogenic responses arising from the auditory nerve and low midbrain structures, known as auditory brainstem response (ABR). The middle latency response (AMLR), identified as Na, Pa, Nb, and Pb, is primarily generated from thalamus/cortex (Yvert et al., 2001, 2005). The late latency response (ALLR), defined as P1, N1, P2, and N2 in non-oddball paradigm recordings and MMN and P300 (i.e., P3a, P3b) in oddball paradigm recordings, primarily originates from spatially distributed cortical regions including temporal, parietal, and frontal lobes (for a review, see White & Atcherson, 2012).

The American Speech-Language-Hearing Association (ASHA) Task Force on Central Auditory Processing (1996) has suggested that electrophysiologic measures are useful for the diagnosis of central auditory processing disorders (CAPDs) and the clinical utility of both AMLRs and ALLRs needs to be established. More recently, it has been recommended that a

minimal test battery for the diagnosis of CAPDs in school-aged children should include ABR and AMLR testing, comprising P300 testing in the optional procedure for strengthening the diagnosis of CAPD (Jerger & Musiek, 2000; Chermak, 2001). However, the assessment of CAPD is likely to be overlooked in presbycusic listeners even though one of the most common complaints is the difficulty understanding speech in adverse listening situations. Practically age-related perceptual deficits are a major contributor to dissatisfaction with conventional therapeutic strategies. Unsuccessful communication experiences due to hearing loss may cause older adults psychological problems such as social isolation, depression, and loss of self-esteem (e.g., Gordon-Salant & Fitzgibbon, 1993; Frisna & Frisna, 1997). The comprehensive diagnostic strategies associated with presbycusis may, therefore, enhance audiological management and rehabilitation and thereby ameliorate age-related communication difficulties, which would further the well-being and quality of life for the elderly population.

For better diagnosis of presbycusis, valid and reliable evidences to enhance clinical judgement are needed to identify age-related auditory processing abnormalities. Most clinicians use behavioral measures of speech-in-noise intelligibility to assess central auditory function in presbycusis, but the behavioral tests may not be appropriate for the diagnosis of individuals with cognitive impairments such as attention and memory problems. Electrophysiological testing can be used as an objective complementary test battery to cross-check the behavioral performance on speech-in-noise tests, in particular for difficult-to-test patients.

Accordingly, **the first significance of this research** is to broaden and deepen the knowledge base of presbycusis by examining age-related neural changes in the central auditory system. The electrophysiological findings will provide neural evidence of auditory coding at different levels of the central auditory pathway. The results of the present study may contribute

to developing age-related norms for central neural activity and establishing the diagnostic criteria for neurophysiological changes associated with presbycusis. **The second significance of this research** is to identify clinical potentials of electrophysiological testing in the diagnosis of age-related CAPD (i.e., central presbycusis) by examining whether there exist any relationship between age-related changes in neural activities and diminished ability to process speech sounds in noise. Electrophysiological measures can be used as objective neural index of speech-in-noise intelligibility in presbycusis, which may complement conventional behavioral test battery, thereby strengthening the diagnosis of age-related CAPD.

Chapter 2:

Literature Review

2.1. Presbycusis

Aging results from neurophysiological changes with age, best characterized by age-related neural decline across multiple neural systems. The degree and rate of aging are more likely to be affected by individual's environment including social class and educational attainment. For these reasons, the aging process varies across individuals, resulting in a wide range of individual variations and a highly heterogeneous group of older adults. Age-related declines in auditory function is one of the most common effects of aging. Presbycusis is an umbrella word for hearing loss in older adults with no known cause, which represents the combined effects of aging on the auditory system, superimposed on the effects of cochlear dysfunction. The cochlear dysfuction can be caused by exposure to noise and ototoxins, and various age-related diseases (Gates & Mills, 2005). It is generally accepted that presbycusis is associated to age-related declines in spectral and temporal resolution in the aging auditory system, which impair temporal processing ability. Consequently, the presbycusis is symptomized by reduced hearing sensitivity, poor speech understanding in noisy environments, slower auditory processing speed, and impaired localization of sound sources, showing a variety of audiometric threshold configurations ranging from normal to profound.

The presbycusis is classified into six categories (Schuknecht, 1974; Schuknecht & Gacek, 1993): (1) sensory, mainly due to defects in cochlear hair cells and supporting cells; (2) metabolic, with degeneration of the lateral wall and stria vascularis (strial atrophy); (3) neural,

typified by the loss of afferent neurons in the cochlea (spiral ganglion cell loss); (4) cochlear conductive or mechanical, where there seemed to be stiffness of the basilar membrane and organ of Corti. To date, no real evidence has been found that the mechanical structure of the organ of Corti stiffens with age (Schmiedt, 2010). Mechanical presbycusis was often coupled with degeneration in the spiral ligament along the cochlear lateral wall. The spiral ligament was originally thought to offer structural support to the basilar membrane and is now known to consist of ion-transport fibrocytes involved in the recycling of K+ efflux from the hair cells back to the endolymph. The final two categories are (5) mixed and (6) indeterminate.

According to Schuknecht and Gacek (1993), typical audiometric pattern of sensory presbycusis was steeply sloping high-frequency loss above the speech frequency range, often with a notch or dip in the 4 kHz region. The most typical audiogram configuration for metabolic presbycusis was slowly progressive hearing loss with flat audiometric pattern and relatively good speech discrimination. The neural presbycusis appeared to be possible in any audiometric pattern ranging from normal thresholds to anacusis with progressive loss of speech discrimination. The typical audiometric configuration of mechanical presbycusis was a gently sloping high frequency loss and flat hearing loss of 30-40 dB. The Mechanical presbycusis described by Schuknecht can be considered as a severe case of metabolic presbycusis (for a review, see Schmiedt, 2010). Schuknecht and Gacek (1993) reported that many individual have mixtures of these pathologic types, termed mixed presbycusis. Based on their findings, about 25% of all cases of presbycusis are classified as indeterminate presbycusis. Schuknecht's framework has limitations in that it focuses on the effects of peripheral pathophysiology on age-related hearing loss, ignoring degenerations of central nervous system with advancing age.

Age-related degeneration of the stria vascularis is the most prominent anatomical characteristic of age-related hearing loss, reducing the endocochlear potential, which provides a voltage to the cochlear amplifier (Mills et al., 2006). The stria vasculairis is the battery of the inner ear, providing metabolic energy to power outer hair-cell motility responsible for high-frequency hearing sensitivity. Collectively, age-related changes in stria vascularis and endocochlear potentials affect high-frequency hearing sensitivity, which directly reduces the audibility of high-frequency energy, thereby decreasing the ability to perceive consonant cues to fricatives and affricates, most of which have more energy in higher part of spectrum. Certainly, the age-related high-frequency hearing loss is a critical contributor to many listening difficulties which older listeners may experience in the early stages of presbycusis. Typically, high-frequency hearing loss is the classic audiometric signature of presbycusis, followed by progressively lower frequencies, eventually producing the pattern of flat hearing loss that is typical of advanced cases (Schuknecht, 1964).

Besides the age-related peripheral auditory dysfunction, age-related declines in brain function including cognitive changes are also important contributors to the difficulties the older listeners experience understanding speech in the presence of interfering noises. In particular, age-related loss of inhibition caused by neuroanatomical changes to the aging brain increases neural noises (Caspary 2005, 2008; Willot, 1996), resulting in the degradation of neural coding throughout the central auditory nervous system (e.g., Frisina, 2001; Lister, Maxfield, Pitt, & Gonzalez, 2001; Tremblay et al., 2003), thereby reducing the ability to understand speech in noisy environments. The reduced speech perception in noise is primarily due to age-related declines in perceptual processing, including, but not limited to, a lack of audibility, impaired frequency and temporal resolution. Impaired frequency resolution has been observed by the

broadening of auditory filters (e.g., Sommers & Humes, 1993) and an increase in frequency difference limens (e.g., Moore & Peters, 1992) that leads to decreased frequency selectivity, which plays a key role in detecting formant cues to understand speech (for a review, see Tun et al., 2012). Indeed, the elderly listeners with poor word recognition abilities have significantly poorer frequency resolution for complex signals compared to those with good word recognition abilities, indicating difficulty with discrimination of differences in the spectral characteristics of a complex signal. Similarly, impaired temporal resolution has been demonstrated by elevated gap detection, poor gap discrimination and impaired binaural processing (e.g., Fitzgibbons & Gordon-Salant, 1994; Schneider, & Pichora-Fuller, 2001), giving difficulty with identifying auditory objects and differentiating spectrotemporal transitions in a signal. Such age-related deficits in auditory perceptual processing are a sign of central presbycusis, also termed "age-related central auditory processing disorders" (Gates, 2005). Central presbycusis is usually superimposed on peripheral (cochlear) dysfunction, which is poorly indicated on audiograms. Older listeners with central presbycusis may have normal or near-normal word recognition in quiet environments but have considerable difficulty understanding speech in noisy or reverberant listening situations.

One of the main contributors to central presbycusis is the age-related imbalances between excitatory and inhibitory neurotransmission. An age-related loss of GABAergic inhibitory function is associated with abnormal neural synchrony, which impairs the processing of timing information in noise and auditory stream segregation at higher auditory centers (for a review, see Anderson et al., 2010). At the cellular level, GABAergic inhibitory interneurons appear to be important in producing neural synchronization in local circuits and can modulate firing rates of projection neurons (Whittington, et al., 2000; Bhattacharya, 2001). The age-related loss of

GABAergic and glycinergic inhibition may cause the increase in maximum discharge rate and spontaneous activity, driving the increased neural excitation. The increased neural noise and decreased neural synchronization, in concert with a loss of inhibition, may impair the abilities to extract salient signals from a cluttered acoustic environment and to use phase locking information (for a review, see O'Donnell et al., 2004), degrading neural coding of temporal envelop and fine structure. According to the findings of Caspary et al. (1995, 2005, 2008), GABAergic neurotransmission in midbrain (e.g., inferior colliculus), thalamus (e.g., medial geniculate body), and cortex (e.g., primary auditory cortex) plays a pivotal role in inhibitory coding for the accurate processing of spectral, temporal, spatial, and intensity information.

Age-related inhibitory changes would be either the result of normal aging process within the central nervous system or the compensatory central changes secondary to a loss of peripheral input or both. For example, noise-exposed animals with cochlear damage showed highly enhanced neural responses to supra-threshold acoustic stimulation in the inferior colliculus and primary auditory cortex, reflecting plastic reorganization in central auditory system (Willott & Lu, 1982; Popelar et al., 1987; Salvi et all., 1990; Gerken et al., 1991; Syka et al., 1994; Szczepaniak & Moller, 1995; Wang et al., 1996; Syka & Rybalko, 2000; Aizawa & Eggermont, 2007). GABA uptake and release following ossicle removal or cochlear ablation resulted in complex long-term changes in GABAergic and glycinergic neurotransmission (Suneja et al., 1998a,b). In other words, the age-related loss of peripheral afferent input, viz. cochlear deafferentation leads to pre- and postsynaptic compensatory down-regulation of GABAergic inhibition in central nervous system (Betts et al., 2007), possibly in an effort to return toward the original levels of neuronal activity (Rich and Wenner, 2007), in accord with the theory of homeostatic plasticity (Turrigiano, 2007). The imbalance between excitation and inhibition

produces an increased central gain in compensation for diminished afferent input (Qiu et al., 2000; Chambers et al., 2016). As a consequence of homeostatic plasticity, the enhanced central gain is a physiological basis of central changes such as central neural hyperexcitability, loudness recruitment (i.e., disproportionate loudness gain with sound level), and neuronal hypersynchronization, resulting in a deterioration in signal processing.

The primary auditory cochlear damage associated with presbycusis includes the damage to hair cells (outer and inner hair cells), stiral atrophy, loss of spiral ganglion cells, degeneration of auditory nerve fibers (e.g., demyelination), and pre-and post-synaptic damage to auditory nerve fibers. Without hair cell loss, the synaptic/neuronal loss (e.g., ribbon synapse loss) and cochlear nerve damage may cause significant hearing impairment in the absence of hearing loss. Though synapse loss and auditory nerve damage does not affect conventional threshold detection, such disruption in cochlear processing can hamper the ability to process complex sounds such as speech. For example, the functional loss of auditory nerve fibers, such as the selective loss of low-spontaneous-rate auditory nerve fibers, may be an important contributor to age-related degeneration of auditory performance, particularly with respect to speech-in-noise difficulties and deficits in fine temporal precision at supra-threshold levels (for a review, see Liberman & Kujawa, 2017). Age-related deficits in cochlear neural output, which may result from the interruption to synaptic communication between sensory inner hair cells and auditory nerve fibers, can alter auditory information processing, whether or not accompanied by threshold elevations, resulting in auditory perceptual difficulties. Intact hair cells and normal or near-normal audiogram may hide other critical cochlear pathology such as loss of cochlear afferent synapses and cochlear nerve degeneration, which may be primary contributors to age-related deficits in auditory perceptual processing. Auditory perceptual abnormalities with clinically

normal or near-normal hearing are commonly observed in older adults and this type of age-related hearing loss resembles neural presbycusis. A newly termed "hidden" hearing loss, which is ongoing but controversial research, also indicates a similar form of hearing loss-deficits in speech intelligibility in noisy environment in the presence of a normal audiogram.

The reduced neural output following auditory peripheral damage, such as degeneration of auditory nerve fibers and disruption of synaptic transmission, triggers central changes which could be the consequence of homeostatic plasticity in central networks. Cochlear dysfunction, with or without threshold elevation, can lead to auditory deafferentation to central auditory system, resulting in functional reorganization in higher auditory centers (e.g., midbrain, thalamus, and cortex). Collectively, compensatory down-regulation of inhibitory process following cochlear deafferentation to central auditory structures, increases central gain, particularly at cortical levels, which may be sufficient to restore basic neural sensitivity to sound (e.g., audibility, intensity discrimination) but not for signal processing of complex acoustic features, such as fine temporal resolution (Chambers et al., 2016). The neural hyperactivity and hypersynchrony in central auditory pathway, consistent with homeostatic responses of higher auditory circuits deprived of bottom-up afferent drive (Chambers et al., 2016), may interfere with precise temporal coding, thereby compromising hearing in noisy environments (Liberman, 2017).

Central presbycusis limits traditional rehabilitation such as amplification (e.g. hearing aids) and in late cases dominates treatment challenges. Although the most common intervention for peripheral hearing loss is to improve sound audibility by hearing aids, this approach does not compensate for central auditory dysfunction that may coexist with peripheral pathology. For this reason, older listeners keep reporting difficulties comprehending speech in noise, even after

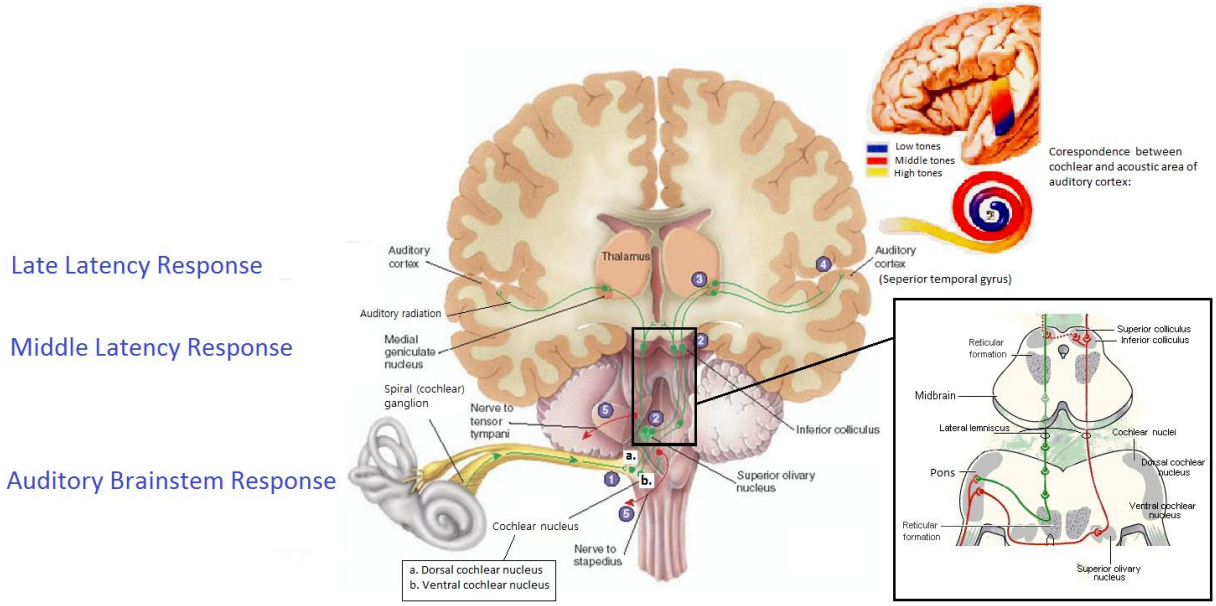
being fitted with hearing aids. Consequently, comprehensive diagnostic protocol is needed in the evaluation of presbycusis to improve therapeutic intervention for the elderly listeners with central presbycusis. The diagnosis of central presbycusis is generally performed using central auditory behavioral test battery, which are focused on evaluating a notable loss of the ability to extract speech out of a background of competing speech. Such behavioral testing increases cognitive load and normal cognitive function, such as attention, memory, and executive functions, is required to complete the behavioral test performance. Hence, the objective test performance will be useful in diagnosing central presbycusis for difficult-to-test elderly patients. Electrophysiological testing can be considered more effective diagnostic tool by which to cross-check behavioral speech recognition scores.

2.2. Auditory Evoked Potentials

2.2.1. Background overview of auditory evoked potentials

Auditory evoked potentials (AEP) are voltage responses resulting from synchronous neural activity along the auditory pathways (Figure 2-1), evoked by, and time-locked to, acoustic sounds. The entire AEP may last several hundred milliseconds or longer. The AEP is analyzed on logarithmic time-base to reveal the component of potentials with approximately equal weighting and categorized in arbitrary but commonly use time windows of short, middle, and long latency responses (Figure 2-2). The AEP can be evoked by a variety of acoustic sounds including, but not limited to clicks, pure tones, transient tone bursts, or complex/long sounds such as speech. AEP is classified according to the latencies of components relative to the eliciting stimulus onset. The responses which are typically evoked within the first

Figure 2.1. Human central auditory pathways



(1) Neurons from spiral ganglion travel to cochlear nucleus, which bifurcates into dorsal cochlear nucleus and ventral cochlear nucleus ; (2) the neurons in ventral cochlear nucleus project to superior olivary nucleus and then up to the inferior colliculus and the neurons in dorsal cochlear nucleus projects directly to the inferior colliculus via the lateral lemniscus, respectively; (3) neurons in inferior colliculus proceed to the medial geniculate nucleus of thalamus; (4) thalamic neurons pass through the auditory radiation to the tonotopically organized primary auditory cortex; and (5) the superior olivary nucleus and inferior colliculus send efferent fibers back to stapedius and tensor tympani muscles, respectively. *Figure modified and adapted by permission from John Wiley and Sons, Inc.*

10-15 ms after stimulus onset include electrocochleography (ECochG) and auditory brainstem responses (ABR).

In ECochG, there are three associated components: cochlear microphonic (CM), summating potential (SP), and action potentials (AP). CM and SP arise from the cochlea hair cells in the organ of Corti and AP from the auditory nerve, respectively. ECochG is typically recorded from the vicinity of the ear drum within 3 to 4 ms after stimulus onset. The CM is an alternating current voltage generated by outer hair cells (Wever & Bray, 1930). This component is stimulus-dependent, appearing as a series of peaks and troughs that mirror the waveform, or

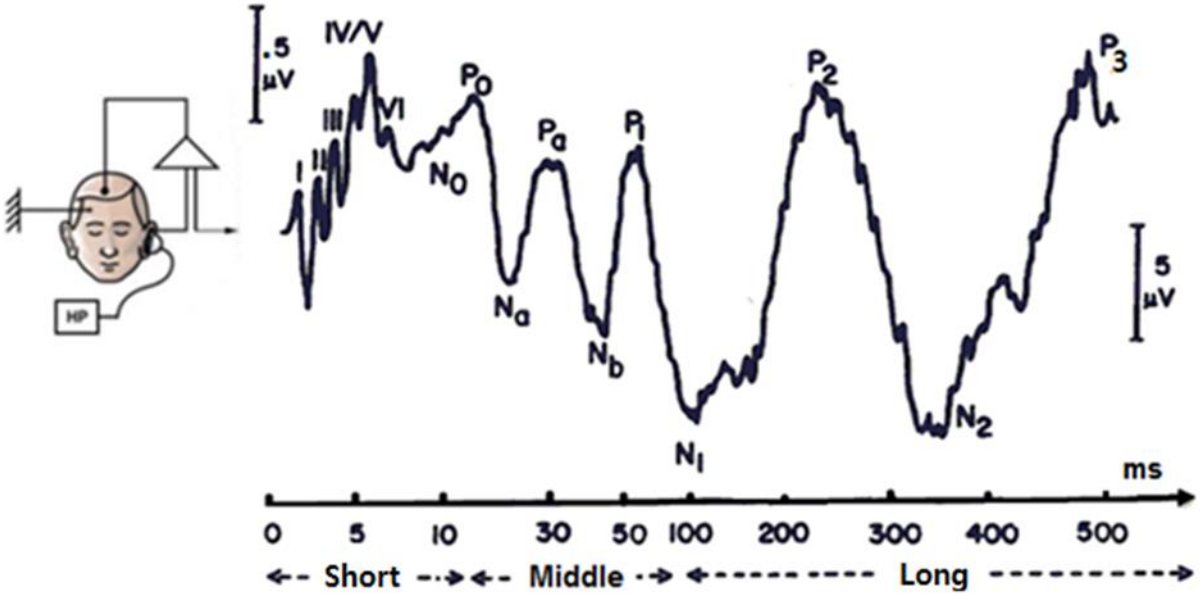
frequency, of the acoustic stimulus that is presented. The second component of the ECochG, SP, is a direct current voltage that is thought to reflect the extracellular activity of the hair cells during acoustic stimulation (Davis, Deatherage, Eldredge, & Smith, 1958). The last component of the ECochG, AP, represents the synchronous firing of thousands of auditory nerve fibers in response to a transient auditory stimulus, such as click or tone burst (Goldstein & Kiang, 1958). The AP is virtually identical to wave I of the auditory brainstem response (ABR) components.

The ABR is considered a far-field, early exogenous potential, often grouped with ECochG for its short latencies within 10 ms of stimulus onset. The ABR components arise from the auditory nerve and various auditory brainstem structures, which are identified as waves I through VII (Jewett & Williston, 1971). The wave I arises from the distal portion of the auditory nerve (within inner ear), wave II from the proximal portion of the auditory nerve (brainstem termination), wave III from the cochlear nucleus, wave IV from midline brainstem structures (perhaps acoustic stria, trapezoid bodies, and the superior olivary complex), and wave V from the termination of the lateral lemniscus within the inferior colliculus on the contralateral side (Moller, 2006).

The waves following the ABR, up to roughly 80 ms, are collectively known as the middle latency response (MLR). Auditory middle latency responses (AMLR) originate in both thalamus and cortex. AMLR is known to consist of Po, Na, Pa, Nb, and Pb components (Hari, 1990; Picton et al, 1974; Reite et al., 1988).).

Na typically falls between 18 and 20 ms relative to stimulus onset, depending on the type of stimulus used. Both subcortical and cortical structures appear to contribute to wave Na (Hashimoto, 1982; Jacobson et al., 1990; Kileny, Paccioretti, & Wilson, 1987).

Figure 2.2. Auditory evoked potentials



Based on response latency, AEPs are classified into three categories: (1) Short Latency (the first 10-15 ms), Middle Latency (10 to 80 ms), and Long Latency (50 to +500 ms). *Figure modified and adapted from Michelini et al., 1982.*

The Na component is recorded reliably in individuals with normal auditory systems and serves as a robust visual marker for the onset of the AMLR. The Na is generally unaffected by subject arousal state unlike other AMLR components (Pa, Nb, Pb), indicating that the reticular formation does not appear to contribute to Na (Kraus, McGee, Littman, & Nicol, 1992). However, it is more likely to be contaminated by postauricular muscle responses (Bell, Smith, Allen, & Lutman, 2004).

Among AMLR components, Pa (30 ms) is the first prominent positive component, which occurs generally at 25 to 35 ms relative to stimulus onset and is believed to arise from the temporal lobe and/or thalamocortical pathway (Buchwald et al., 1992; Erwin & Buchwald, 1986, Woods et al., 1987). Recently, more detailed source localization data suggest that Heschl's gyrus and sulcus, the planum temporale, the superior temporal gyrus, and reticular formation are

simultaneously activated to generate the Pa component (Collet, Duclaux, Challamel, & Revol, 1988; Osterhammel, Shallop, & Terkildsen, 1985; Yvert et al., 2001; Yvert et al., 2005).

Nb generally falls between 35 and 45 ms relative to the onset of the stimulus and is influenced more by arousal and attention. The reticular formation is more involved in generating Nb, as do the supratemporal gyrus (Yvert et al, 2001) and the primary auditory cortex.

Pb generally occurs at 50 to 80 ms relative to stimulus onset and is attributed to activation of the anterolateral portion of Heschl gyrus, the planum temporale, the superior temporal gyrus, secondary auditory cortical areas, and the reticular formation (Yvert et al, 2001, 2005). Pb is also known as P1, P50, or P60 (Tucker, Dietrich, McPherson, & Salamat, 2001).

AMLR may be used to assess central auditory nervous system function. It has been reported that AMLR is a valuable part of the test battery for identifying deficits related to pathologies of the thalamocortical pathways, including but not limited to central/cortical deafness (e.g., Musiek, Charette, Morse, & Baran, 2004), auditory processing deficits (e.g., Purdy, Kelly, & Davies, 2002), and traumatic brain injury (Munjal, Panda, & Pathak, 2010).

The late latency responses are cortical in origin and are much larger and lower in frequency than early and middle latency responses because of the more superficial location of their generators within the cortex. The auditory late latency responses (ALLR) consist of both exogenous and endogenous components. The exogenous responses are determined mostly by external stimuli such as physical features of stimulus such as pitch, loudness, timbre, etc. while endogenous responses are determined mostly by internal factors such as some level of cognitive processing related to relevant stimuli (e.g., attention, memory, processing speed) and sleep. However, the distinction between exogenous and endogenous responses is not consistent and

clear. In other words, the exogenous responses can be affected by the internal factors and endogenous responses are also dependent on external stimuli. The early responses such as ECochGs and ABRs are predominantly exogenous and later responses such as AMLR and ALLR are likely to have both exogenous and endogenous characteristics. In general, the endogenous long-latency potentials are thought to reflect higher level processing than are the exogenous potentials.

Examples of endogenous AEPs include the P300 (P3) and N400, sequentially occurring later in time, which reflect higher levels of sound processing than other potentials evoked before P300. The P300 belongs to the late latency responses that occur starting about 250 ms and peak as late as 600 ms. The P300 is elicited when a listener consciously discriminates an infrequent target stimulus in a chain of frequent standard stimuli (i.e. oddball paradigm). The P300 is divided into P3a and P3b. The P3a occurs passively in response to large stimulus differences, whereas the P3b is evoked by the activity to discriminate the different stimulus when the listener is actively attending (Polish, 1989). The P300 is often referred to as a cognitive response in that stimulus evaluation and classification demand a certain level of cognitive load. The selective attention and short-term memory, which contribute to decision making, are the most involved cognitive process underlying P300 (Harrison, Buchwald, & Kaga, 1986; Donchin, 1981). Additionally, it is thought to be a neural index of the timing of cognitive processes, specifically succession and speed of mental processes (Kutas, McCarthy, & Donchin, 1977). Neural generators of the P300 include hippocampus, which is part of the limbic system (Halgren et al., 1980; McCarthy et al., 1982), thalamus (Wood et al.,1980), reticular formation, prefrontal cortex (Yingling & Hosobuchi, 1984; Yingling & Skinner, 1977), frontal region (Desmedt & Debecker,

1979; Courchesne, 1978), centroparietal regions (Goff, Allison, & Vaughan, 1978; Simson, Vaughn, & Ritter, 1977), and auditory cortex (Richer, Johnson, & Beatty, 1983).

N400 responses reflect a higher level of cognitive process than P300, which is evoked by speech stimuli inducing semantic incongruity, thereby reflecting language processing (Kutas & Hillyard, 1983).

Bridging the exogenous and endogenous categories is the mismatch negativity (MMN) occurring approximately 100 to 250 ms after the onset of deviant sound. The MMN represents the detection of stimulus change (Kraus & McGee, 1994; Kraus et al., 1993; Kujala, Kallio, Tervaniemi, & Naatanen, 2001; Naatanen, 1992; Naatanen, Gaillard, & Mantysalo, 1978) and it is elicited using an oddball paradigm in which infrequently occurring deviant sounds are embedded in a series of frequently occurring standard sounds. The MMN appears as an enhanced negativity in response to the deviant sound relative to that obtained in response to the standard sound, best observed by subtracting responses to sounds presented as standard from responses to sounds presented as deviants. The deviant sounds include the following sound attributes: changes in intensity, frequency, and duration, spatial changes, gaps in stimuli, sound omissions, and changes in stimulus onset asynchrony. The amplitude and latency of MMN reflect the amount of sound deviance, with larger amplitudes and shorter latencies for larger acoustic deviations. The MMN often temporally overlaps the N1 component when the acoustic difference between the standard and deviant sounds is large. The MMN could be a continuation of the same processes that generate the usual N1 wave (Naatanen & Picton, 1987). Since the MMN is recorded relatively independently of attention and even in sleep, it is considered a preattentive response (Martin, Tremblay, & Stapells, 2007). The major generators are located in the supratemporal plane and/or lateral posterior temporal gyrus of the auditory cortex (Kropotov et al., 2000;

Halgren, Marinkovik, & Chauvel, 1998) and frontal cortex (Rinne et al., 2000; Deouell, Bentin, & Giard, 1998; Paavilainen et al., 1991).

The exogenous components, considered an obligatory consequence of the inducing sound, include the P1, N1, P2, and N2 responses that are thought to arise from the temporal and temporal-parietal region of the brain (Wood & Wolpaw, 1982; Celesia & Puletti, 1969), occurring between 50 and 350 ms post-stimulus onset (Hay & Davis, 1971). The later components are more likely to involve both exogenous and endogenous characteristics.

The P1 component, also assumed to be the same as the Pb component of AMLR (e.g., Ponton et al, 2002), is the earliest positive peak of the ALLR occurring between 50 and 80 ms. The P1 appears to arise from sources from the primary auditory cortex, specifically Heschl's gyrus, but may have thalamic and auditory association area contributions as well (Buchwald et al., 1992; Liegeois-Chauvel, et al., 1996; Ponton & Eggermont, 2001). In adults, the amplitude of P1 is small and N1 and P2 often dominate the response. In contrast, for young children, when stimuli are presented at the same rate typically used for adults, P1 dominates the response and is followed by a slow negativity (Ponton, et al., 1996a, b).

The N1 is the first large negative peak of ALLR which occurs at about 100 ms, ranging from 80 to 150 ms. N1 appears to have multiple temporally overlapping, spatially distributed cortical sources in primary and secondary auditory cortex. These sources include activation of Heschl's gyri and the planum temporale with contribution from frontocentral sources, the cingulate gyrus, and other auditory association areas in the lateral temporal and parietal lobe (Atcherson et al., 2006; Picton, et al., 1999; Anderer, Pascual-Marqui, Semlitsch, and Saletu, 1998; Giard et al., 1994; Pascual-Marqui, Michel, & Lehmann, 1994; Naatanen & Picton, 1987;

Scherg &Von Cramon, 1985; 1986; Wolpaw & Penry, 1975a). N1 is best known as an onset response (e.g., Naatanen, 1992; Naatanen & Picton, 1987) and can be evoked by almost any transient sounds, such as clicks, noise bursts, tone bursts, and speech elements (Hyde, 1997). The N1 is easily affected by changes in stimulus parameters such as intensity, pitch, duration, and any other spectrotemporal acoustic features. Such physical stimulus parameters have strong effects on N1 (i.e., exogenous features) but also stimulus-oriented attention changes N1 (i.e., endogenous features), indicating that N1 may reflect conscious perception of a sound (Naatanen, 1990) and present part of detection or attention triggering process (Naatanen & Picton, 1987).

Naatanen and Picton, (1987) identified three underlying components of the N1. The first component of N1 is a frontocentral negativity known as N1b, which is generated bilaterally by vertically oriented sources in the supratemporal plane (for a review, see Martin, Tremblay, & Korczak, 2008). This response is therefore largest when measured by electrodes at /near the vertex electrode site (Cz) (Vaughan & Ritter, 1970). The second component, referred to as the T-complex, is a positive wave occurring at approximately 100 ms followed by a negative wave occurring at approximately 150 ms (Naatanen & Picton, 1987; Wolpaw & Penry, 1975). The T-complex is generated by a radially oriented generator in secondary auditory cortex located in the superior temporal gyrus and recorded over the temporal areas. It is therefore largest when measured by midtemporal electrodes (Tonnquist-Uhlen, et al., 2003).The third component is a negative wave seen at approximately 100 ms, which is also maximally recorded at the vertex and possibly generated in the nonspecific parts of the thalamo-reticular system that project directly to the frontal pre-motor cortices (Velasco et al., 1985; Velasco & Velasco, 1986). The processes behind this component might induce a widespread transient arousal of the neural networks,

facilitating the efficient processing of sound information. This response is different from N1b in that it is most sensitive to interstimulus intervals longer than 4 sec (Naatanen & Picton, 1987).

The P2 is the positive peak following N1, which occurs at approximately 180 ms, ranging from 150 to 250 ms. P2 appears to be generated in the vicinity of the primary auditory cortex within the temporal lobe (Hari et al., 1984; Vaughan & Ritter, 1970). However, dipole source modeling does not fit a single source solution (Jacobson, 1994), representing that P2 have multiple generators located in multiple auditory area, including the mesencephalitic reticular activating system (Knight et al., 1980; Naatanen and Picton, 1987; Rif et al., 1991; Woods et al., 1993), primary auditory cortex (Baumann, et al., 1990; Scherg, et al., 1989), and secondary auditory cortex (Hari, et al., 1987). According to Godey et al. (2001), the P2 activation was generated from planum temporale as well as the auditory association complex, with contributions from neural network involving a center of activity near Heschl's gyrus. In addition, Hari et al. (1990) have speculated that P2m (from MEG data) may receive contributions from cortical areas in the upper lip of the sylvian fissure, at or near the second somatosensory areas.

The P2 is usually referred to in the context of the N1-P2 complex, assuming that P2 covaries with N1 along many stimulus dimensions. However, according to Adler & Adler (1989), the essential differences between these two peaks occurs at stimulus intensities above 70 dB, where with further increases in intensity level, the N1 amplitude decreased whereas the P2 amplitude increased. They also reported that the latency changes of P2 were much greater than those of N1 particularly at low intensity levels (between 30 and 70 dB). An increase in the level of attentiveness of a subject enhances the amplitude of the N1 peak but decreases P2 amplitude. P2 matures early reaching adult values by as early as 2-3 years of age, while N1 follows a longer developmental time course, extending into adolescence (Barnet, 1975; Bruneau et al., 1997;

Ceponiene et al., 2001; Kushnerenko et al., 2002; Paetau et al., 1995; Pang & Taylor, 2000; Ponton et al., 2000b). The distinct differences in the maturational time course between the deflections of N1 and P2 suggest the different pathways and neural generators between these components (Crowley, & Colrain, 2004). Hence, it is important to recognize that P2 may not be simply obligatory part of the N1/P2 complex but rather generate independent component process, consistent with the assumption that a wide range of perceptual representations may be involved within the latency of P2 (for a review, see Crowley & Colrain, 2004). The P2 may reflect a sensory-attentional interface, playing a role as a preattentive alerting mechanism contributing to improved perception (Tremblay & Kraus, 2002). The P2 may reflect inhibitory processes that modulate the thresholds for conscious perception (Ceponiene et al., 2005; Melara Rao & Tong, 2002), indexing fidelity of memory traces available in short-term memory (Atienza et al., 2002) and representing long-term plasticity by perceptual training (Crowley & Colrain, 2004). In discrimination paradigms involved in attention-demanding tasks, the P2 mechanism serves to efficiently regulate access to perceptual representations that subsequently trigger MMN comparison processes (during passive listening) or P3 processes of working memory (during active discrimination) (for a review, see Tong, Melara, & Rao, 2009).

The N2 is the second negative component following P2, which falls between 200 and 350 ms after stimulus onset. N2 is localized to the temporal lobe, specifically superior/middle temporal gyrus, the frontal lobe, limbic system, or other obscure subcortical structures (Kiehl et al., 2001; Naatanen, 1982). The N2 component is the last of the ALLR components. The N2 is often barely distinguishable from background activity, though sometimes N2 is rather prominent at high intensity level. The N2 wave is variable and may or may not be present in normal adults. While the earlier components N1 and P2 reflect mainly exogenous sensory-perceptual processes,

the later N2 is considered to represent both stimulus-related, exogenous and event-related, endogenous responses. The N2 is related in part to higher-order (integrative) sensory processing, reflecting subject-dependent manifestations of perceptual-cognitive activity and thereby being affected by top-down facilitation or inhibitory modulations (Ceponiene et al., 2008). With attention, the N2 amplitude increased as a function of the difficulty of the discrimination tasks (Fitzgerald & Picton, 1983), reflecting long-latency inhibitory process of irrelevant stimuli (Ceponiene et al., 2008). The more the attention directed to the stimuli, the more negative the processing negativity of N2 is thought to be (Naatanen, 1982). On the other hand, when sensory processing is disconnected from perception, for example, during sleep, or relaxed states, the N2 increases in amplitude, signifying less net inhibition. However, this component, labeled the basic N2 (Naatanen & Picton, 1986), is not to be confused with the N2b component, which is often associated with the MMN and P300 in oddball paradigm recordings (e.g., Patel & Azzam, 2005). The N2b is considered processing negativity, the ERP (i.e., event-related potentials) sign of selective attention, which is recorded in attention and discrimination tasks (Naatanen & Picton, 1986; Ritter, 1982; Vaughan & Kurtzberg, 1992) and thus associated with controlled process (Naatanen et al., 1986). The N2 elicited by attended-channel stimuli is related to perceptual processing and stimulus classification (Ritter, 1982; Vaughan & Kurtzberg, 1992). A positive correlation between N2 latency and the difficulty of discrimination tasks has been reported for children and adults (Maiste et al., 1995; Steinschneider et al., 1992). For example, the latencies became longer in complex linguistic tasks such as phonetic categorization and semantic classification, than in a simple nonlinguistic oddball paradigm (for a review, see Tonnquist, 1996).

In addition, the N2 may represent the complementary selective attention process of inhibition of irrelevant information. Recent findings suggest that the N2 is subject to inhibitory modulation, indexing a prerequisite for successful inhibition (Falkenstein et al., 2002). According to the findings, the N2 became larger when time pressure increased (Jodo & Kayama, 1992) and when responses had to be inhibited, which have been specifically primed by a preceding cue (Kopp et al., 1996). Additionally, Falkenstein et al. (1999) reported a smaller N2 in subjects with a high error rate than subjects with a low error rate. The inhibition process as reflected in the N2 may be modality specific (Falkenstein et al., 1999). The amplitude of the N2 is much smaller in response to auditory relative to visual stimuli (Falkenstein et al., 1995, 1999; Kiefer et al., 1998; Schroger, 1993).

The N2 is subject not only to maturational changes in children, but also to degenerative changes that occur with normal aging (Bertoli & Probst, 2005). In children, a large N2 is the most prominent peak of auditory obligatory ERPs. The N2 is present as early as 6 months of age (Kushnerenko et al., 2002), increases until the age of 10 years, and thereafter decreases to reach adult values by age of 17 years (Ponton et al., 2000). The decrease in N2 with maturation might reflect the functional refinement of the underlying networks, or could be linked to the structural reorganization of the generators underlying maturational changes of N2 (Bertoli & Probst, 2005). Ceponiene et al. (2005) suggested that a steadily decreasing N2 amplitude with increasing age of children might be a reflection of the N2 becoming subject to substantial inhibitory control. On the other hand, the morphological changes in the N2 of the elderly is more related to degeneration process. The age-related reduction in the negativity of N2 in a go/no-go paradigm, viz. selective attention tasks for the filtering of irrelevant information, could represent the age-related decrease in the capability to suppress the processing of irrelevant stimuli, reflecting an

age-related declines in inhibitory control of irrelevant information processing (Bertoli & Probst, 2005; Ceponiene et al., 2008). The N2 correlates of inhibition have been suggested by smaller no-go N2 amplitudes in children with attention deficit/hyperactivity disorder (Broyd et al., 2005) and patients with impulsive-violent offending behavior. Those pathologies are characterized by a deficit of inhibitory function. The reduced no-go N2, therefore, may reflect a deficient inhibitory process (Chen et al., 2005).

2.2.2. Effects of aging and presbycusis on auditory evoked potentials

AEPs undergo considerable morphological changes in their amplitudes and latencies with advancing age, yielding a different pattern of change along the auditory pathway (peripheral auditory system vs. central auditory system). The morphological changes in AEP may be attributed to the net change resulting from the compensatory central reorganization following peripheral (cochlear) damage. The gain enhancement in the auditory cortex which is associated with compensatory down-regulation of inhibitory neurotransmission (e.g., glycinergic/GABAergic neurons) compensates for the reduced neural output of the cochlea (i.e., cochlear deafferentation) by turning up its gain so that weak signals once again become comfortably loud (Chambers et al., 2016; Salvi et al., 2017). The enhanced central gain may amplify the neural activity, triggering neural hyperexcitability at multiple stages of the central auditory pathway, manifested electrophysiologically as enhanced neural responses (i.e., increased amplitude).

In line with this idea, Qiu et al. (2000) have reported that the damage to inner hair cells led to different morphological changes in the amplitudes of potentials obtained at three different levels of auditory pathway in chinchilla. The compound action potentials were reduced roughly in proportion to the loss of inner hair cells and the inferior colliculus potentials were less reduced

than compound action potentials. Auditory cortex potentials were, however, increased, reflecting functional reorganization at the cortical level. Compensatory enhancement of central neural gain may lead to morphological changes in the electrophysiological manifestation of neural plasticity following cochlear damage. The process of homeostatic plasticity occurs at multiple stages of auditory pathway, producing more pronounced increase in the central gain at higher auditory structures and thereby inducing larger increase in neural response at the cortical level.

For example, ABR, which occurs within early time window (10 ms), produces the decrease in the amplitude (Rowe 1978; Jerger & Hall, 1980), along with the increase in the latency (Fujikawa & Weber, 1977; Thomsen e al., 1978; Allison et al., 1984), with advancing age. The morphological changes in the ABR reflect age-related neural activity at the early stage of auditory processing, which are more involved in peripheral auditory system. A very recent findings have suggested that age-related reduction in ABR wave I may be due to the functional loss of auditory nerve fibers, proportional to diminished auditory nerve input (Lin et al., 2011). The delayed latency may reflect a disruption in synaptic transmission (Mehraei et al., 2016).

In contrast, studies on AMLR (e.g., Jerger et al., 1988; Chambers & Griffiths, 1991; Azumi et al., 1995; Amenedo & Diaz, 1999) have consistently reported the enhanced amplitude of AMLR, especially Pa, with the latency which was either unchanged or prolonged with advancing age under the following conditions: (1) when stimuli were presented at a constant physical or sensation level; and (2) when young and older groups were matched according to audiometric thresholds. The convergence from these studies supports the view that the enhancement of Pa amplitude may be a primary consequence of age-related functional reorganization in central auditory pathway (for a review, see Wu & Stapells, 1994).

According to the findings of Woods and Clayworth (1986), the older adults with sensorineural high-frequency hearing loss yielded the prolonged latency and markedly enhanced amplitude of Pa component. This age-related variation in the Pa component was not necessarily accompanied by changes in the Na, reflecting that Na and Pa may be involved in different neural sources, respectively. According to their findings, Na-Pa and Pa-Nb amplitudes approximately doubled in the older adults and baseline-peak measures of Pa component showed even more substantial increase. The age-related increase in Pa amplitude has been consistently reported. Besides, age-related enhancement of middle latency evoked potentials has been also reported in visual (Dustman & Beck, 1969) and somatosensory (Desmedt & Cheron, 1981) modalities, supporting the view that age-related increase in the central gain, the consequence of compensatory GABAergic down-regulation, may change the neural activity in central neural circuits. In other words, normal aging process reduces concentrations of glutamic acid decarboxylase (GAD, the rate-limiting enzyme in GABA synthesis) in the human thalamus (McGreer & McGreer, 1976). The thalamic reticular nucleus is a major source of the GABAergic projections. The attenuated GAD in thalamic reticular nuclei (Yingling & Skinner, 1977; Shosaku & Sumitomo, 1983) drives a gradual reduction in inhibitory inputs into the midbrain (e.g., medial geniculate nucleus). Thus, the enhancement of Pa amplitude may reflect age-related central modifications in sensory processing, as neural manifestation of central plasticity following peripheral changes. Jerger et al (1988) also provided further evidence to support that the enhanced Pa amplitude may be a strong indication of age-related central modification. They reported consistently the enhanced Pa amplitudes in older adults as the rate increased from 2 to 12/sec. The age-related morphological changes in Pa component, however, are highly variable among elderly individuals.

The late latency (e.g., P1, N1, P2, N2) involves more central process (i.e., perceptual, cognitive, inhibitory) of auditory coding (for a review, see Alain et al., 2013), and morphological changes in neural representations for older adults may reflect age-related variations in the higher auditory centers. For instance, the amplitude of the P1 wave is often larger for older than young adults (e.g., Pekkonen et al., 1995; Soros et al., 2009). For the N1 wave, the amplitude is enhanced (e.g., Alain &Woods, 1999; Soros et al., 2009) and the latency is increased (e.g., Anderer et al., 1996; Tremblay et al., 2003a) in an active and passive listening paradigm for older adults. P2 wave is commonly delayed for older than young adults under active (e.g., Lister 2011) and passive (e.g., Tremblay et al., 2003a; Lister et al., 2011) conditions.

Age-related cochlear degeneration compromises the precision of synchrony across neural fibers, or phase-lock to time-varying acoustic cues (He et al., 2008; Konrad-Martin et al., 2012), which is likely to be especially detrimental to central temporal coding of envelope fluctuations (Joris & Yin, 1992). Abnormal neural synchrony (e.g., hypersynchrony, dyssynchrony), which is based on plastic neural changes, undermines complex sound processing, for example speech or speech-like sounds, contributing to auditory perceptual deficits. The older adults, regardless of their audiometric thresholds, are likely to have more difficulties perceiving time-varying spectral cues. Lister et al. (2011) reported the electrophysiological findings of detection to silent gaps in sounds (maskers) for older adults. The typical paradigm of gap detection task includes a standard stimulus comprised of one contiguous or two contiguous sounds (markers) and a target stimulus comprised of two markers separated by a silent gap. A shortest gap that a listener can detect, relative to a standard, is called a gap detection threshold. They recorded the P1-N1-P2 response to the onset of silent gaps embedded in spectrally identical markers (within-channel conditions) and spectrally different markers (across-channel conditions). The across-channel gap

detection is more difficult and GDTs are generally larger than within-channel gap detection task. The across-channel gap detection is thought to be more representative of the temporal cues important for speech perception and thus can be applied to examine age-related changes in speech understanding. Older adults produced larger amplitudes of P1, N1, and P2, and longer N1 latencies for the across-channel conditions compared to the within-channel conditions. Besides, older adults exhibited larger P1 amplitude and longer P2 latency relative to young adults. Their findings demonstrated the slower neural travel time in response to temporal cues for older adults. The authors have suggested that delayed neural processing of gap cues observed for older adults may represent the inefficiency of the aging auditory system and central changes responsible for auditory inhibition/arousal regarding irrelevant stimuli.

Tremblay et al. (2003) examined the effects of aging and age-related hearing loss on the perception and neural representation of a time-varying speech cue using voice-onset-time (VOT) contrast. VOT is defined as the time interval between the release from the consonant stop closure and the onset of voicing (Lisker & Abramson, 1970). Neural coding of VOT cues can be represented by synchronized responses of neuronal ensembles time-locked to both consonant release and voicing onset (Eggermont, 2000; Steinschneider et al., 1999). They used synthetic speech tokens representing 10 ms increments along a /ba/-/pa/ VOT continuum in order to assess participant's ability of speech discrimination. According to their findings, older adults with/without hearing loss, compared with young adults, had more difficulty in perceptually discriminating 10 ms VOT contrasts. There were no significant age-related differences for P1 latencies while abnormally prolonged N1and P2 latencies were demonstrated by the older adults. N1 is described as an onset response and obligatory or sensory response. N1, therefore, may signal neural encoding of the time-lock to the simultaneous onset of the consonant burst and

voicing, dominated by the initial burst of the consonant and the onset of brief silent gap of VOT interval. Older adults demonstrated the prolonged N1 latencies with increasing VOT duration and prolonged P2 latencies regardless of VOT duration, indicating the reduced ability to time-lock to the onset of voicing and slower neural processing in the aging auditory system, probably due to age-related declines in neural synchrony and prolonged neurophysiological recovery process (i.e., longer period time to recover from the initial excitation before next neural excitation). Tremblay et al. (2003) suggested that age-related variations of N1-P2 complex may reflect differences in neural timing patterns and neural representations of dynamic spectral cues, which may account for the reduced speech understanding in older adults. Reduced neural synchrony can be enhanced with increase in stimulus intensity, improving synchronous neural firing in the relative refractory period (e.g., Tremblay, Billings, & Rohila, 2004).

In addition to delayed latencies, the presence of age-related hearing loss resulted in a significant increase in N1 amplitude in response to voiceless stimuli (Tremblay et al., 2003). The age-related alteration in structural and/or neurochemical mechanisms regulating the balance between excitatory and inhibitory process underlies the enhanced neural responses in the aging central auditory system. As previously mentioned, the significantly increased N1 amplitude in older adults is associated with diminished GABA-mediated inhibition whereby compensatory central gain increases.

The age-related down-regulation of GABAergic inhibition may impair dynamic neural synchronization to relevant acoustic inputs, compromising neural processing of attended sensory inputs. The synchrony of inhibitory input can modulate the neural firing rate and coherence of interneuron networks, which may be responsible for shaping the temporal pattern of spiking activity in the cortical network (Tiesinga et al., 2004). Inhibitory synchronization of neuronal

activity, which contribute to the dynamic control of effective interactions along selective subsets of the neuronal network tuned to the attended sensory input, is crucial to auditory selective attention (for a review, see Womelsdorf & Fries, 2007). The neuronal representations that pertain to attended, relevant information are mutually phase-synchronized across long distances. Neural synchronization is instrumental in establishing a selective neuronal firing of attended, relevant acoustic cues. The neural synchronization to attended information can thus predict behavioral response speed (e.g., reaction time) and perceptual accuracy (Womelsdorf & Fries, 2007). In other words, age-related changes in neural synchronization can modify auditory selective attention process in the aging central auditory system, resulting in the age-related modifications of neural representations in response to attended and unattended stimuli. For instance, N1 amplitude, exogenous component, was apparently increased with advancing age for attended and unattended stimuli, while P3 and target negativity (e.g., attended N2 in mismatch negativity), endogenous component, showed the reduced amplitude and delayed latency with increasing age in attentional trace (Woods, 1992; Karayanidis et al., 1995). The selective attention mechanism encompasses an active inhibitory process involved in suppressing or terminating processing of the representation of irrelevant information (e.g., Tipper, 1985). The effects of attention may be a consequence of changes in the synchrony of inhibitory interneuron networks (Tiesinga et al., 2004). Age-related changes in the neural coding of attention-demanding task may reflect reduced inhibitory gating of irrelevant input, which may lead to processing overload (Karayanidis et al., 1995).

Aging also significantly affects the processing of dynamic spectral information. Aging reduces neural responsiveness to dynamic spectral cues, which decreases the ability to resolve the dynamic spectral information present in the F2 formant transition, especially for the stop

consonant sounds (Plyer & Hedrick, 2002), even at the higher stimulus presentation level which ensure audibility of the entire stimulus. In order to determine the effects of hearing loss and spectral shaping on a dynamic spectral speech cue, Harkrider et al. (2006) measured behavioral identification and neural response patterns of stop-consonant stimuli varying along the /ba-da-ga/ place-of-articulation continuum for three groups: young normal-hearing adults, older normal-hearing adults, and older hearing-impaired adults. All older adults, regardless of audiometric thresholds, had more difficulty utilizing the F2 formant transition cue compared to young adults. Notably, behavioral identification of F2 formant transitions did not differ between older groups and the difficulty in identification of F2 transition could be minimized with spectrally shaped stimuli, wherein a gain was enhanced in the mid-to-high frequencies for spectrally shaped amplification. Categorization of stop-consonant CVs appears to be affected primarily by aging rather than peripheral hearing loss in that older adults with hearing loss performed similarly to older adults with normal hearing.

As for age-related variations of neural responses to F2 formant, older adults showed enhanced N1 and P2 amplitudes and prolonged P2 latencies regardless of hearing status compared to young adults. Of note, N1 amplitudes were larger for older hearing-impaired adults versus older normal-hearing adults, suggesting that age-related neural processing appears to be compounded by the presence of peripheral hearing loss. Spectral shaping significantly increased neural responsiveness to the F2 formant transition for older normal-hearing adults and improved behavioral performance. However, the spectral shaping did not alter the neural representations in older hearing-impaired adults, indicating that enhancing the audibility of the F2 formant transition may not solve the neurophysiological consequences of age-related hearing loss.

Collectively, age-related cochlear damage leads to a net increase in the excitability of central neurons due to homeostatic regulation of excitatory and inhibitory synapses (i.e., increased ratio of excitation/inhibition), interfering with synchronous neural firing among ensembles of neurons receiving relevant information. Selective attention may modulate synaptic efficacy for neural communication, corresponding to the degree of synchrony of inhibitory inputs in the central neural network. The interconnected relationship between attention and neuronal synchrony, mediated by central inhibitory (GABAergic) system (i.e., circuits, synapses), underlies the neural coding of temporal and spectral cues. In other words, attentional modulation of synaptic efficacy, resulting from feedforward inhibition, may serve to enhance signal transmission with temporal precision (Briggs et al., 2013).

Age-related loss of GABAergic inhibition may increase spontaneous activity (i.e., firing rate, discharge rate), accompanied by decreased ability to signal auditory stimuli above background neural activity (signal-to-noise ratio). The compensatory neural changes, attributable to age-related down-regulation of inhibitory GABA neurotransmission following peripheral deafferentation, can be manifested by amplified neural potentials (hyperactivity). More recently, Kim et al. (2012) demonstrated the age-related changes in neural representations when the auditory inputs are presented in noise. They examined the effects of background noise on the cortical response, N1-P2, for older normal-hearing adults. The signal was presented at the level of 60 to 100 dB SPL, accompanied by noise at the level of 70 dB SPL. The main finding was that N1 and P2 latencies were prolonged for older normal-hearing adults in the presence of noise and at the lower signal-to-noise ratio (i.e., 0, +10), consistent with other findings that confirm an age-related delay in neural conduction and decrease in neural precision (Anderson et al., 2012). Young and older adults exhibited similar N1 latencies at the higher stimulus level, indicating that

increased signal-to-noise ratio can improve neural coding. The N1-P2 amplitudes were larger for older relative to younger adults, consistent with other studies (Amenedo & Diaz, 1999; Tremblay et al., 2002, 2003), supporting the view that enhanced neural responses may reflect age-related compensatory modification of central inhibitory mechanism.

As aforementioned, selective attention, a critical component of perception, may modulate neural coding. For example, attention directed towards stimuli generally results in increases in neuronal firing rate and synchrony in young normal auditory system. In oddball tasks requiring active involvement of attentional mechanism (controlled process) wherein subjects count or press a response key to infrequent target stimuli, the effects of aging on ERP latencies and amplitudes have been contradictory, producing inconsistent findings. Multichannel analysis in auditory oddball tasks demonstrated that ERP amplitudes and latencies depended on electrode location (Friedman et al., 1993; Iragui et al., 1993; Anderer et al., 1996).

Concerning N1 component in response to standard stimuli, some findings of age-related ERP changes reported no significant effects of aging on latency (e.g., Pfefferbaum et al., 1984; Barrett et al., 1987), whereas an increase in N1 latency has been found in other studies (e.g., Iragui et al. 1993). Some studies reported that N1 amplitude did not change with advancing age (Barrett et al., 1987; Iragui et al., 1993), while other studies reported the significant increase of N1 amplitude in older adults (e.g., Pfefferbaum et al., 1984; Ford & Pfefferbaum, 1991; Anderer et al., 1996; Amenedo & Diaz, 1999).

Concerning P2 component in response to standard stimuli, some studies reported the increase of P2 latency with advancing age (e.g., Iragui et al., 1993; Tremblay et al., 2002, 2003, 2004) while others found no significant age-related change in P2 latency (e.g., Pfefferbaum et al., 1984; Barrett et al., 1987; Ford & Pfefferbaum, 1991). The increase in P2 amplitudes was

found with advancing age in an oddball task with adjusted stimuli intensity relative to each subject's threshold (e.g., Pefferbaum et al., 1984; Anderer et al., 1996; Tremblay et al., 2002, 2003, 2004; Ceponiene et al., 2008). The studies that found no age-related changes in N1amplitude reported no age-related changes in P2 amplitude as well (e.g., Barrett et al., 1987; Iragui et al., 1993; Anderer et al., 1996).

Concerning N2 component, there is general agreement that N2 latency increases with advancing age to a lesser degree than later component such as P3 (for a review, see Anderer et al., 1996). While some studies reported no significant changes in N2 amplitudes at Cz and/or Pz with advancing age (e.g., Barrett et al., 1987), others reported a significant decrease in N2 amplitudes at Fz, Cz, and/or Pz with advancing age (Pfefferbaum et al., 1980; Enoki et al., 1993; Bertoli & Probst, 2005; Ceponiene et al., 2008). Iragui et al (1993) reported the increase in central and parietal N2 amplitude with advancing age.

2.3. Speech-in-Noise Perception

Speech perception is dependent on multiple spectral, temporal and intensity cues. The ability to identify acoustic cues from speech degrades with advancing age. The aging results in delayed synchronous firing to the onset of acoustic sound in association with the events occurring along the central auditory pathways, consequently leading to impaired temporal acuity in the aging central auditory system. The impaired temporal precision impedes speech understanding ability in the elderly, compounded by the presence of significant high-frequency age-related hearing loss. Indeed, abnormal neural processing at the brainstem level has been reported in populations with impaired speech understanding (Cunningham et al., 2001; King et al., 2002). For example, N1-P2 complex, considered to reflect underlying neural timing patterns

that contribute to perception, have been reported to have abnormal patterns in children and adults with varying types of speech perception impairments (Kraus et al., 2000; Tremblay et al., 2001). For this reason, it is possible that abnormal neural response patterns may be one of many factors contributing to the reduced speech understanding in older adults (Tremblay et al., 2002).

A number of factors potentially contribute to the elderly listener's reduced ability to understand speech in adverse listening situations. The principal factor is associated with acquired changes in the peripheral auditory system, including loss of hair cells, tissue of the stria vascularis, and neural cells. In particular, loss of strial tissue appears to be a consequence of the aging process and results in a decrease in the endocochlear potential (Mills et al., 2006). A decrease in the endocochlear potential affects hearing sensitivity in the high frequencies more than in the low frequencies. Loss of hearing sensitivity in the high frequencies directly reduces the audibility of weak, high frequency energy that is critical for conveying consonant cues, which eventually reduces speech recognition performance (ANSI, 1969). The age-related deterioration of spiral ganglion cells results in a loss of neural synchrony, affecting the ability to code the onsets of signals and the successive onsets of a sequence of changing signals, such as occurs in speech. Along with age-related changes in the peripheral auditory system, neural losses in the CNS with aging (Willot, 1991) disrupt spectral and temporal coding of incoming auditory information, thereby leading to distorted sound perception and slowed neural processing. Additional age-related changes that occur in the CNS, which contribute to perceptual declines, relate to the reduced inhibitory control. Caspary et al. (1995, 2005, 2008) have observed increases in spontaneous firing and maximum firing rates, and decreases in nonmonotonic rate-level functions in the IC and AI in aging fischer 344 rats. These types of changes appear to be related to an age-related decrease in inhibitory neurotransmitter function in the CNS.

More specifically, increased neural noise in the aged cortex caused by the decreased GABAergic inhibition undermines the ability to inhibit irrelevant semantic, phonetic, and voice information (Sommers & Danielson, 1999). The age-related declines in GABAergic inhibitory function impairs the ability to use pitch and temporal cues in older adults, which may contribute to loss of speech-in-noise (SIN) perception (e.g., Anderson et al., 2011). Pitch cues, derived primarily from the fundamental frequency (F0) and its second harmonic (H2) (Meddis & O'Mard, 1997), facilitate auditory object identification, enabling the listener to identify target voice and to follow this particular voice from among a stream of competing voices or other noises (Oxenham 2008; Shinn-Cunningham & Best, 2008; Chandrasekaran et al., 2009). The age-related declines in processing pitch cues (e.g., Helfer & Freyman, 2008; Helfer & Vargo, 2009; Huang et al., 2010) allow background noise to interfere with signal detection and identification, inducing difficulties in extracting one particular sound source amid a background of competing sounds (for a review, see Anderson & Kraus, 2010). Furthermore, down-regulation of inhibitory function may lead to degraded temporal resolution (Caspary et al., 2008) by decreasing selectivity of pertinent acoustic features in the stimulus (Burger & Pollak 1998; Hall 1999; Edwards et al., 2008) and by limiting the ability to code signals accurately (Caspary et al., 1995, 2008; for reviews, see Anderson et al., 2001).

Age-related declines in temporal resolution affect two aspects of temporal cues involving SIN perception: temporal envelope (TE) and temporal fine structure (TFS). Complex broadband sounds like speech are decomposed by the auditory filters into a series of relatively narrowband signals, each of which can be considered as a slowly varying TE superimposed on a more rapid TFS (Moore, 2008). Both TE and TFS information are represented in the timing of neural discharges, although TFS information depends on phase locking to individual cycles of the

stimulus waveform (Moore, 2008). TE cues are sufficient to provide good speech intelligibility in quiet (Flanagan, 1980; Shannon et al., 1995; Smith et al., 2002), but not in the presence of fluctuating background noise. Rather TFS information plays a significant role in speech perception in fluctuating background noise (for reviews, see Moore, 2008). Age-related hearing loss deteriorates the sensitivity to TFS (Buss et al., 2004; Lacher-Fougere and Demany, 2005; Moore et al., 2006; Hopkins and Moore, 2007, 2010b, 2011). The majority of studies (Lorenzi et al., 2009; Strelcyck & Dau, 2009; Papakonstantinou et al., 2011; Hopkins & Moore, 2011) suggested that hearing loss at high frequencies could be associated with a reduced ability to process TFS cues which are normally comprised of low frequencies. Moore et al. (2011) clarified whether elevated audiometric thresholds at high frequencies had adverse influence on TFS processing independently of the effects of age, testing only older adults (> 60 yrs). They concluded that sensitivity to TFS worsens with advancing age rather than hearing loss. Taken together, the age-related down-regulation of inhibitory control may compromise the following auditory function: (1) auditory stream segregation, or the ability to extract one particular sound source amid a background of competing sounds; (2) spectrotemporal resolution or selectivity; and (3) the ability to code pitch cues. Collectively, age-related imbalances in neurotransmitters/receptors underlying inhibitory function degrade speech intelligibility in a noisy background (for a review, see Caspary, 1995), impairing precise neural timing in coding acoustic features accurately and/or the ability to suppress irrelevant information amid competing voices.

The impoverished auditory inputs that results from perceptual declines including peripheral hearing loss can adversely affect other perceptual operations that are essential for accurate speech perception (Summers, 1997). Speech perception is a complex task involving

interplay of sensory and cognitive processes (Anderson & Kraus, 2010). In other words, perceptual difficulties are, in part, mediated by top-down cognitive processes (Best et al., 2007; Heinrich et al., 2007), indicating that age-related perceptual deficits can be partially compensated by higher-level cognitive process. For example, elderly listeners utilize syntactic and semantic cues, which accrue from increased linguistic experience (Sommers & Danielson, 1999), in order to compensate for their reduced speech perceptual ability in noisy listening situations. In fact, older adults with age-related hearing loss showed better word recognition ability when syntactic and semantic cues were provided (Shum & Mattews, 1992; Owen, 1981).

Shum & Mattews (1992) obtained speech perception in noise (SPIN) test scores from both ears of 98 elderly hearing-impaired listeners for the purpose of determining the elderly listener's ability to make full use of the linguistic cues in the PH items. The SPIN test (Kalikow et al., 1977) was designed to assess word recognition skills under two controlled levels of contextual information: High-Predictability (HP) items, which contain a few pointer words or clues to the identity of the final word, and Low-Predictability (LP) items, which contain no such semantic or syntactic clues to the final, key word. HP items measures verbal auditory closure (i.e., top-down processing and utilization of semantic/syntactic contextual clues), whereas recognition of the key words of LP items is achieved primarily by bottom-up processing of the acoustic signal. PL items are thus similar to classic word recognition test, reflecting basic word recognition skills in noise (for a review, see Elliott, 1995). The better performance typically seen on the HP items compared to the LP items reflects the listener's ability to use contextual information when listening to speech. However, cases in which the HP is lower than expected based upon a given LP scores reflect a situation in which the listener apparently uses the available contextual cues less effectively than most hearing-impaired listeners. The elderly

listeners demonstrated performance on the SPIN test similar to that of the generally younger hearing-impaired subjects from the normative guidelines of Bilger et al (1984), which tested 128 listeners aged 19 to 69 years, with 79 percent of the sample less than 65 years old. However, for a certain percentage of the aged ears, the contextual cues provided in the HP items were not used as effectively as expected based on the normative guidelines. Given a relatively large body of literature documenting declines in cognitive and information processing skills in the elderly (for a review, see Cohen & Wu, 1980; Woodruff, 1983; Welford, 1985; Kausler, 1988), it is reasonable to assume that older listeners will be at greater risk for certain perceptual difficulties that extend beyond the peripheral hearing loss because age-related declines in cognitive functions limit the ability to understand speech in noisy listening conditions (Frisina & Frisina, 1997; Gordon-Salant & Fitzgibbons, 1997; Tremblay et al., 2002; Tun et al., 2002). The associated cognitive functions include working memory capacity, selective attention, and speed of information processing (for a review, see Gordon-Salant et al., 2011). The age-related decline in working memory capacity is manifested as difficulty in holding information in a temporal storage while processing its meaning or while waiting for additional information. The decline in selective attention may impede the listener's ability to ignore background noise or suppress relatively unimportant signals in a spoken message, disrupting the ability to identify primary signals. As a result, elderly listeners are not as capable as younger listeners in the processing of auditory information when speech is presented at a rapid rate (Salthouse, 1996; Wingfield et al., 1985).

Elderly listeners are more vulnerable to the distracting effects of semantic content in background noise than younger adults, indicating that cognitive factors contribute to their SIN perception difficulties (Tun et al., 2002). Indeed, age-related sensory declines, including those in

SIN perception, are accompanied by increased activation in more general cognitive regions (i.e., working memory and attention) as a means of compensating for these declines (Wong et al., 2009). Therefore, older adults who have experienced declines in memory or attention are more likely to be affected by decreased sensory perception (Shinn-Cunningham & Best, 2008).

Age-related structural and functional changes throughout the auditory system modify how the central auditory system encodes incoming stimuli (for a review, see Tremblay et al., 2007). More specifically, some of the perception-in-noise variability seen across these populations may be related to each person's ability to tolerate/code signals in noise in the central auditory system. Cortical responses such as P1-N1-P2 complex is useful tool in coding SIN perceptual processing (for a review, see Martin et al., 2008). In fact, abnormal P1-N1-P2 responses have been demonstrated to be associated with subject populations who experience perception difficulties, such as elderly people and those with hearing impairment (Kraus et al., 2000; Oates et al., 2002; Tremblay et al., 2003, 2004). Such abnormal responses can be obtained in part from the week audibility resulting from peripheral hearing loss. Billings et al. (2007) pointed to the importance of signal-to-noise ratio (SNR) rather than absolute signal level as a means of improving the week audibility in that the morphology of the cortical responses was more positively affected by SNR methodology. The systematic SNR is a useful measure in improving the ability to perceive a signal in relation to the level of background noise, adjusting the sound level difference between the signal and the continuous background noise. The SNR has been reported to be the key contributor to timing and magnitude of the evoked response, eliciting the overall waveform morphology. Billings et al. (2009) demonstrated the effects of SNR across cortical evoked response components, P1, N1, P2, and N2: that is, as SNR increased, the latencies decreased significantly for all components, and the amplitudes increased

significantly for all components except P1 that is close to the noise floor of the electroencephalography. To put it in another way, the impaired speech recognition at poor SNR is related to the increased N1 latencies and decreased N1 amplitudes (Martin et al., 1997, 2005).

Recently, Billings et al. (2011) determined the effect of signal type and noise type on the P1-N1-P2 complex. Tones (1000 Hz, 500 Hz) and speech stimuli (/ba/, /da/) were presented at SNR of -3 dB in three types of background noise: continuous speech spectrum noise, interrupted speech spectrum noise, and four-talker babble. Speech-evoked peaks generally occurred later for all components than tone-evoked peaks. The general effect of noise type on peak waves was that four-talker babble resulted in longest latencies and smallest amplitudes, and that interrupted noise resulted in shortest latencies and largest amplitudes, with continuous noise results falling between the two other noise types though the differences between interrupted and continuous noise were not robust. The findings of this study indicate that one of the most difficult listening situations is the perception of speech in speech background noise (Billings et al., 2011), which would also be another evidence to support the great difficulty with perceptual grouping and segregation of sounds in informational masking.

Informational masking reflects vulnerability of certain central portions of the auditory processing system (e.g., related to attentional phenomena) while energetic masking is defined as the masking that results from completion between target and masker at the periphery of the auditory system (i.e., at the level of the basilar membrane or auditory nerve) (for a review, see Durlach et al., 2003a). Substantial amounts of informational masking can be created through the introduction of uncertainty in the acoustic stimulus. More specifically, at an intuitive level, informational masking occurs because the listener finds it difficult to focus attention on the target in the presence of a distracting or confusing masker. Although masker uncertainty is clearly

relevant to the masking effects, so is the similarity between target and masker in a variety of dimensions including spectrotemporal pattern, duration, and interaural (i.e., spatial) relationship. Leek et al. (1991) defined the informational masking as "degradation of auditory detection or discrimination of a signal embedded in a context of other similar sounds" and "a target that is sufficiently different from the surrounding tones along some acoustic dimension will be heard with increased precision" (pp. 205-206). The informational masking can be reduced by increasing the perceptual differences. As perceptual differences increase, auditory stream segregation of sound components from different sound sources is facilitated. Counteracting the effects of maker uncertainty by decreasing target-masker similarity can cause significant release from masking (Durlach et al., 2003). The SNR may play a significant role in increasing perceptual segregation by producing the release from masking.

The elderly, even those with relatively good audiograms, are disadvantaged in everyday situations where they must understand speech in noise primarily because of the deterioration of central auditory processing with age. For example, there was the significant reduction in the LP scores for presbycusic subjects even when high enough SNR was provided, resulting in a larger difference in SPIN scores between LP and HP sentences. According to Owen (1981), because of the consistent reduction in the LP scores for older adults, it may be possible to use the LP sentences as a measure of central auditory processing.

Speech recognition ability reduces in adverse context and under poor SNR conditions due to increased perceptual demands. Increasing the perceptual load by decreasing SNR does adversely affect the ability of listeners to remember the words that they heard, thereby limiting the auditory informational processing. When perceptual processing became difficult, more of the available pool of reallocable resources was dedicated to perceptual processing to the detriment of

the storage of information in working memory and possibly to the detriment of other cognitive processes required for speech understanding (for a review, see Pichora-Fuller et al., 1995). In other words, decreases in SNR and/or declines in auditory function, not only reduce the amount of information coming through the perceptual channel, but they also draw resources away from other cognitive processes. As a result, these variables have deleterious effects on speech-in-noise perception. Pichora-Fuller et al. (1995), hence, suggested that the perceptual difficulties experienced by the elderly affect speech understanding ability directly by altering the proportion of correctly to incorrectly perceived words and indirectly by consuming resources that could otherwise be allocated to the storage of information in working memory and to other cognitive processes necessary for speech understanding ability.

There is little known about relationships between SIN perception and neural responses. Nevertheless, there are a few remarkable studies on determining the neural basis associated with SIN perceptual ability. Anderson et al. (2011) investigated a neural basis of SIN perception in older adults by testing behavioral performance with the Hearing in Noise Test (HINT) and neurophysiologically using speech-evoked auditory brainstem responses recorded in quiet and in background noise. The participants were divided based on their HINT scores into top and bottom performing groups that were matched for audiometric thresholds and intelligent quotients. They compared brainstem responses in the two groups, specifically, the average spectral magnitudes of the neural response and the degree to which background noise affected response morphology. The results demonstrated the importance of subcortical encoding of the F0 for successful SIN perception in older adults. Participants in the top SIN group had greater subcortical representation of F0 magnitudes in response to a speech syllable than participants in the bottom SIN group; furthermore, the neural response timing of participants with better SIN was less

affected by noise, having higher quiet-to-noise correlations between responses. The bottom SIN group (i.e., older adults with poorer SIN perception) demonstrated reduced neural responses and greater disruption in noise, reflecting reduction in neural synchrony. All physiologic measures were correlated with SIN perception, suggesting strong relationships between subcortical representation of speech and behavioral measures of SIN perception. They concluded that adults in bottom SIN group differed from the audiometrically matched up SIN group in how speech was neutrally encoded. Their findings suggested that effective subcortical encoding of the fundamental frequency appears to be a factor in successful speech-in-noise perception in older adults

Paludetti and his colleagues (1991) examined whether the increase in Pa amplitude have the relationship with the decreased speech understanding in the elderly. They tested older adults aged between 60 and 80 years for behavioral speech discrimination test and AMLR recordings in order to evaluate possible correlations between behavioral and electrophysiological results. No correlation between speech discrimination tests and AMLRs were observed. They concluded that AMLR might reflect a central involvement in speech discrimination, but this connection was not demonstrated. Furthermore, they suggested that the cortical evoked potentials could offer better information on the electrophysiological substrate for age-related disturbances in speech discrimination.

Chapter 3:

Purpose, Research Questions, and Hypotheses

As aforementioned, age-related auditory perceptual deficits are largely attributed to two causes: 1) peripheral degeneration involving cochlear damage such as age-related losses of spiral ganglion neurons, stria vascularis, and inner and outer hair cells; and 2) central degeneration involving age-related functional changes in central neural networks. However, little is yet known about neurophysiological mechanisms underlying presbycusis and there are a number of unanswered questions, including at which stage of neural processing the compensatory functional changes occur, at which level of the central auditory pathway, and how central neural processing changes and interacts with peripheral changes.

Therefore, the goals of this research are: (1) to determine the effects of aging and age-related hearing loss on auditory neural coding in central auditory system, by investigating how age-related peripheral degeneration affects the neural activity generated at different levels along the central auditory pathways; (2) to identify the connections between early and later stages of auditory neuroelectric responses in the aging central auditory pathway; and (3) to identify the neural correlates of age-related declines in central auditory processing (i.e., speech-in-noise intelligibility).

To summarize, the present research was designed to achieve the following three specific aims:

1. To test the first hypothesis that aging and (peripheral) hearing loss produce differential effects on the morphological changes in AEP responses, the following research questions were devised:

A. Do the effects of aging, which are examined by comparing young normal-hearing adults with older adults with near-normal hearing, give rise to morphological changes in the AEP responses?

   (a) How does the aging affect the amplitude and latency of AMLR (Pa) and ALLR (N1, P2, N2) as a function of stimulus type (i.e., simple acoustic sound vs. speech syllable)?

   (b) How does the aging affect the amplitude and latency of AMLR (Pa) and ALLR (N1, P2, N2) as a function of noise condition (i.e., in quiet vs. in temporally fluctuating background noise)?

   (c) How does an altered AEP morphology induced by the effects of aging differ from morphological changes by the combined effects of aging and hearing loss, which are examined by comparing young normal-hearing adults with older hearing-impaired adults? In other words, how are the morphological consequences of aging per se different from those of age-related hearing loss?

B. Do the effects of (peripheral) hearing loss, which are examined by comparing older adults with near-normal hearing with older adults with hearing loss, give rise to morphological changes in the AEP responses?

   (a) How does the hearing loss affect the amplitude and latency of AMLR (Pa) and ALLR (N1, P2, N2) as a function of stimulus type?

   (b) How does the hearing loss affect the amplitude and latency of AMLR (Pa) and ALLR (N1, P2, N2) as a function of noise condition?

2. To test the second hypothesis that there may possibly exist the connections between neuroelectric responses taking place at early and later stages of auditory processing, which

may suggest the interrelationships between the underlying neural substrates of AEP components, the following research questions were devised:

A. Is there any correlation between the amplitudes of AMLR Pa and respective components of ALLR (N1, P2, N2)?

B. Is there any correlation between the latencies of AMLR Pa and respective components of ALLR (N1, P2, N2)?

C. Which of ALLR components is more strongly correlated with Pa component?

3. To test the third hypothesis that age-related variations in auditory neural coding may have a relationship with age-related declines in speech-in-noise perception, the following research questions were devised:

A. How does behavioral performance on Speech Perception in Noise (R-SPIN) test correlate with the amplitudes of respective AEP components (Pa, N1, P2, N2)?

(a) Which of AEP components is more strongly correlated with SPIN-LP scores?

(b) Which group shows higher neural correlates of SPIN-LP scores? Which amplitude is significantly correlated with SPIN-LP scores in each group?

B. How does behavioral performance on Speech Perception in Noise (R-SPIN) test correlate with the latencies of respective AEP components (Pa, N1, P2, N2)?

(a) Which of AEP components is more strongly correlated with SPIN-LP scores?

(b) Which group shows higher neural correlates of SPIN-LP scores? Which latency is significantly correlated with SPIN-LP scores in each group?

Chapter 4:

Methods

4.1. Subjects

30 healthy young normal-hearing adults (mean = 21 years; range = 18-28 years; SD = 2.9 years), 26 older adults with near-normal hearing (mean = 63.9 years; range = 56-75 years; SD = 5.5 years), and 26 older adults with age-related high-frequency hearing loss (mean = 72.8 years; range = 59-89 years; SD = 7.9 years) participated in this study. The young subjects were recruited from the general student population at University of Wisconsin-Madison primarily by flyers and university online postings and older subjects were recruited from Wisconsin area through Institute of Aging and Wisconsin Alzheimer's Disease Research Center. The following auditory examination was performed to identify eligible participants: a case history, otoscopy, tympanometry, audiometric testing, and auditory brainstem responses. Young adults had normal hearing sensitivity with (air-and bone-conduction) pure tone thresholds of ≤15 dB HL and air-bone gaps < 15dB for octave frequencies ranging from 250 to 8000 Hz in at least one ear. The older adults with near-normal hearing had normal or near-normal hearing sensitivity with pure-tone thresholds ≤ 30 dB HL over the frequency range from 250 to 8000 Hz in at least one ear. The older adults with age-related hearing loss had varying degrees of sloping sensorineural hearing loss above 1000 Hz. Figure 4-1 shows the mean audiometric thresholds of the tested ear for three listener groups. Individual audiometric thresholds for the tested ear and demographic data are given in Appendix A. All subjects had normal 226 Hz tympanometric measures (single admittance peak between ±50 daPa, 0.2-1.8 mmho), indicating normal middle ear function.

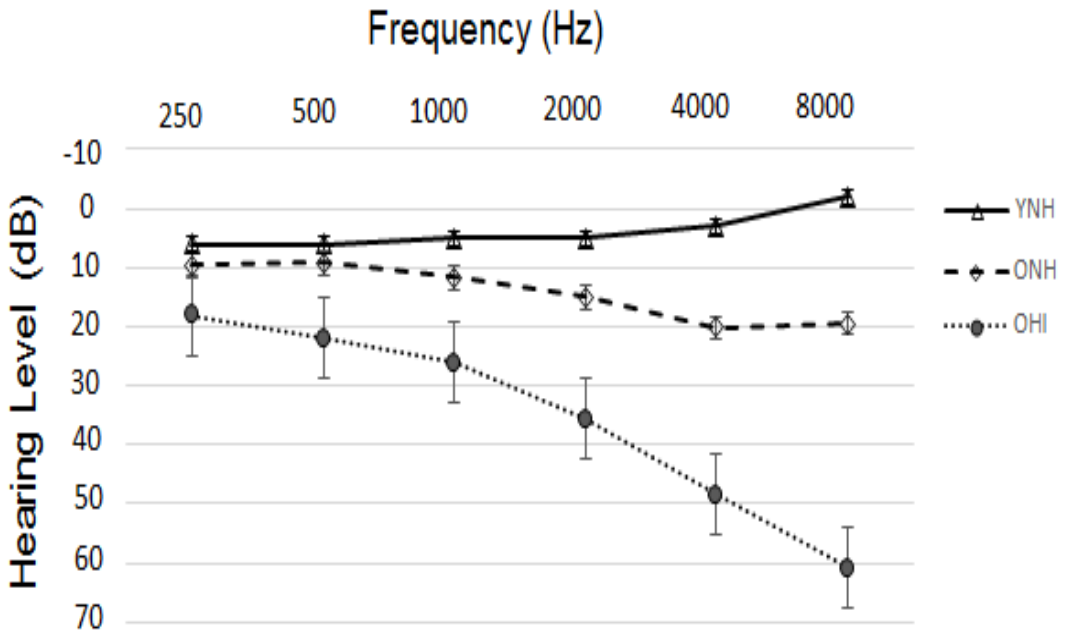


Figure 4.1. Mean audiometric thresholds (±1 standard error) of the tested ears for three listener groups: young normal-hearing adults (YNH, solid line with open triangle), older adults with near-normal hearing (ONH, dashed line with open diamond), and older hearing-impaired adults (OHI, dotted line with filled circle).

To rule out any major age-related cognitive impairment for the control of confounding effects, the following cognitive screening assessment has been performed: animal naming task[1] and MoCA[2] (Montreal Cognitive Assessment, version 7.1). Animal naming task was administered for some older subjects, who generated animal names more than 14 for 60 seconds, indicating normal cognitive function. For other older subjects, the MoCA was administered and all of them obtained a score of 26 or above that is considered normal. The animal naming task is one of best ways to assess semantic verbal fluency, as measured by an individual's ability to generate semantic category (e.g. animals, food, things to wear). A disproportionate deficit in

[1] Sager MA, Hermann BP, LaRue A, Woodard JL (2006). Screening for Dementia in Community-based Memory Clinics. Wisconsin Medical Journal 105(7), 25-29.

[2] Nasreddine ZS, et al. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. Journal of the American Geriatric Society 53, 695-699.

semantic verbal fluency has been demonstrated in patients with Alzheimer's disease (Appell, Kertesz, & Fisman, 1982; Bayles & Tomoeda, 1983; Butters et al.,1987; Chertkow &Bub, 1990; Cummings, Benson, Hill, & Read, 1985; Hodges, Salmon, & Butters, 1992; Martin & Fedio, 1983; Ober et al., 1986; Pachana et al., 1980; Tombaugh et al., 1996; Canning, Leach, Stuss, & Black, 2004). Animal naming task has thus been reported to a brief cognitive screening tool to discriminate patients with cognitive impairment from a normal aging population (Canning et al., 2004; Tombaugh, Kozak, & Rees, 1999). The MoCA is a brief cognitive screening instrument to detect mild cognitive impairment. Thirty items contained in the MoCA assess the following multiple cognitive domains: attention and concentration, executive functions, memory, language, visuoconstructional skills, conceptual thinking, calculations, and orientation. Animal naming task and MoCA are provided in Appendix B and C, respectively.

All subjects had normal ABRs (auditory brainstem response), indicative of normal brainstem function. None of the subjects reported a history of chronic middle ear pathology, retrocochlear pathology, or otological or neurological medical problems. All subjects reported to be right-handed and healthy, free of medication during the experimental sessions.

4.2. Experiment 1: Recording of Auditory Evoked Potentials

4.2.1. Materials

Stimuli

The stimuli was 500 Hz tone burst and synthesized stop consonant-vowel (CV) syllable /ba/. The total duration of 500 Hz tone burst was 20 ms, consisting of rise/fall time of 5ms and

plateau of 10ms. Extended cosine^2 windowing was applied to generate the 500 Hz tone burst. Figure 4-2 illustrates the acoustic characteristics of 500 Hz tone burst.

The synthetic speech syllable /ba/, which included three parts of noise burst, formant transition, and steady-state vowel portion, was composed of five-formants. The overall duration of syllable /ba/ was 115 ms, the initial 10 ms of which was the stop release burst of /b/ preceding the voicing (fundamental frequency, F_0) onset, containing diffuse high-frequency energy (2500-4000 Hz). The formant transition from the /b/ to the /a/ was 30 ms in duration following the noise burst and was characterized by a linearly rising first formant F_1 (543-734 Hz), second formant F_2 (1085-1245 Hz), and third formant F_3 (2425-2584 Hz), with flat forth formant F_4 (3095 Hz) and fifth formant F_5 (3700 Hz). The initial frequency information of F_1, F_2 and F_3 provides the acoustic cues for consonant identity and relative spacing between the frequencies of F_1 and F_2 at the end of the transition provides the information relevant to vowel identity. The steady-state portion of the vowel /a/ lasted 65 ms, representing the constant five formants following the formant transition. Bandwidth (BW) values for the vowel /a/ were: BW1 = 90 Hz, BW2 = 90 Hz, BW3 = 300 Hz, BW4 = 600 Hz, BW5 = 400 Hz. Figure 4-3 illustrates the acoustic characteristics of synthetic syllable /ba/. All stimuli were digitally generated at a sampling rate of 40 kHz by the auditory evoked potential protocol software (Intelligent Hearing Systems, SmartEP).

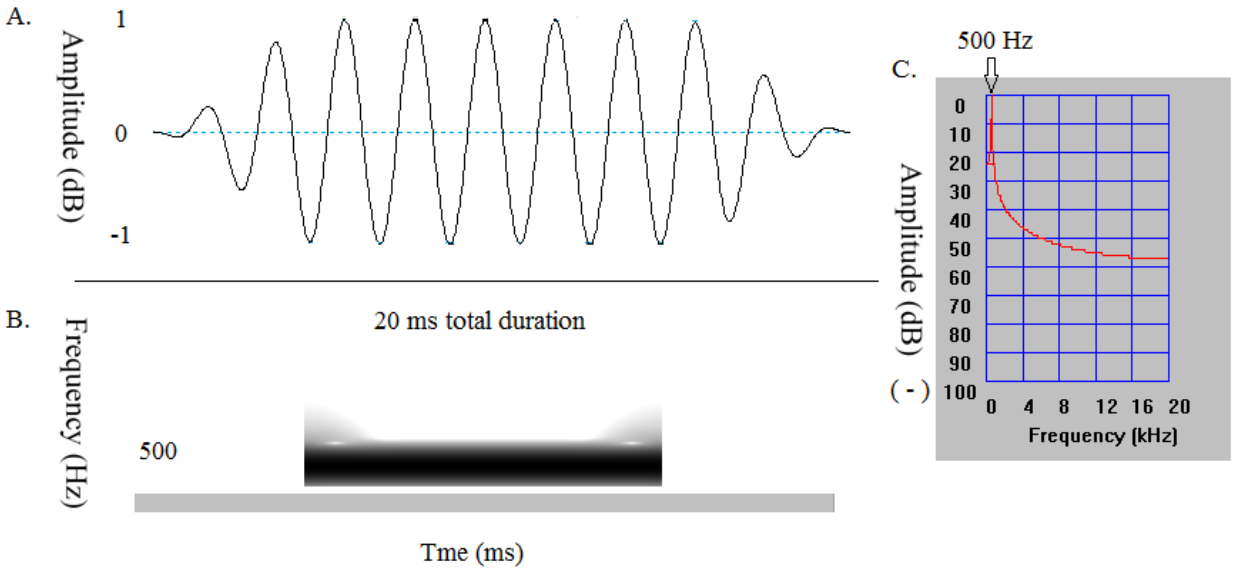


Figure 4.2. 500 Hz tone burst: (A) Waveform, (B) Spectrogram, and (C) Frequency spectrum.

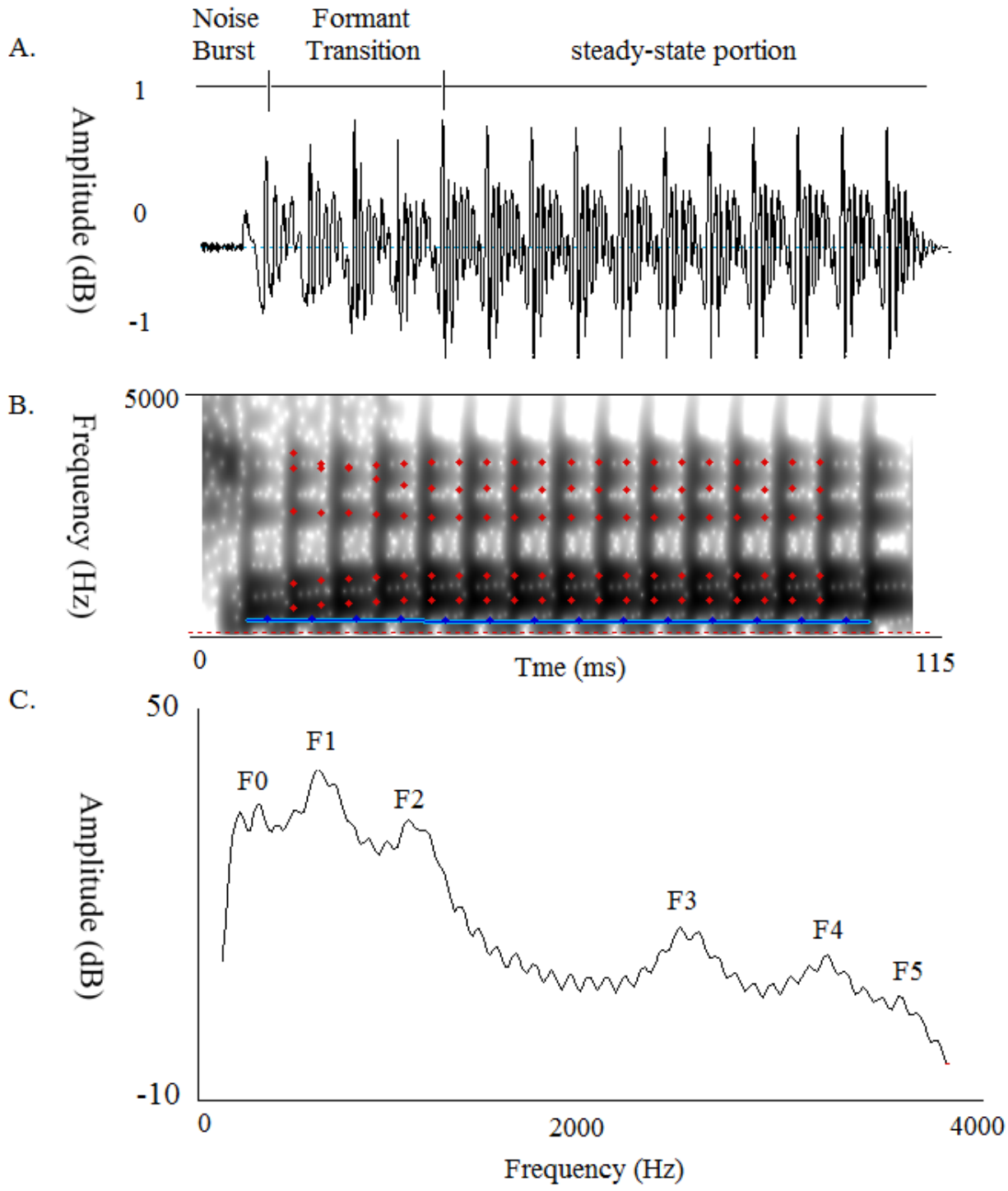


Figure 4.3. Synthesized speech /ba/: (A) Waveform, marked by onset burst, formant transition, and steady-state portion. (B) Spectrogram. The blue line represents pitch (F_0) and red dotted lines represent formants. (C) Frequency spectrum.

Type of Masker

The stimuli were presented in quiet and noise conditions. The type of noise was time-varying twelve-talker babble from the revised Speech Perception in Noise (R-SPIN) test (Bilger et al., 1984). The babble was generated by recording each of six adult talkers (three male, three female) reading the same section from a child's storybook in an anechoic chamber, mixing these six recordings (each at the same RMS level), and then combining two repetitions of this six-talker babble to produce the final twelve-talker babble. Figure 4-4 illustrates the acoustic waveforms and frequency spectral analysis of babble noise. The temporal alignment of sentences and babble was measured carefully to avoid possible deleterious effects related to the temporal fluctuations in the babble. The overall RMS level of the babble was constant during the test items, recorded at the same level as that of the sentences. Just prior to the onset of the number cue for each test sentence, the overall level of the babble was smoothly diminished 10 dB, held at that level through the cue, and smoothly stored to its original level prior to the onset of the test sentence. The babble was recorded on the second channel of two-channel compact disc. For more details, please see Kalikow, Stevens, & Elliott, (1977).

The time-varying babble noise is a representative type of informational masker. Informational masking refers to listening situations where the target signals and maskers are similar to one another and clearly audible so the listener is unable to segregate the elements of the target signals from the elements of the similar-sounding distracters (Freyman et al., 1999; Doll and Hanna, 1997; Kidd et al., 1995; Kidd et al., 1994; Lutfi, 1990; Watson et al., 1976; Pollack, 1975). Energetic masking can physically and informational masking perceptually interfere with target signals (Lidestam et al., 2014).

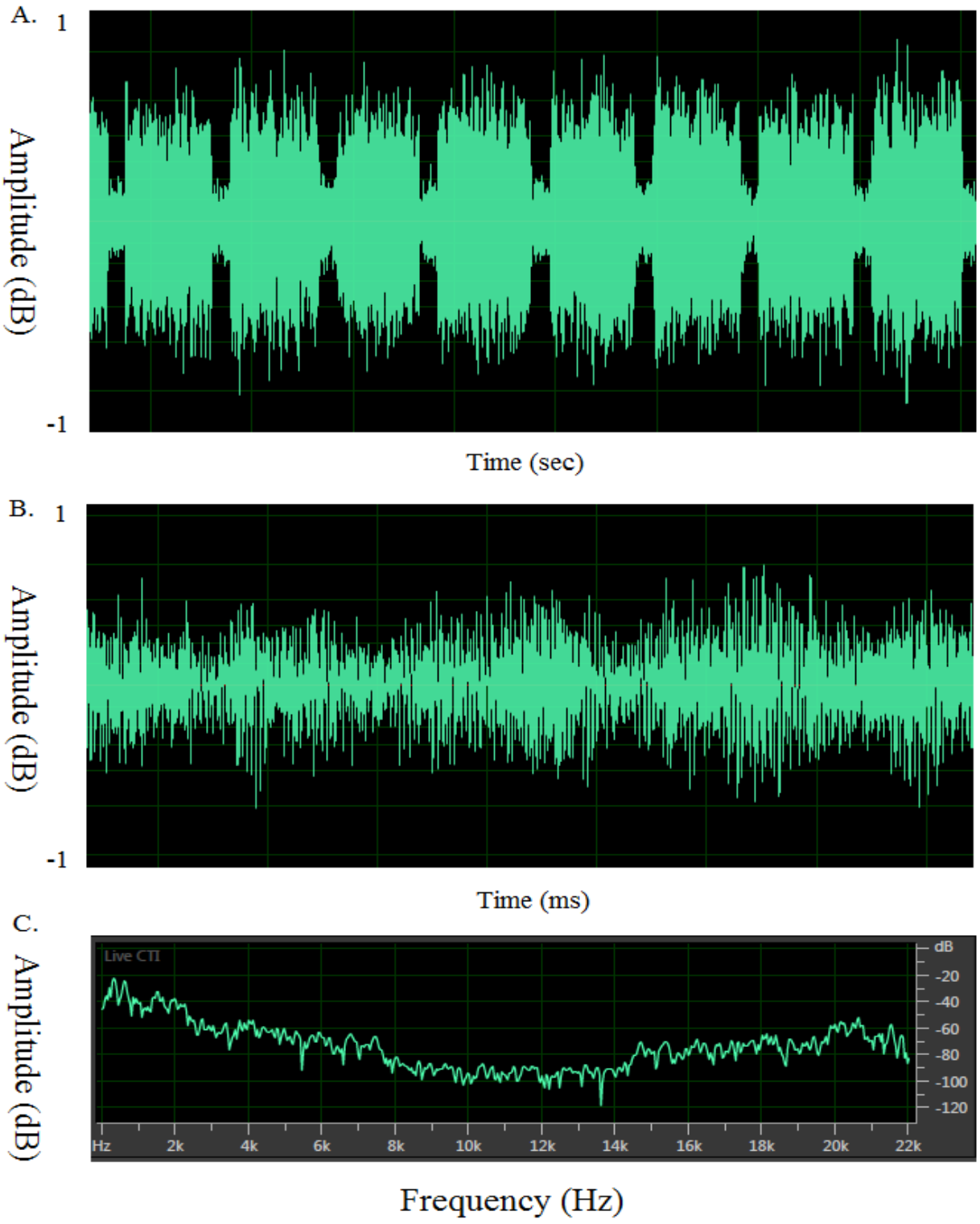


Figure 4.4. Twelve-talker babble noise: (A) Waveform (zoom-out), (B) Waveform (zoom-in), and (C) Frequency spectrum

4.2.2. Procedure

Two-channel electrode system was applied to record AMLRs and ALLRs using Intelligent Hearing Systems (IHS), SmartEP diagnostic software. One channel was attached to the midline central or vertex (Cz) recording site as the noninverting electrode (+) and to the ipsilateral earlobe of the stimulated ear as the inverting electrode (−), with the ground electrode placed on either lower forehead (Fpz) or unused earlobe. The other channel was placed above (supraorbital ridge) and below (zygomatic bone) one of the eyes to monitor ocular artifacts (e.g., eye movements, eyeblinks). Electrodes impedances were less than 5K Ohms and the interelectrode impedances were kept less than 2K Ohms.

The AMLRs were recorded in a time-locked window which consists of 10 ms pre-stimulus interval for baseline correction and 85 ms post-stimulus period. The responses were amplified for a voltage gain of 100k and collected with 1000 sweeps per average at a rate of 11.1/s, with the rejection of an amplitude exceeding ±50 uV. Evoked responses were band-pass filtered on-line from 10 to 1500 Hz (12 dB/octave roll off) and were filtered off-line at 10-300 Hz (12 dB/octave roll off) for analysis if needed. The responses were replicated to insure test reliability. During AMLR recordings, participants were asked to remain awake and recline in a comfortable chair to prevent post-auricular muscle artifact which particularly contaminates AMLR recordings.

The recording window of ALLRs included 100 ms pre-stimulus baseline and 600 ms post-stimulus time. Evoked responses were band-pass filtered online from1 to 300 Hz (12 dB/octave roll off) and then were filtered off-line at 1-30 Hz (12 dB/octave roll off) for analysis if needed. Responses were amplified for a voltage gain of 50k and averaged over 100 stimulus

repetitions at a rate of .71/s. During a recording of ALLRs, participants were asked to watch a closed-captioned silent (muted) movie, sitting in reclining chair, while passively hearing the stimuli. Participants were monitored visually to ensure that they kept awake during testing. The silent movie was provided to help participants stay awake and for a decrease in eyeblinks.

For ERP recording, 500 Hz tone bursts and synthesized speech syllable /ba/ were presented in quiet and in babble noise at the level of 90 dB Leq (equivalent continuous sound level), accompanied by noise at the level of 65 dB(A) Leq, resulting in a SNR (signal-to-noise ratios) of +25 dB. Each type of stimulus and babble noise were combined acoustically in a custom double-barreled foam ear tip for simultaneous monaural presentation. The order of presentation of the conditions was randomized across participants to control potential order effects. One ear was tested and the choice of test ear was counterbalanced across participants. Stimuli and masker were presented ipsilaterally and simultaneously to the test ear through ER-3A insert earphones, with an equal number of right and left ears. The recording order of AMLRs and ALLRs was also counterbalanced across participants. If one ear only met the inclusion criteria, that ear was chosen.

The presentation levels of stimuli and masker were calibrated acoustically with a sound level meter (Larson Davis System 824, Serial 1756) through an ER3-A insert earphone, connected to a $2cm^3$ coupler (Brüel and Kjær, type 4152). Each stimulus will be calibrated at the "linear (flat)" weighting set to Leq mode and the masker at the "A" weighting scale with Leq mode setting.

4.2.3. Data Analysis

For the purpose of this study, amplitude and latency measures recorded at electrode Cz were analyzed. Amplitudes were measured from baseline to peak (Figure 4-5). If the wave had a single peak, the amplitude was measured at the point of the largest peak and latency was marked at the center of the peak. If the wave had multiple peaks, the largest peak was taken and the latency was measured at the midpoint between the preceding and following negative peaks. For example, Pa latency was marked at the mid-point between Na (the largest preceding negative peak) and Nb (the largest following negative peak) (Figure 4-6). AMLR Pa response to syllable /ba/ displayed double peaks, in which the first peak may correspond to the onset of stop burst /b/ and the second peak may correspond to the onset of vowel /a/. The analysis of AMLRs was limited to Pa and the ALLRs were analyzed for N1, P2, and N2.

The latency windows of peaks were quite wide because ERP responses can be delayed for the effects of following factors: stimulus type (tone bursts vs speech /ba/), masking, aging and presbycusis, and/or considerable individual variability. Pa was identified as the maximum vertex-positive peak preceding Nb, occurring between 20 and 50 ms after stimulus onset. N1 was identified as the largest negative deflection between 70 and 200 ms after stimulus onset. P2 was identified as the largest positive peak between N1 and 300 ms. N2 was identified as the negative deflection following P2 and before 400 ms. Amplitudes and latencies were respectively obtained by averaging the replicated waveforms of each recording. ERP components were marked and labeled by two judges including a primary investigator and a doctoral student who was proficient in ERP analysis. The inter-rater reliability was assessed for one-third of the data by determining percent agreement between two judges. The judges were in agreement on 95 % of the markings.

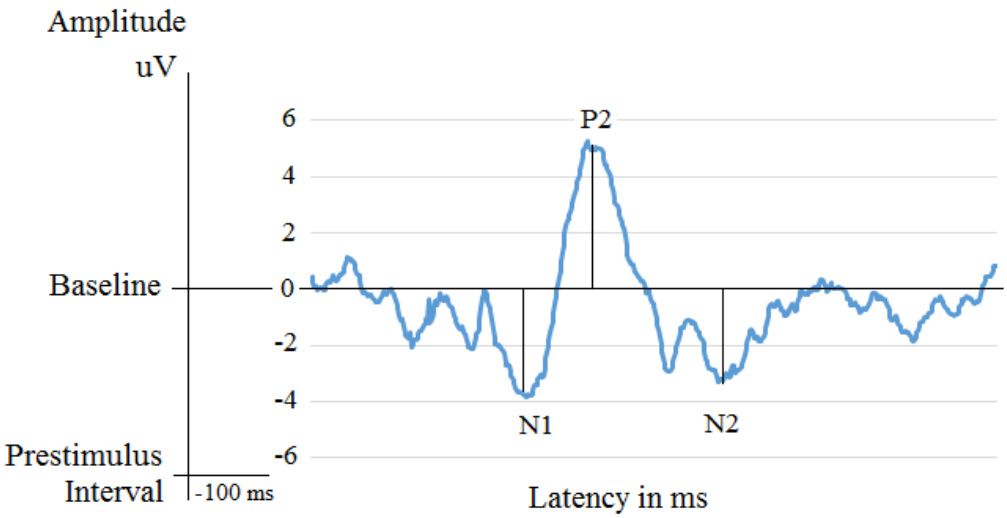


Figure 4.5. Amplitude measurement from baseline to peak. An example of ALLR waveform elicited by 500 Hz tone bursts from one young normal-hearing subject. Horizontal line at 0 represents baseline and (-) 100 ms before onset of response represents prestimulus interval.

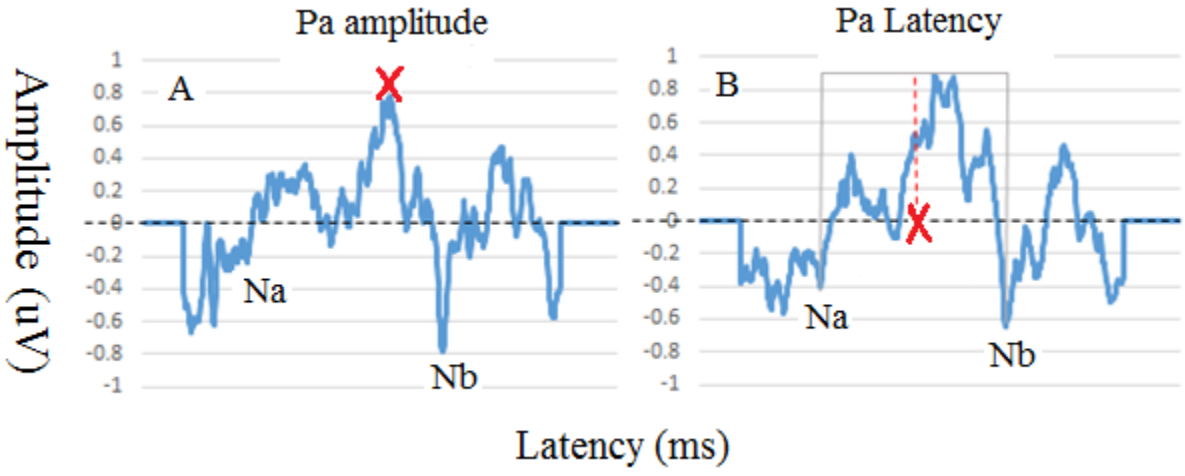


Figure 4.6. (A) Pa amplitude with multiple peaks, (B) Pa latency with multiple peaks. An example of AMLR waveform elicited by speech syllable /ba/ from one young normal-hearing subject. Double-peaked response to the consonant-vowel syllable /ba/ is a combination of the responses to the onsets of the two constituent phonemes, the stop /b/ and the vowel /a/.

A separate three-way mixed ANOVA [group x stimulus type x noise condition] was applied to analyze the effects of aging (YNH vs. ONH) and age-related hearing loss (ONH vs. OHI) on amplitudes and latencies of AMLR Pa and N1, P2, and N2 of ALLRs as a function of stimulus type and noise condition. Post-hoc pairwise comparisons were carried out for significant main effects and interactions using Bonferroni correction. All results were considered significant if $p<.05$.

In addition, Pearson's Correlation Coefficient (r) between Pa component of AMLRs and each of ALLR components (N1, P2, N2) was computed to determine if there exist any correlation between Pa, early stage of neural processing in the central auditory pathway, and respective components of ALLRs, later stage of neural processing originating from cortical area. Scatterplots were created to show the patterns of relationships of neural connection between AMLRs and ALLRs. Correlation was significant at the 0.01 level (2-tailed).

4.3. Experiment 2: Speech Perception in Noise Test

4.3.1. Materials

The Revised Speech Perception in Noise (R-SPIN) test (Kalikow et al, 1977; Bilger et al., 1984) is a sentence test which measures the contribution of contextual information to the word recognition skills. R-SPIN test is composed of 50 test sentences, 25 High-Predictability (HP) and 25 Low-Predictability (LP) sentences. Each of sentences contains five to eight words, ending with a monosyllabic noun called the "key word". R-SPIN-HP sentences provide several syntactic and semantic cues as to the identity of the final key word (e.g., "The guests were welcomed by the HOST"). R-SPIN-LP sentences provide little or no information about the final word (e.g., "Bill heard we asked about the HOST"). An example of R-SPIN test is provided in

Appendix D. In R-SPIN-LP sentences, the only cue to the final word is the word itself, but in SPIN-HP sentences, the other words in the sentence may help the listener to identify the word. SPIIN-HP sentences measure utilization of semantic/syntactic contextual clues (top-down processing) in the recognition of reduced acoustic information, whereas R-SPIN-LP sentences measure basic word recognition skills to process acoustic cues (bottom-up processing). When bottom-up auditory processing of the incoming acoustic signal is impoverished, top-down processing may enable compensation insofar as stored knowledge facilitate the listener' ability to make up for the degraded incoming acoustic information (Craik, 2007). Therefore, the compensatory rebalancing of top-down and bottom-up processing is more marked for older adults (Pichora-Fuller, 2008), resulting in similar R-SPIN-HP performance outcomes to those obtained by young adults. In other words, in the absence of contextual cues, the loss or distortion of acoustic inputs involving auditory (temporal) processing deficits may account for poor speech-in-noise perception in older adults.

The speech sentences were recorded onto the first channel, accompanied by the babble noise on the second channel of the R-SPIN test compact disc. Extreme care was taken to insure that the sentences and the babble were recorded at exact the same RMS level. A 1000 Hz calibration tone was placed at the beginning of each channel, equal to the long-term RMS level.

4.3.2. Procedure

R-SPIN test (Bilger et al., 1984) was administered to each subject via a Grason-Stadler GSI 61 audiometer and delivered through ER-3A insert earphones. Standard administration of R-SPIN test was easily possible using recorded materials. The recorded materials include sentence materials spoken by a practiced, male talker with standard American dialect and a

babble of 12 talkers simultaneously reading continuous texts. Each subject was tested for both ears separately (right ear and then left, or vice versa) and provided verbal responses to one 50-item list that consists of 25 HP and 25 LP items. The speech sentences were presented at the level of 50 dB SL with reference to babble threshold, accompanied by the babble noise presented with the level of 8 dB lower than the presentation level of speech (i.e. dB S/B ratio of +8 dB). The babble threshold was obtained by audiometric threshold test of the babble noise. The listener was asked to listen to R-SPIN sentences in the presence of babble noise and then repeat back the last word of each sentence. The order in which the ears were tested was counterbalanced and R-SPIN test list was chosen at random. Each track was calibrated with 1000 Hz tone to adjust both the speech track and the babble track to 0 VU.

4.3.3. Data Analysis

Older adults have more difficulty perceiving the acoustic properties of the speech signal in the presence of interfering background sounds and may take more advantage of contextual information to compensate for speech with significantly reduced acoustic cues (Bilger, 1984; Elliot, 1995; Owen, 1981; Morgan, Kamm, & Velde, 1981). Indeed, older adults have demonstrated similar R-SPIN-HP scores but significantly lower R-SPIN-LP scores compared to the young adults, resulting in the larger mean difference between HP and LP scores (Owen, 1981; Schum, 1992; Kewley-Port, Burkle, & Lee, 2007). Therefore, R-SPIN-LP items may serve as more sensitive measures of basic auditory processing skills in older adults (Owen, 1981), allowing no advantage of top-down or knowledge-based resources . R-SPIN-PL scores were only calculated to examine the correlation with auditory evoked potentials. The correlation between R-SPIN-LP scores and auditory evoked potentials was computed to find electrophysiological correlates of speech-in-noise perception.

The number of correct responses to R-SPIN-LP items was counted and computed as a percentage. Pearson's Correlation Coefficient (r) was applied to evaluate the correlation between the R-SPIN-LP scores and the amplitude or latency of auditory evoked potentials (Pa, N1, P2, and N2). Scatterplots were also created to identify the pattern of relationship.

Chapter 5:

Results

5.1. Descriptive Data for Three Listener Groups

To determine the effects of aging and peripheral hearing loss produce on morphological changes in AEP responses, we measured amplitudes and latencies of Pa in AMLRs and N1, P2, and N2 in ALLRs for the following three listener groups: young normal- hearing adults (YNH group), older adults with near-normal hearing (ONH group), and older hearing-impaired adults (OHI group).

The representative AMLR waveforms from three individuals (one from each of the three groups) are provided in Figure 5.1-1. AMLR waveforms represent Pa components elicited by 500 Hz tone burst and syllable /ba/ in quiet and in babble for three listener groups. OHI and ONH groups showed the overall enhancements of AMLR waveforms for both 500 Hz tone burst and syllable /ba/ in both quiet and babble, compared with YNH. OHI group showed slightly enhanced waveforms for both stimulus types in both noise conditions. The representative ALLR waveforms from three individuals are provided in Figure 5.1-2. ALLR waveforms represent N1, P2, and N2 components elicited by 500 Hz tone burst and syllable /ba/ in quiet and in babble. Similar to AMLR waveforms, ALLR waveforms were enhanced for both 500 Hz tone burst and syllable /ba/ in both quiet and babble in OHI group, compared with ONH, which showed enhanced waveforms compared with YNH group.

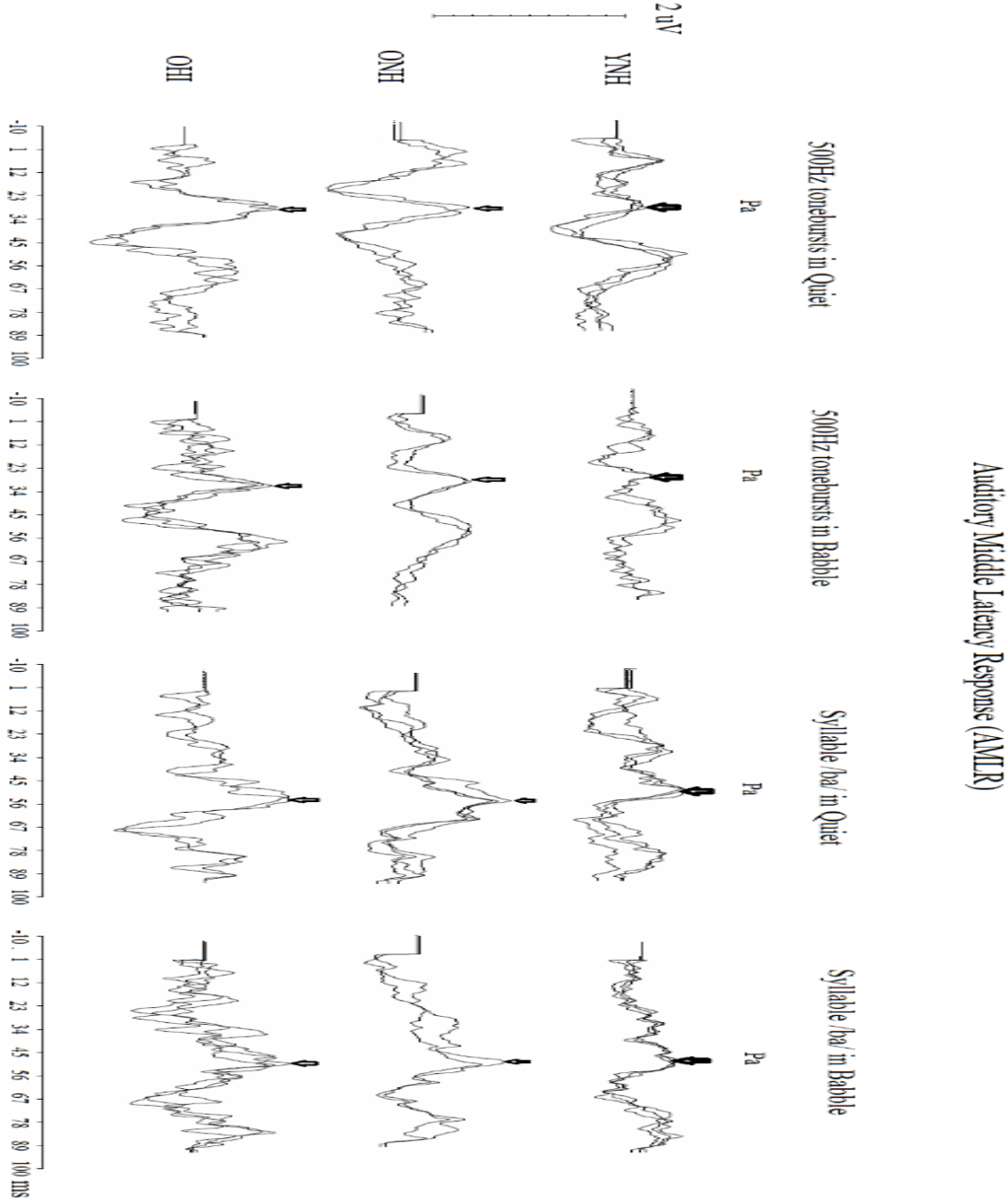


Figure 5.1-1. Representative example of **AMLR** waveforms from three individuals, one from each listener group. The abscissa axis denotes analysis time window (ms). Bold arrows mark the largest positive peak (Pa), which occurs around at 30-40 ms for 500 Hz tone burst and 40-50 ms for syllable /ba/. The mark peaks indicate a maximum base-to-peak amplitude. OHI (order adults with hearing loss) and ONH (older adults with near-normal hearing) groups show overall enhancements of AMLR waveforms in both quiet and babble, compared with YNH group. OHI group shows slightly enhanced waveforms compared with ONH group.

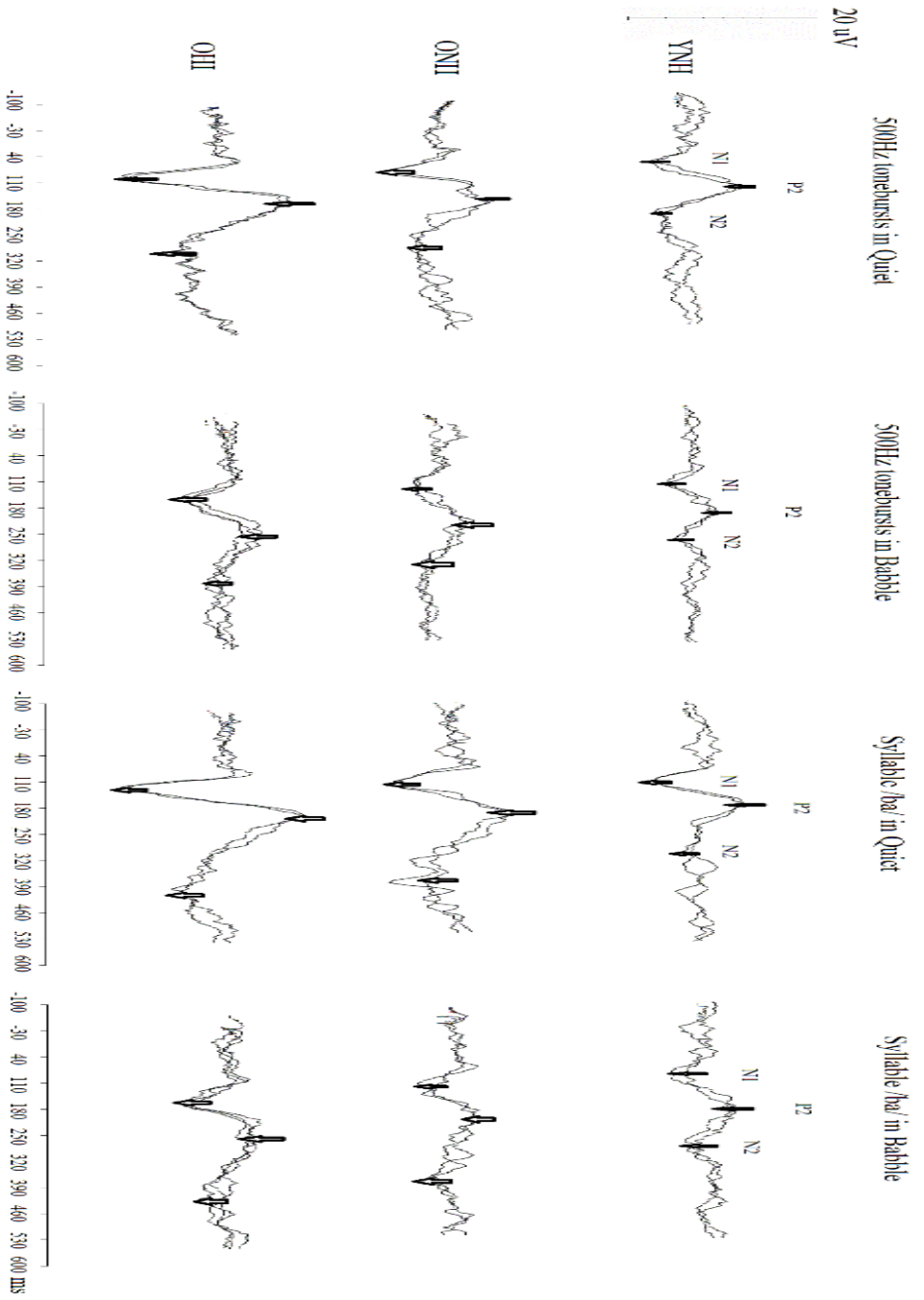


Figure 5.1-2. Representative example of **ALLR** waveforms from three individuals, one from each listener group. The abscissa axis denotes analysis time window (ms). Bold arrows mark the first large negative peak (N1, 80-130 ms) to the following positive peak (P2, 140-210 ms), and the second large negative peak (N2, 240-390 ms). The marked peaks indicate a maximum base-to-peak amplitude. OHI (order adults with hearing loss) group shows overall enhancements of ALLR waveforms for both 500 Hz tone burst and syllable /ba/ in both quiet and babble, compared with both ONH (older adults with near-normal hearing) and YNH (young normal-heraing adults) groups. ONH group shows enhanced waveforms compared with YNH group.

Table 5.1-1.

Mean amplitudes (μV) of Pa of AMLRs and N1, P2, and N2 of ALLRs (standard deviations of the mean) as a function of stimulus type (i.e., 500Hz vs. /ba/), noise condition (i.e., Quiet vs. Babble), and group (i.e., YNH, ONH, and OHI).

Amplitudes (μV)			**AMLRs**	**ALLRs**		
Group	Noise	Stim.	Pa	N1	P2	N2
YNH	Quiet	500Hz	.44 (.17)	-3.66 (1.21)	4.82 (2.04)	-3.89 (1.33)
(N=30)		/ba/	.59 (.12)	-4.38 (1.44)	3.88 (1.56)	-3 (.9)
	Babble	500Hz	.39 (.14)	-2.91 (1.01)	2.66 (1.1)	-2.42 (.92)
		/ba/	.48 (.11)	-3.46 (1.01)	2.72 (.85)	-2.29 (.61)
Overall/Grand Mean			**.48 (.15)**	**-3.6 (1.28)**	**3.52 (1.7)**	**-2.9 (1.15)**
ONH	Quiet	500Hz	.73 (.25)	-5.36 (2.34)	5.13 (2.75)	-4.07 (1.48)
(N=26)		/ba/	.88 (.24)	-6.18 (2.38)	4.67 (2.14)	-3.47 (1.11)
	Babble	500Hz	.51 (.19)	-3.67 (1.78)	2.9 (1.8)	-2.43 (1.05)
		/ba/	.79 (.25)	-4.33 (1.8)	2.94 (1.65)	-2.36 (.94)
Overall/Grand Mean			**.73 (.27)**	**-4.89 (2.28)**	**3.91 (2.32)**	**-3.08 (1.36)**
OHI	Quiet	500Hz	.76 (.32)	-6.09 (2.73)	5.47 (2.36)	-4.52 (1.19)
(N=26)		/ba/	.9 (.17)	-7.22 (2.86)	5.34(1.72)	-3.91 (.96)
	Babble	500Hz	.63 (.3)	-3.79 (1.32)	2.91 (1.35)	-2.55 (.67)
		/ba/	.87 (.24)	-4.93 (1.82)	3.53 (1.36)	-2.68 (.84)
Overall/Grand Mean			**.79 (.28)**	**-5.51 (2.58)**	**4.31 (2.05)**	**-3.41 (1.24)**

Table 5.1-2.

Mean latencies (ms) of Pa of AMLRs and N1, P2, and N2 of ALLRs (standard deviations of the mean) as a function of stimulus type (i.e., 500Hz vs. /ba/), noise condition (i.e., Quiet vs. Babble), and group (i.e., YNH, ONH, and OHI).

Latencies (μV)			**AMLRs**	**ALLRs**		
Group	Noise	Stim.	Pa	N1	P2	N2
YNH	Quiet	500Hz	31.77 (3.57)	89.69 (9.77)	148.39 (12.41)	249 (20.72)
(N=30)		/ba/	38.11 (2.29)	108.19 (8.03)	171.95 (7.31)	287.79 (32.77)
	Babble	500Hz	32.99 (3.1)	101.15 (8.95)	165.01 (18.42)	284.56 (28.23)
		/ba/	39.71 (2.99)	120.94 (9.15)	198.69 (19.69)	339.62 (31.85)
Overall/Grand Mean			**35.65 (4.49)**	**104.99 (14.44)**	**171.01 (23.65)**	**290.24 (43.14)**
ONH	Quiet	500Hz	33.27 (2.28)	92.46 (7.09)	154.72 (20.17)	272.28 (25.28)
(N=26)		/ba/	43.04 (3.92)	110.87 (6.79)	174.57 (12.69)	324.39 (28.25)
	Babble	500Hz	33.78 (2.61)	105.54 (9.93)	186.98 (21.57)	325.94 (29.39)
		/ba/	45.24 (4.4)	122.38 (6.17)	200.51 (17.13)	367.65 (16.99)
Overall/Grand Mean			**38.83 (6.36)**	**107.81 (13.16)**	**179.19 (24.67)**	**322.57 (42.23)**
OHI	Quiet	500Hz	33.27 (4.33)	95.5 (8.37)	156.97 (16.7)	284.93 (29.73)
(N=26)		/ba/	44.79 (3.64)	112.33 (8.33)	177.13 (11.91)	352.84 (27.52)
	Babble	500Hz	33.82 (4.19)	109.11 (9.48)	191.52 (21.17)	344 (36.02)
		/ba/	46.42 (3.68)	124.31 (8.28)	204.62 (27.4)	383.19 (29.26)
Overall/Grand Mean			**39.58 (7.24)**	**110.31 (13.36)**	**182.56 (26.63)**	**341.24 (46.92)**

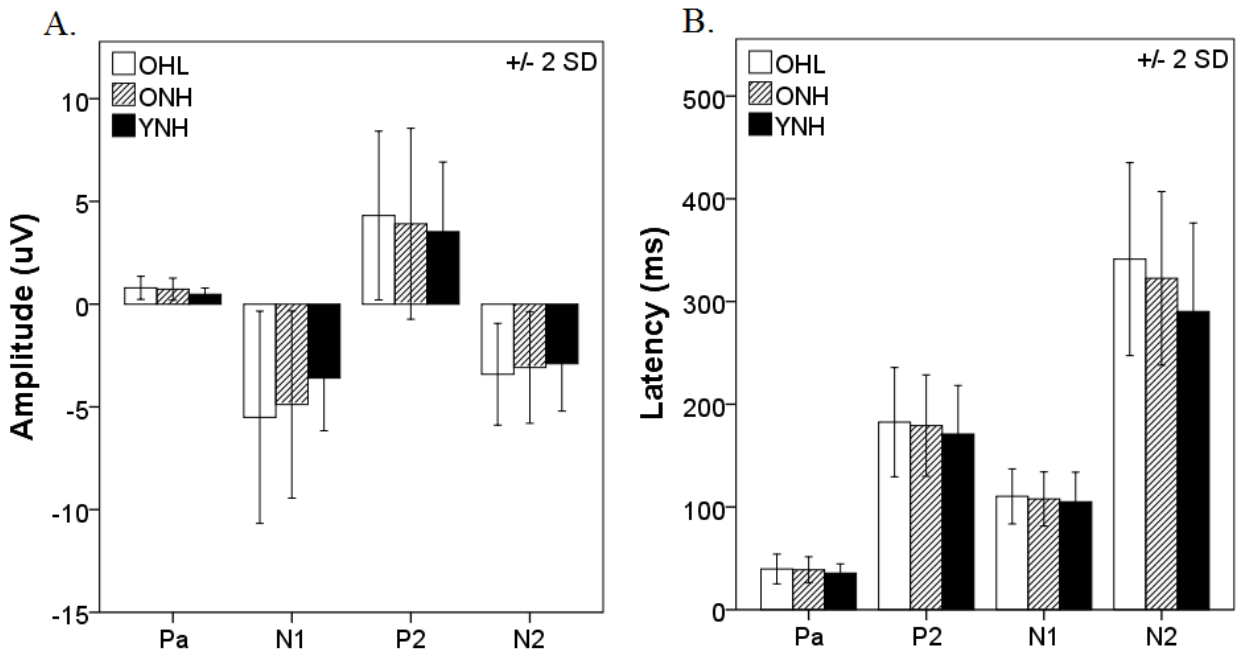


Figure 5.1-3. (A) Mean difference in the amplitudes of each AEP component among three listener groups. The largest amplitudes across all components in older hearing-impaired (OHI, open bar), followed by older adults with near-normal hearing (ONH, hatched bar), and young normal-hearing (YNH, black bar) group. The abscissa denotes the wave components and the ordinate denotes the amplitude. (B) Mean difference in the latencies of each AEP component among three listener groups. The most prolonged latencies across all components in OHI, followed by ONH, and YNH group. Later components shows more pronounced difference in the latencies among listener groups. The abscissa denotes the AEP components and the ordinate denotes the latency. Error bars indicate ±2 standard deviations.

Table 5.1-1 presents means and standard deviations for amplitudes of each AEP component. The amplitudes of all AEP components were the most enhanced in OHI, followed by ONH and YNH group, in descending order, as graphically shown in Figure 5.1-3 (A). In line with enhanced amplitudes, the latencies of all AEP components were the most prolonged in OHI, followed by ONH and YNH group, in descending order, as graphically shown in Figure 5.1-3 (B).

5.2. Effects of Aging and Hearing Loss on AMLRs and ALLRs

To test the first hypothesis that peripheral hearing loss and aging may have differential effects on morphological changes in AEP components (Pa, N1, P2 and N2), we examined the amplitudes and latencies as a function of stimulus type (500 Hz tone burst, syllable /ba/) and noise condition (quiet, babble) by comparing YNH and ONH groups (i.e., effects of aging) and by comparing ONH and OHI groups (i.e., effects of hearing loss). Finally, we determined the combined effects of aging and hearing on AEP morphology to find how the effects of aging on AEP morphology alter in combination with hearing loss.

5.2.1. Effects of aging on AEP amplitudes

The effects of aging on AEP amplitudes were determined by testing group difference between YNH and ONH groups in the amplitudes of each AEP component, with tests of two-factor within-subject effects (stimulus type × noise conditions), using three-factor mixed ANOVA. Table 5.2-1 presents the summary of the ANOVA analyses on amplitudes of each AEP component for YNH and ONH groups.

Pa and N1 amplitudes were significantly different between YNH and ONH groups, indicating the effects of aging on Pa and N1 amplitudes. P2 and N2 amplitudes, however, were not significantly different between listener groups, indicating no effects of aging on P2 and N2 amplitudes. The group differences in the amplitudes of each AEP component were depicted in Figure 5.2-1. ONH group demonstrated significantly enhanced Pa and N1 amplitudes compared with YNH group. However, P2 and N2 amplitudes were not significantly enhanced in ONH relative to YNH group. The significant age-related enhancements of amplitudes were thus found in Pa and N1 components for ONH compared with YNH group.

Table 5.2-1.

Analyses on the effects of aging: ANOVA summary table for the amplitudes (μV) of Pa, N1, P2, and N2 as a function of stimulus type (500 Hz vs. /ba/), noise condition (Quiet vs. Babble), and listener group (YNH vs. ONH).

Source	*df*	Error	*F*	*p*-value
Pa				
Group	1	54	42.511	<.0001 *
Stimulus Type	1	54	37.778	<.0001*
Noise Condition	1	54	96.451	<.0001*
Stimulus x Noise	1	54	2.943	.092
Stimulus x Group	1	54	2.930	.093
Noise x Group	1	54	9.082	.004*
Stimulus x Noise x Group	1	54	20.135	<.0001*
N1				
Group	1	54	9.867	.003*
Stimulus Type	1	54	42.732	<.0001*
Noise Condition	1	54	108.290	<.0001*
Stimulus x Noise	1	54	1.176	.283
Stimulus x Group	1	54	.237	.629
Noise x Group	1	54	13.946	<.0001*
Stimulus x Noise x Group	1	54	.000	.983
P2				
Group	1	54	.796	.376
Stimulus Type	1	54	7.010	.011*
Noise Condition	1	54	168.971	<.0001*
Stimulus x Noise	1	54	18.989	<.0001*
Stimulus x Group	1	54	.871	.355
Noise x Group	1	54	1.284	.262
Stimulus x Noise x Group	1	54	2.306	.135
N2				
Group	1	54	.557	.459
Stimulus Type	1	54	19.504	<.0001*
Noise Condition	1	54	178.872	<.0001*
Stimulus x Noise	1	54	20.989	<.0001*
Stimulus x Group	1	54	.905	.346
Noise x Group	1	54	2.418	.126
Stimulus x Noise x Group	1	54	.600	.442

* Significant at $p < .05$

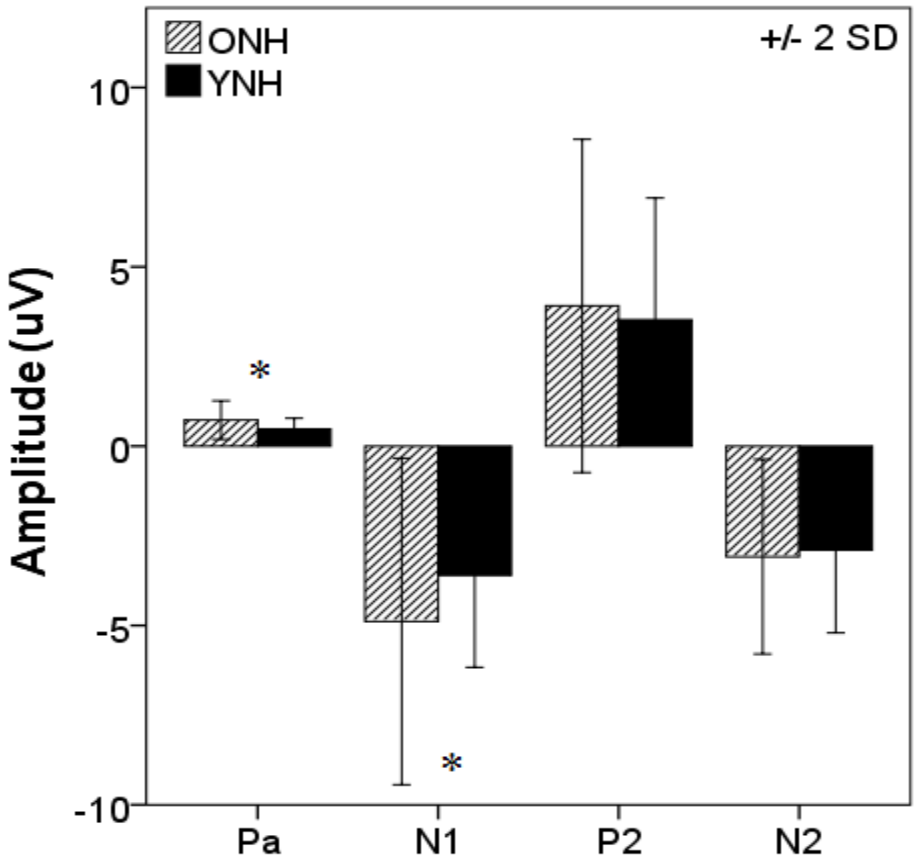


Figure 5.2-1. Group mean difference in the amplitudes of each AEP component. There were significant group differences in the amplitudes of Pa and N1 components, indicating the effects of aging on changes in AEP amplitudes. Older adults with near-normal hearing (ONH, hatched bar) demonstrates larger amplitudes across all components compared with young normal-hearing adults (YNH, black bar). The abscissa denotes AEP components and the ordinate denotes the amplitude. Error bars represent ±2 standard errors of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

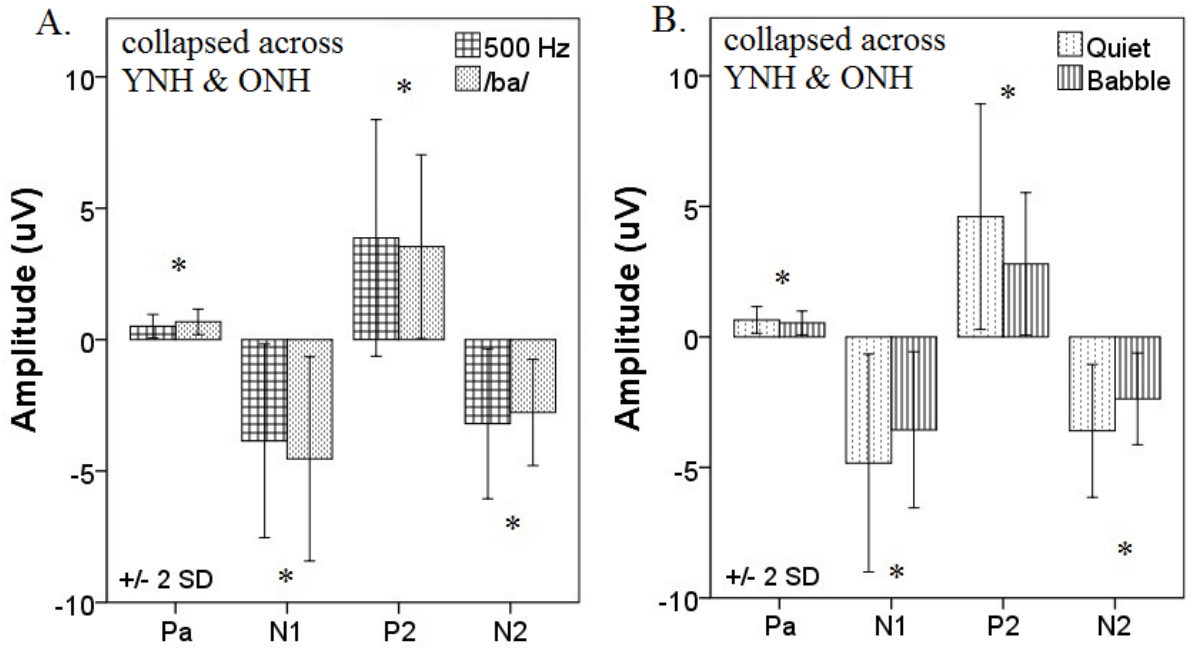


Figure 5.2-2. (A) Mean differences in the amplitudes of each AEP component as a function of stimulus type. Significantly larger Pa and N1 amplitudes for syllable /ba/ (stippled bar) vs. 500 Hz tone burst and significantly larger P2 and N2 amplitudes for 500 Hz tone burst (grid bar) vs. syllable /ba/. (B) Mean differences in the amplitudes of each AEP component as a function of noise condition. Significantly larger amplitudes in quiet (dotted bar) versus babble (vertical striped bar) across all AEP components. The abscissa denotes AEP components and the ordinate denotes the amplitude. Error bars represent ±2 standard deviations of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

There were significant main effects of stimulus type and noise condition on the amplitudes of all AEP components. The data were collapsed across YNH and ONH groups. Figure 5.2-2 (A) illustrates the main effects of stimulus type. Syllable /ba/ elicited larger Pa and N1 amplitudes and 500 Hz tone burst elicited larger P2 and N2 amplitudes for YNH and ONH groups, indicating that the acoustic features of the stimulus induce the changes in the amplitudes of all AEP components for YNH and ONH listeners. Figure 5.2-2 (B) illustrates the main effects of noise condition. The amplitudes were significantly larger in quiet than in babble across all AEP components, indicating that the noise masker induces the reductions of amplitudes for YNH and ONH groups.

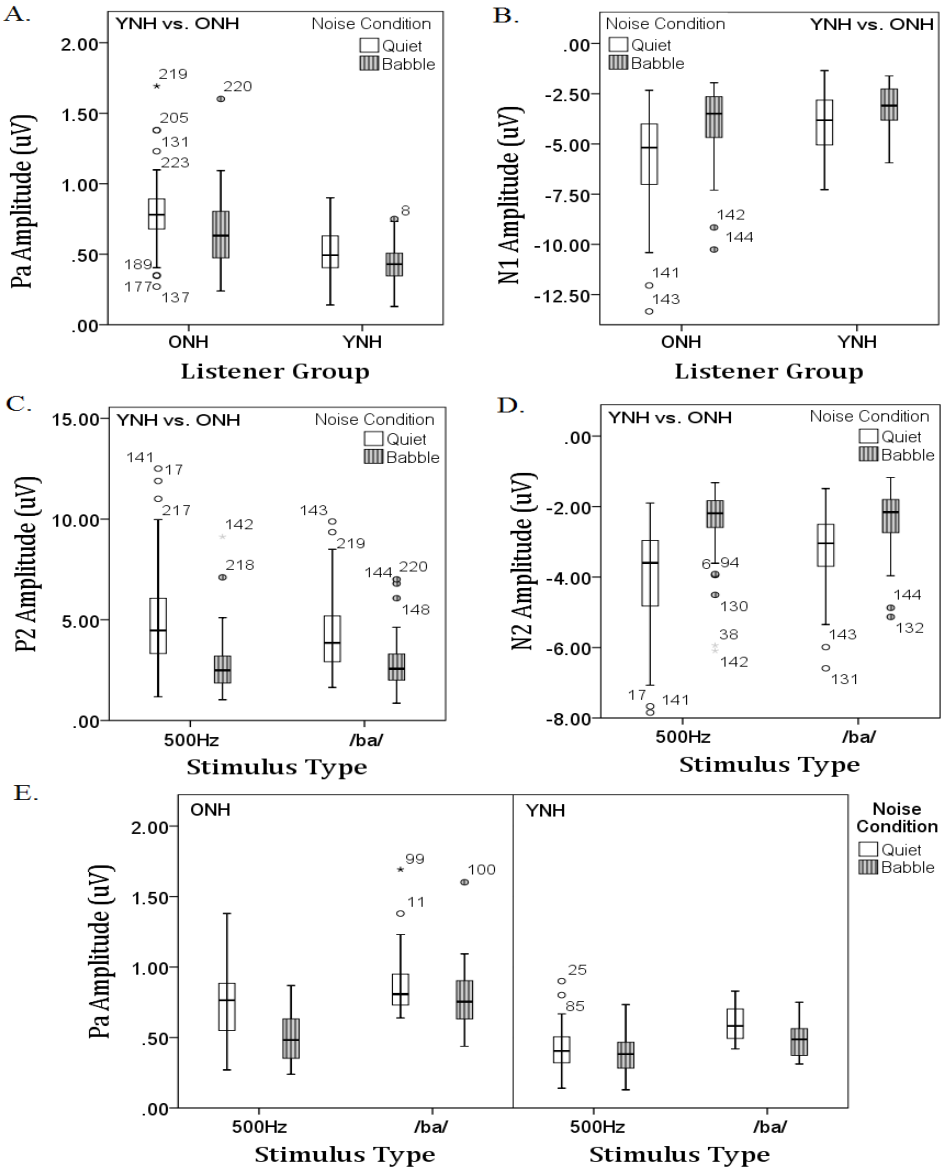


Figure 5.2-3. **Effects of interactions on the amplitudes for YNH and ONH groups**. **Upper panels**: two-way interactions of noise condition × listener group on Pa (A) and N1 (B) amplitudes. Greater reductions of Pa and N1 amplitudes in babble (gray box with vertical stripes) versus quiet (open box) for ONH group than those for YNH group. **Middle panels**: two-way interactions of stimulus type × noise condition on P2 (C) and N2 (D) amplitudes. Greater increases in P2 and N2 amplitudes for 500Hz tone burst vs. syllable /ba/ in Quite than those in babble. **Lower panels**: three-way interactions of stimulus type × noise condition × listener group on Pa amplitudes (E). For ONH group, greater reductions of Pa amplitudes in babble vs. quiet for 500 Hz tone burst than those for syllable /ba/. For YNH group, greater reductions of Pa amplitudes in babble vs. quiet for syllable /ba/ than those for 500 Hz tone burst. The box represents the range of the middle 50% of responses. The top horizontal line represents the upper 25% of responses and the bottom horizontal line represents the lower 25% of responses. The thick horizontal line in the middle of the box represents the median. Circles represent mild outliers and asterisks represent extreme outliners.

The significant two-way interactions between noise condition and listener group were found for Pa and N1amplitudes and the significant two-way interactions between stimulus type and noise condition were found for P2 and N2 amplitudes. In addition, one significant three-way interaction was found in Pa amplitudes. Figure 5.2-3 illustrates interactions. Pa amplitudes (graph A) and N1 amplitudes (graph B) showed greater reductions in babble versus quiet for ONH than those for YNH group. P2 amplitudes (graph C) and N2 amplitudes (graph D) showed greater reductions in babble versus quiet for 500 Hz tone burst than those for syllable /ba/. Gragh (E) shows that interactions between stimulus type and noise condition on Pa amplitudes are different between YNH and ONH groups. YNH group produced greater increases in Pa amplitudes for syllable /ba/ versus 500 Hz tone burst in quiet than those in babble, while ONH group produced greater increases in Pa amplitudes for syllable /ba/ versus 500 Hz tone burst in babble than those in quiet. In addition, YNH group produced greater reductions of Pa amplitudes in babble versus quiet for syllable /ba/ than those for 500 Hz tone burst, while ONH group produced greater reductions of Pa amplitudes in babble versus quiet for 500 Hz tone burst than those for syllable /ba/.

Post-hoc pairwise comparisons were conducted for the significant interactions using Bonferroni corrections to adjust the alpha level (.05). For Pa amplitudes, ONH group produced significantly reduced Pa amplitudes for 500 Hz tone burst in babble (p <.0001) than those for syllable /ba/, while YNH group produced significantly reduced Pa amplitudes for syllable /ba/ in babble (p <.0001) than those for 500 Hz tone burst. Pa amplitudes for 500 Hz tone burst showed significantly greater enahncements for ONH relative to YNH group (p <.0001) in quiet than those in babble; however, Pa amplitudes for syllable /ba/ showed significantly greater enhancements for ONH relative to YNH group in babble (p <.0001) than those in quiet.

For N1 amplitudes, ONH group produced significantly greater reductions in babble ($p < .0001$) than YNH group. N1 amplitudes were significantly enhanced for ONH relative to YNH group in quiet ($p = .001$) than in babble. P2 ($p < .0001$) and N2 amplitudes were significantly larger for 500 Hz tone burst versus syllable /ba/ in quiet [P2 ($p < .0001$), N2 ($p < .0001$)] than those in babble. Both P2 and N2 amplitudes showed significantly greater reductions in babble for 500 Hz tone burst [P2 ($p < .0001$), N2 ($p < .0001$)] than those for syllable /ba/.

5.2.2. Effects of aging on AEP latencies

The effects of aging on AEP latencies were determined by testing the group differences between YNH and ONH listeners in the latencies of each AEP component, with tests of two-factor within-subject effects (stimulus type × noise conditions), using three-factor mixed ANOVA. Table 5.2-2 presents the summary of the ANOVA analyses on the latencies of each AEP component for YNH and ONH groups.

There were significant group differences between YNH and ONH groups in Pa, P2 and N2 latencies, indicating the effects of aging on the latencies of Pa, P2 and N2 components. N1 latencies, however, were not significantly different between YNH and ONH groups, indicating no effects of aging. Figure 5.2-4 graphically shows the between-group differences in the latencies of each AEP component. ONH group showed significantly prolonged latencies of Pa, P2, and N2 components compared with YNH group. The later AEP component, the longer the age-related delay. The significant age-related prolongations of the latencies were thus found in Pa, P2, and N2 components for ONH compared with YNH group.

Table 5.2-2.

Analyses on effects of aging: ANOVA summary table for the latencies (ms) of Pa, N1, P2, and N2 as a function of stimulus type (500 Hz vs. /ba/), noise condition (Quiet vs. Babble), and listener group (YNH vs. ONH).

Source	*df*	Error	*F*	*p*-value
Pa				
Group	1	54	26.608	<.0001 *
Stimulus Type	1	54	248.478	<.0001*
Noise Condition	1	54	56.704	<.0001*
Stimulus x Noise	1	54	9.081	.004*
Stimulus x Group	1	54	14.144	<.0001*
Noise x Group	1	54	.020	.889
Stimulus x Noise x Group	1	54	3.631	.062
N1				
Group	1	54	3.110	.083
Stimulus Type	1	54	361.262	<.0001*
Noise Condition	1	54	137.344	<.0001*
Stimulus x Noise	1	54	.010	.921
Stimulus x Group	1	54	.623	.434
Noise x Group	1	54	.007	.932
Stimulus x Noise x Group	1	54	1.065	.307
P2				
Group	1	54	6.894	.011*
Stimulus Type	1	54	163.339	<.0001*
Noise Condition	1	54	146.613	<.0001*
Stimulus x Noise	1	54	.324	.572
Stimulus x Group	1	54	11.319	.001*
Noise x Group	1	54	3.133	.082
Stimulus x Noise x Group	1	54	6.092	.017*
N2				
Group	1	54	50.625	<.0001*
Stimulus Type	1	54	163.684	<.0001*
Noise Condition	1	54	156.220	<.0001*
Stimulus x Noise	1	54	.371	.545
Stimulus x Group	1	54	.000	.998
Noise x Group	1	54	.417	.521
Stimulus x Noise x Group	1	54	7.668	.008*

*Significant at $p < .05$

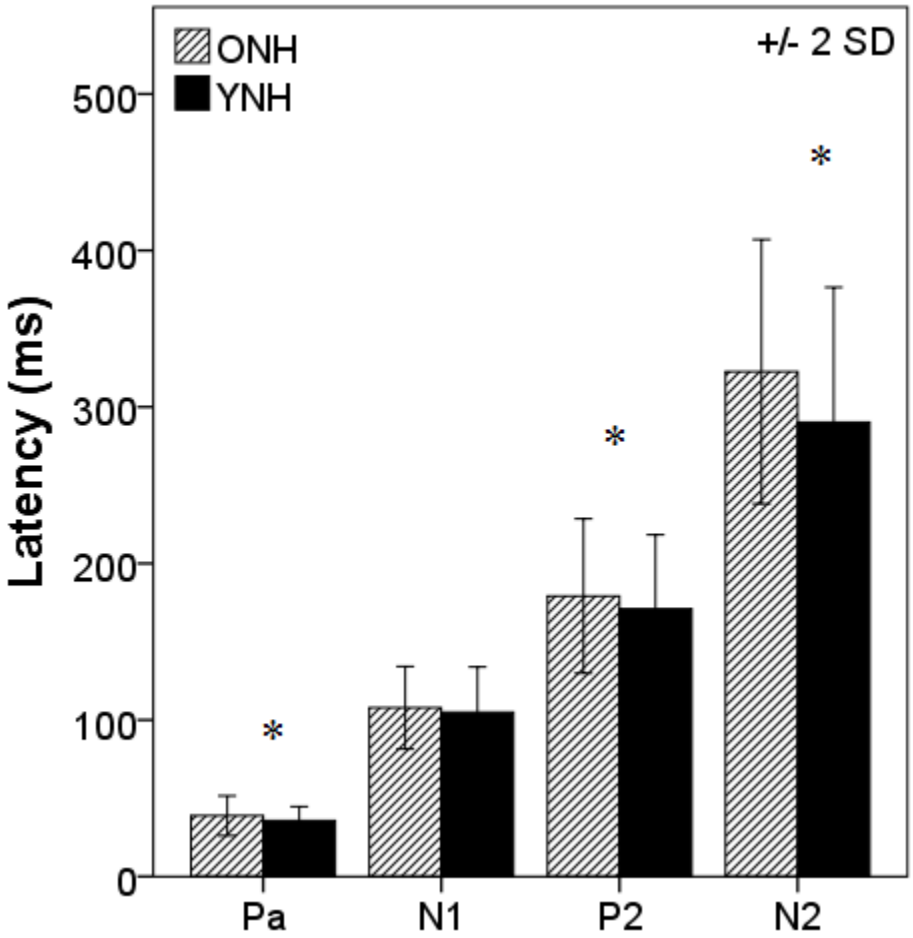


Figure 5.2-4. Group difference in the latencies of each AEP component. Significant group differences in the latencies of Pa, P2, and N2 components, indicating the effects of aging. Older adults with near-normal hearing (ONH, hatched bar) demonstrates longer latencies across all components compared with young normal-hearing group (YNH, black bar). The abscissa denotes AEP components and the ordinate denotes the latency. Error bars represent ± 2 standard deviations of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

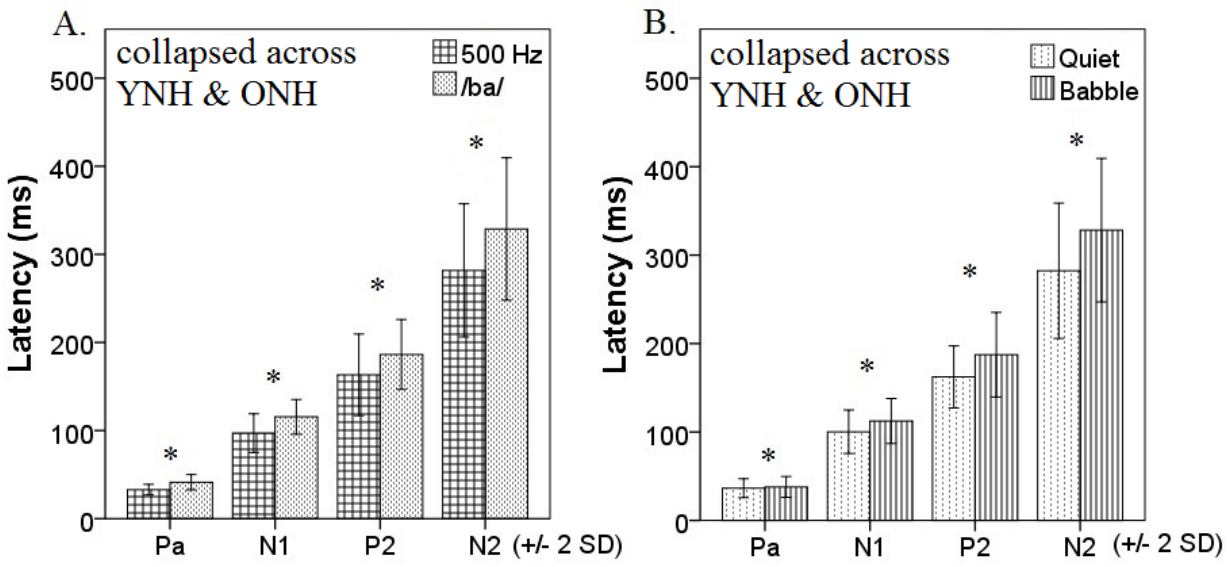


Figure 5.2-5. (A) Mean difference in the latencies of each AEP component as a function of stimulus type. Significantly longer latencies for syllable /ba/ (stippled bar) than 500 Hz tone burst (grid bar) across all AEP components. (B) Mean difference in the latencies of each AEP component as a function of noise condition. Significantly prolonged latencies in babble (vertical striped bar) versus in quiet (dotted bar) across all AEP components. The abscissa denotes AEP components and the ordinate denotes the latency. Error bars represent ±2 standard deviations of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

There were significant main effects of stimulus type and noise condition on the latencies of all AEP components. The data were collapsed across YNH and ONH groups. As depicted in Figure 5.2-5 (A), syllable /ba/ elicited significantly longer latencies than 500 Hz tone burst across all AEP components for YNH and ONH groups, indicating that the acoustic features of the stimulus induce the changes in the latencies of all AEP components for YNH and ONH listeners. As depicted in Figure 5.2-5 (B), the latencies of all AEP components were significantly prolonged in babble compared to in quiet for YNH and ONH groups, indicating that the noise masker induces the prolongations of the latencies of all AEP components for YNH and ONH listeners.

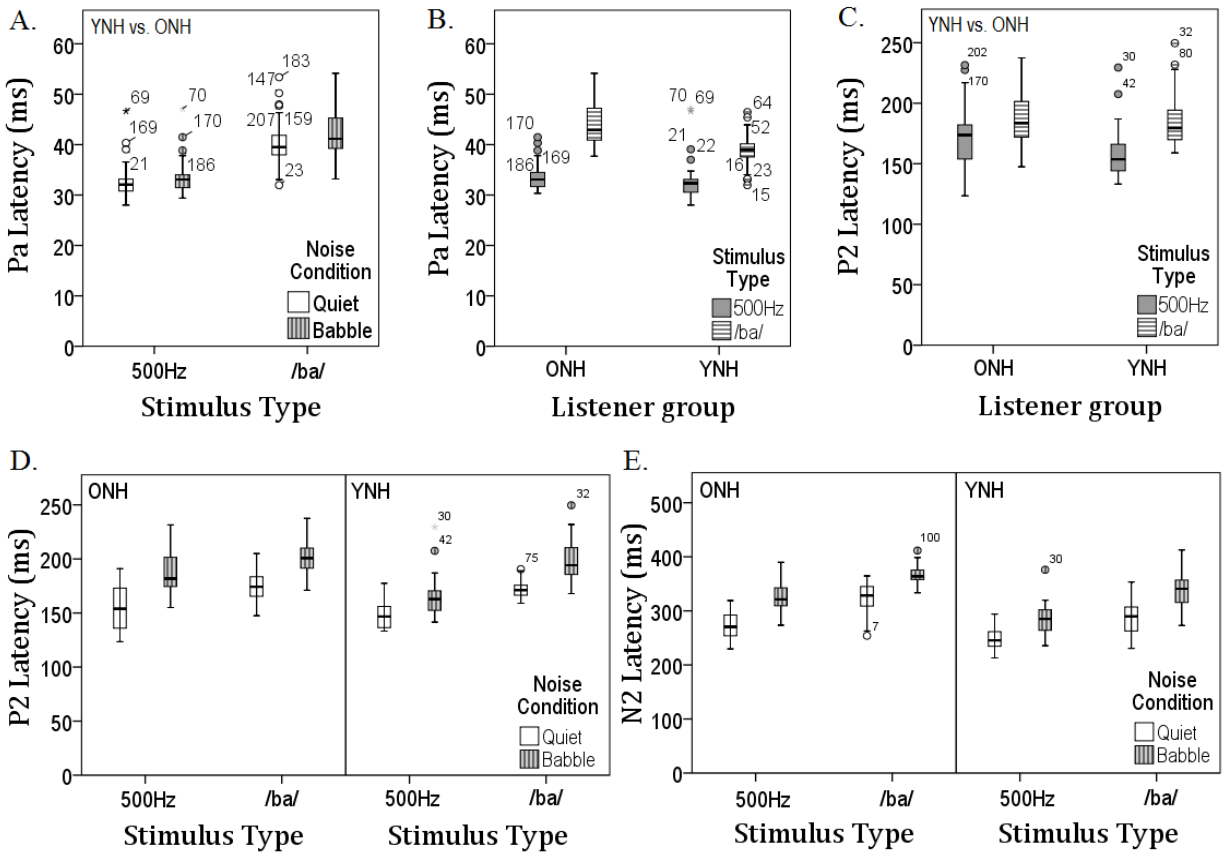


Figure 5.2-6. **Effects of interactions on the latencies for YNH and ONH groups**. **Upper panels**: Significant two-way interactions of stimulus type × noise condition (A), and interactions of listener group x stimulus type (B & C). (A) Greater prolongations of Pa latencies in babble (gray box with vertical stripes) vs. quiet (open box) for syllable /ba/ than those for 500 Hz tone burst. (B) Greater prolongations of Pa latencies for syllable /ba/ (horizontal striped box) vs. 500 Hz tone burst (gray box) in ONH group than those in YNH group. (C) Greater prolongations of P2 latencies for syllable /ba/ vs. 500 Hz tone burst in YNH group than those in ONH group. **Lower panels**: Significant three-way interactions of stimulus type × noise condition × listener group (D & E). (D) For ONH group, greater prolongations of P2 latencies in babble vs. quiet for 500 Hz tone burst than those for syllable /ba/, and greater prolongations of P2 latencies for syllable /ba/ vs. 500 Hz tone burst in quiet than those in babble. For YNH group, greater prolongations of P2 latencies in babble vs. quiet for syllable /ba/ than those for 500 Hz tone burst, and greater prolongations of P2 latencies for syllable /ba/ vs. 500 Hz tone burst in babble than those in quiet. (E) For ONH group, greater prolongations of N2 latencies in babble vs. quiet for 500 Hz tone burst than those for syllable /ba/, and greater prolongations of N2 latencies for syllable /ba/ vs. 500 Hz tone burst in quiet than those in babble. For YNH group, greater prolongations of N2 latencies in babble vs. quiet for syllable /ba/ than those for 500 Hz tone burst, and greater prolongations for syllable /ba/ vs. 500 Hz tone burst in babble than those in quiet. The box represents the range of the middle 50% of responses. The top horizontal line represents the upper 25% of responses and the bottom horizontal line represents the lower 25% of responses. The thick horizontal line in the middle of the box represents the median. Circles represent mild outliers and asterisks represent extreme outliners.

In addition, there were significant two-way interactions on Pa and P2 latencies and three-way interactions on P2 and N2 latencies. Figure 5.2-6 graphically shows the interactions. Graph (A) represents the interactions between stimulus type and noise condition on Pa latencies. There were greater prolongations of Pa latencies in babble versus quiet for syllable /ba/ than those for 500 Hz tone burst. Graph (B) represents the interactions between listener group and stimulus type on Pa latencies. There were greater prolongations of Pa latencies for syllable /ba/ versus 500 Hz tone burst in ONH than those in YNH group. Graph (C) represents the interactions between listener group and stimulus type on P2 latencies. There were greater prolongations of P2 latencies for syllable /ba/ versus 500 Hz tone burst in YNH group than those in ONH group. Graph (D) represents three-way interactions among stimulus type, noise condition, and listener group on P2 latencies. ONH produced greater prolongations of P2 latencies in babble versus quiet for 500 Hz tone burst than those for syllable /ba/, while YNH group produced greater prolongations of P2 latencies in babble versus quiet for syllable /ba/ than those for 500 Hz tone burst. Gragh (E) represents three-way interactions among stimulus type, noise condition, and listener group on N2 latencies. ONH group produced greater prolongations of N2 latencies in babble versus quiet for 500 Hz tone burst than those for syllable /ba/, while YNH group produced greater prolongations of N2 latencies in babble versus quiet for syllable /ba/ than those for 500 Hz tone burst.

Post-hoc pairwise comparisons were conducted for the interactions using Bonferroni corrections to adjust the alpha level (.05). According to the results of post-hoc analyses, Pa latencies were significantly prolonged in babble for syllable /ba/ ($p < .0001$) than 500 Hz tone burst. Pa latencies for syllable /ba/ were significantly prolonged in ONH relative to YNH group ($p < .0001$), but there was no significant difference in Pa latencies for 500 Hz tone burst between

ONH and YNH groups (p = .145). For P2 latencies, ONH group showed significantly greater prolongations of P2 latencies for syllable /ba/ versus 500 Hz tone burst in quiet (p < .0001) than those in babble, while YNH group showed significantly greater prolongations of P2 latencies for syllable /ba/ versus 500 Hz tone burst in babble (p < .0001) than those in quiet.

the age-related prolongations of P2 latencies in ONH versus YNH group were significantly greater for 500 Hz tone burst in babble (p < .0001) than the prolongations of other P2 latencies (i.e., 500 Hz tone burst in quiet, and syllable /ba/ in quiet and in babble). For N2 latencies, ONH group produced significantly greater prolongations of N2 latencies in babble versus quiet for 500 Hz tone burst (p < .0001) than those for syllable /ba/, while YNH group produced significantly greater prolongations of N2 latencies in babble versus quiet for syllable /ba/ (p < .0001) than those for 500 Hz tone burst. The age-related prolongations of N2 latencies in ONH versus YNH group were significantly greater for 500 Hz tone burst in babble (p < .0001) than the prolongations of other N2 latencies (i.e., 500 Hz tone burst in quiet, and syllable /ba/ in quiet and babble).

5.2.3. Effects of hearing loss on AEP amplitudes

The effects of hearing loss on AEP amplitudes were determined by testing the group differences between ONH and OHI listeners in the amplitudes of each AEP component, with tests of two-factor within-subjects effects (stimulus type × noise condition), using three-factor mixed ANOVA. Table 5.2-3 presents the summary of the ANOVA analyses on the amplitudes of each AEP component for ONH and OHI groups.

Table 5.2-3.

Analyses on the effects of hearing loss: ANOVA summary table for the amplitudes (μV) of Pa, N1, P2, and N2 as a function of stimulus type (500 Hz vs. /ba/), noise condition (Quiet vs. Babble), and listener group (ONH vs. OHI).

Source	*df*	Error	*F*	*p*-value
Pa				
Group	1	50	1.262	.267
Stimulus Type	1	50	45.139	<.0001*
Noise Condition	1	50	65.182	<.0001*
Stimulus x Noise	1	50	18.236	<.0001*
Stimulus x Group	1	50	.233	.632
Noise x Group	1	50	5.812	.020*
Stimulus x Noise x Group	1	50	.447	.507
N1				
Group	1	50	1.271	.265
Stimulus Type	1	50	57.914	<.0001*
Noise Condition	1	50	101.047	<.0001*
Stimulus x Noise	1	50	.229	.634
Stimulus x Group	1	50	2.622	.112
Noise x Group	1	50	1.666	.203
Stimulus x Noise x Group	1	50	.293	.591
P2				
Group	1	50	.653	.423
Stimulus Type	1	50	.018	.893
Noise Condition	1	50	177.746	<.0001*
Stimulus x Noise	1	50	17.157	<.0001*
Stimulus x Group	1	50	3.904	.054
Noise x Group	1	50	.436	.512
Stimulus x Noise x Group	1	50	.803	.375
N2				
Group	1	50	1.691	.199
Stimulus Type	1	50	10.315	.002*
Noise Condition	1	50	251.750	<.0001*
Stimulus x Noise	1	50	23.643	<.0001*
Stimulus x Group	1	50	.256	.615
Noise x Group	1	50	1.329	.254
Stimulus x Noise x Group	1	50	.624	.433

*Significant at $p < .05$

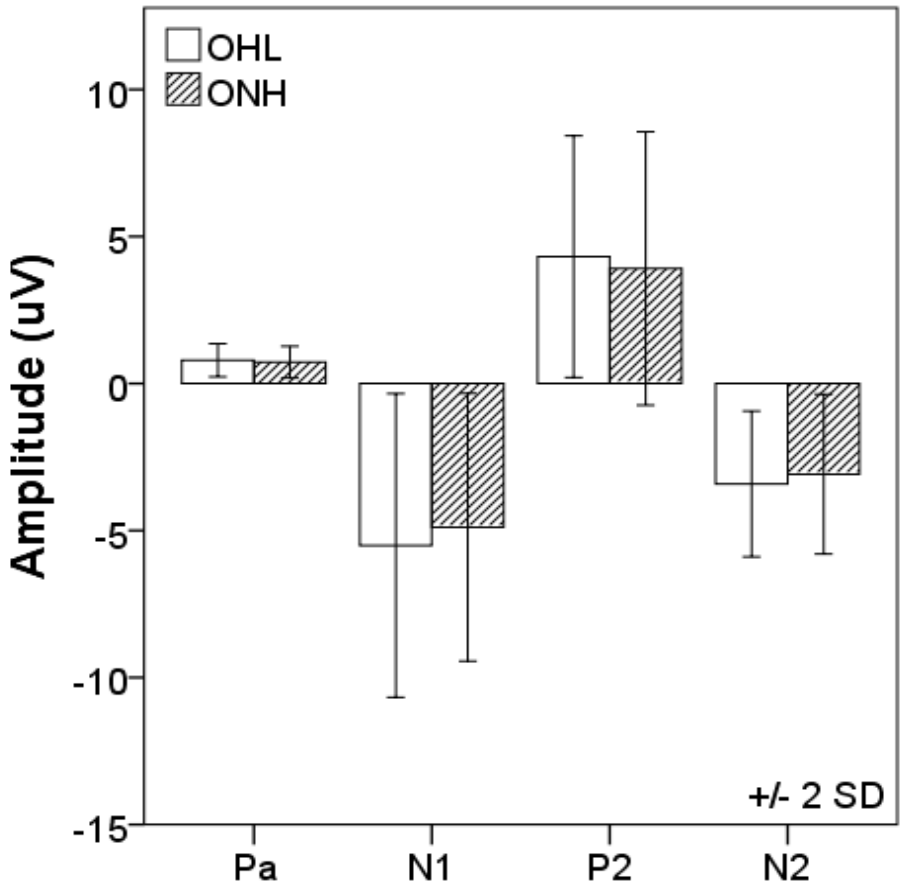


Figure 5.2-7. Group mean difference in the amplitudes of each AEP component. Older hearing-impaired group (OHI, open bar) demonstrates enhanced amplitudes across all AEP components relative to older adults with near-normal hearing (ONH, hatched bar). However, there were no statistically significant group differences in the amplitudes across all AEP components, indicating no effects of peripheral hearing loss on amplitude enhancement. The abscissa denotes AEP components and the ordinate denotes the amplitude. Error bars represent +/- 2 standard deviations of the mean. The mean difference was not significant at the .05 level.

There were no significant group differences between ONH and OHI groups in the amplitudes across all AEP components, indicating no effects of hearing loss on the enhancement of AEP amplitudes. Figure 5.2-7 graphically shows the group differences between ONH and OHI groups in the amplitudes of each AEP component. OHI group produced slightly but insignificantly enhanced amplitudes across all AEP components. No significant enhancements of amplitudes associated with hearing loss were found in all AEP components.

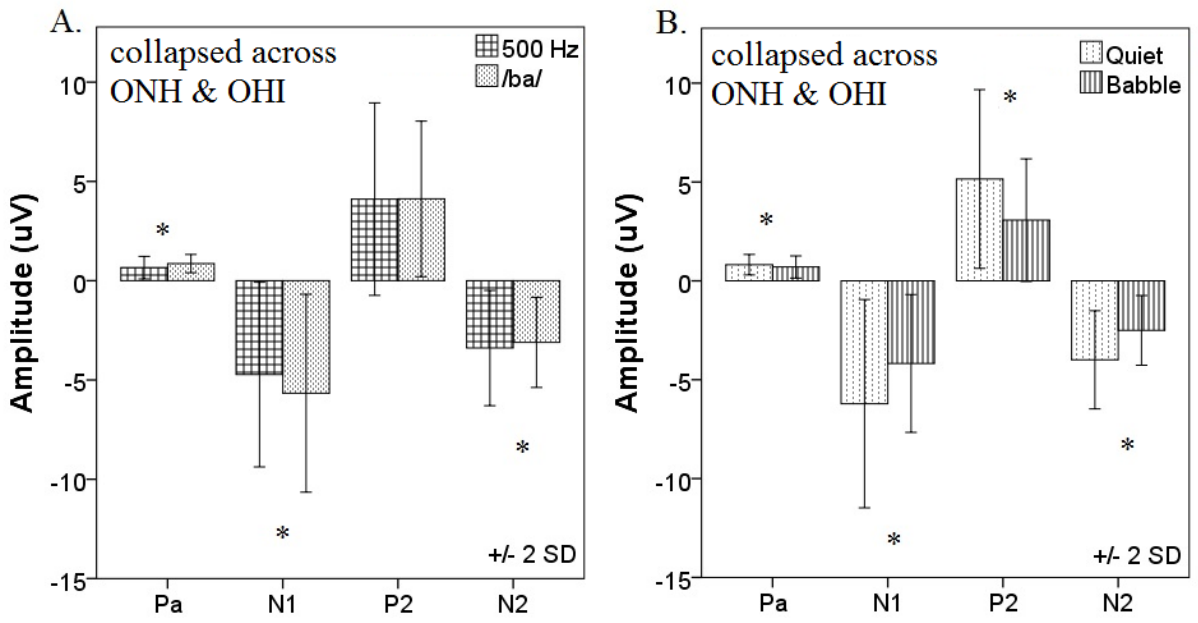


Figure 5.2-8. (A) Mean difference in the amplitudes of each AEP component as a function of stimulus type. Syllable /ba/ (stippled bar) elicited significantly larger Pa and N1 amplitudes and 500 Hz tone burst (grid bar) elicited significantly larger N2 amplitudes. P2 amplitudes for 500 Hz tone burst were not significantly different from those for syllable /ba/. (B) Mean difference in the amplitudes of each AEP component as a function of noise condition. Significantly larger amplitudes in quiet (dotted bar) than babble (vertical striped bar) across all AEP components. The abscissa denotes the AEP components and the ordinate denotes the amplitude. Error bars represent ±2 standard deviations of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

There were the significant main effects of stimulus type on the amplitudes of Pa, N1, and N2 components. The data were collapsed across ONH and OHI groups. As shown in Figure 5.2-8 (A), syllable /ba/ elicited significantly larger Pa, N1, and N2 amplitudes for ONH and OHI groups, indicating that the acoustic features of the stimulus induce the changes in the amplitudes of Pa, N1, and N2 components for ONH and OHI listeners. Additionally, there were the significant main effects of noise condition on the amplitudes of all AEP components, collapsed across ONH and OHI groups. As shown in Figure 5.2-8 (B), the amplitudes were significantly reduced in babble compared to in quiet across all AEP components for ONH and OHI groups, indicating that the noise masker induces the reductions of the amplitudes of all AEP components.

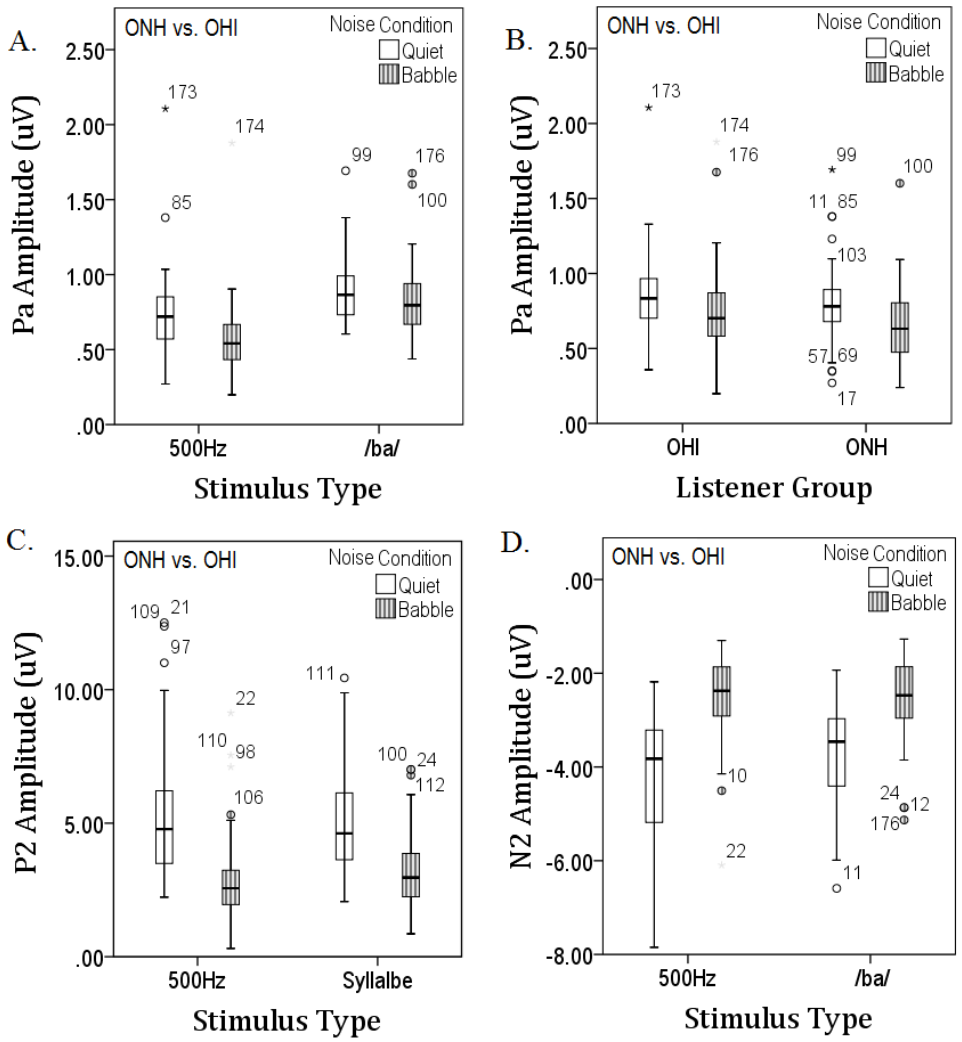


Figure 5.2-9. **Effects of interactions on amplitudes for ONH and OHI groups**. **Upper panels**: significant two-way interactions of stimulus type × noise condition (A) and listener group × noise condition (B) on Pa amplitudes. (A) Greater reductions of Pa amplitudes in quiet (open box) vs. babble (gray box with vertical stripes) for 500 Hz tone burst than those for syllable /ba/. (B) Greater reductions of Pa amplitudes in babble vs. quiet for ONH group than those for OHI group. **Lower panels**: significant two-way interactions of stimulus type × noise condition. (C) Greater reductions of P2 amplitudes in babble vs. quiet for 500 Hz tone burst than those for syllable /ba/. (D) Greater reductions of N2 amplitudes in babble vs. quiet for 500 Hz tone burst than those for syllable /ba/. The box represents the range of the middle 50% of responses. The top horizontal line represents the upper 25% of responses and the bottom horizontal line represents the lower 25% of responses. The thick horizontal line in the middle of the box represents the median. Circles represent mild outliers and asterisks represent extreme outliners.

There were significant two-way interactions on Pa, P2, and N2 amplitudes, as graphically shown in Figure 5.2-9. Graph (A) represents interactions between stimulus type and noise condition on Pa amplitudes. Pa amplitudes for 500 Hz tone burst show greater reductions in babble versus quiet than those for syllable /ba/. Graph (B) represents interactions between listener group and noise condition on Pa amplitudes. ONH group produced greater reductions of Pa amplitudes in babble versus quiet than those in OHI group. Graph (C) and (D) represent interactions between stimulus type and noise condition on P2 amplitudes and N2 amplitudes, respectively. Both P2 and N2 amplitudes showed greater reductions in babble versus quiet for 500 Hz tone burst than those for syllable /ba/.

Post-hoc pairwise comparisons were conducted for the significant interactions using Bonferroni corrections to adjust the the alpha level (.05). According to the results of post-hoc analyses, Pa amplitudes elicited by syllable /ba/ versus 500 Hz tone burst were significantly larger in babble ($p < .0001$) than those in quiet. In addition, Pa amplitudes showed greater reductions in babble versus quiet for ONH group ($p < .0001$) than those for OHI group. The enhancements of Pa amplitudes associated with hearing loss were not significantly different between ONH and OHI groups in quiet ($p = .599$) and in babble ($p = .111$). P2 amplitudes in quiet were significantly larger for 500 Hz tone burst than those for syllable /ba/ ($p = .04$), while Pa amplitudes in babble were significantly larger for syllable /ba/ than those for 500 Hz tone burst ($p = .019$). N2 amplitudes elicited by 500 Hz tone burst were significantly larger than those elicited by syllable /ba/ in quiet ($p < .0001$), while N2 latencies elicited by syllable /ba/ were not significantly different from those elicited by 500 Hz tone burst in babble. N2 latencies elicited by 500 Hz tone burst exhibited significantly greater reductions in babble ($p < .0001$) than those elicited by syllable /ba/.

5.2.4. Effects of hearing loss on AEP latencies

The effects of hearing loss on AEP latencies were determined by testing the group difference between OHI and ONH listeners in the latencies of each AEP component, with tests of two-factor within-subject effects (stimulus type × noise conditions), using three-factor mixed ANOVA. Table 5.2-4 presents the summary of the ANOVA analysis on latencies of each AEP component for ONH and OHI groups.

There was significant group difference in N2 latencies between ONH and OHI groups, indicating the effects of hearing loss on N2 latencies. However, Pa, N1, ane P2 latencies were not significantly different between ONH and OHI groups, indicating no effects of hearing loss on the latencies of Pa, N1, and P2 components. Figure 5.2-10 illustrates the between-group differences in the latencies of each AEP component. N2 latencies were only significantly prolonged in OHI compared with ONH group, indicating a significant prolongation of N2 latencies associated with hearing loss. The later the AEP component, the longer the delay in peak latency associated with age-related hearing loss.

Table 5.2-4.

Analyses on the effects of hearing loss: ANOVA summary table for the latencies (ms) of Pa, N1, P2, and N2 as a function of stimulus type (500 Hz vs. /ba/), noise condition (Quiet vs. Babble), and listener group (ONH vs. OHI).

Source	*df*	Error	*F*	*p*-value
Pa				
Group	1	50	1.081	.303
Stimulus Type	1	50	293.063	<.0001*
Noise Condition	1	50	26.671	<.0001*
Stimulus x Noise	1	50	9.364	.004*
Stimulus x Group	1	50	1.192	.280
Noise x Group	1	50	.316	.576
Stimulus x Noise x Group	1	50	.435	.513
N1				
Group	1	50	2.041	.159
Stimulus Type	1	50	458.846	<.0001*
Noise Condition	1	50	162.060	<.0001*
Stimulus x Noise	1	50	1.407	.241
Stimulus x Group	1	50	1.048	.311
Noise x Group	1	50	.064	.801
Stimulus x Noise x Group	1	50	.000	.983
P2				
Group	1	50	.715	.402
Stimulus Type	1	50	70.312	<.0001*
Noise Condition	1	50	179.921	<.0001*
Stimulus x Noise	1	50	3.139	.083
Stimulus x Group	1	50	.000	.988
Noise x Group	1	50	.184	.670
Stimulus x Noise x Group	1	50	.009	.923
N2				
Group	1	50	11.133	.002*
Stimulus Type	1	50	179.191	<.0001*
Noise Condition	1	50	205.692	<.0001*
Stimulus x Noise	1	50	17.607	<.0001*
Stimulus x Group	1	50	.783	.380
Noise x Group	1	50	.332	.567
Stimulus x Noise x Group	1	50	3.862	.055

*Significant at $p < .05$

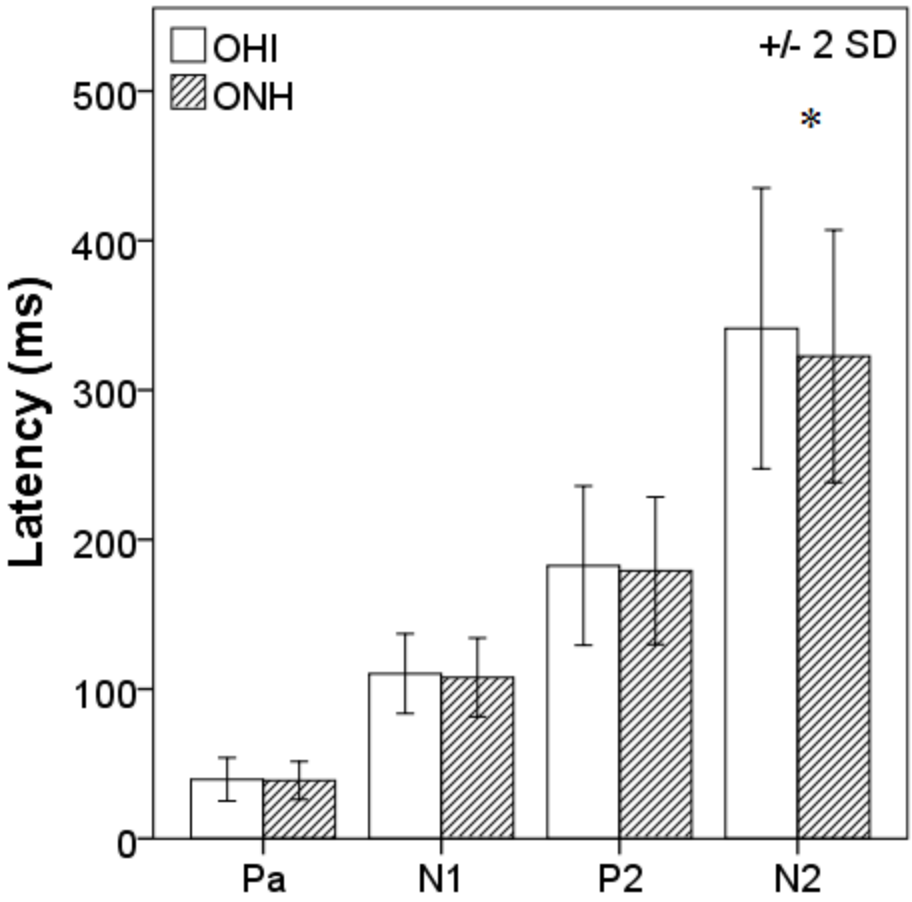


Figure 5.2-10. Group mean difference in the latencies of each AEP component. Older hearing-impaired adults (OHI, open bar) demonstrates longer latencies across all AEP components compared with older adults with near-normal hearing (ONH, hatched bar), producing more delayed latencies in the later components. There was a significant group difference in N2 latencies, indicating the effects of hearing loss on latency prolongation. The abscissa denotes the AEP components and the ordinate denotes the latency. Error bars represent ±2 standard deviations of the mean. An Asterisk (*) indicates that the mean difference is significant at the .05 level.

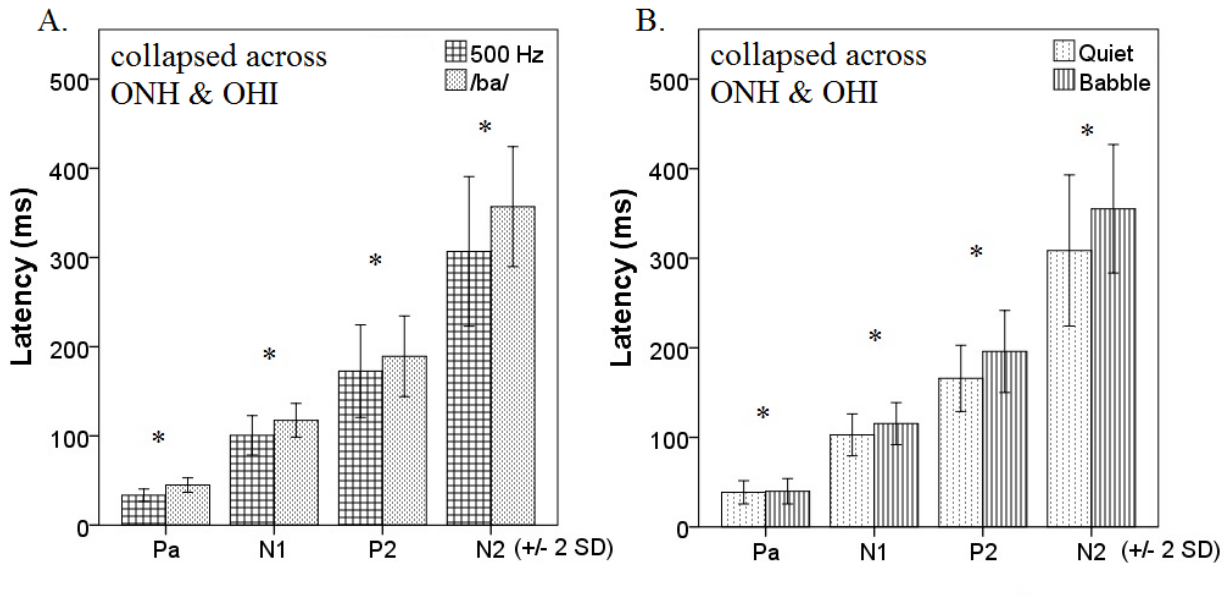


Figure 5.2-11. (A) Mean difference in the latencies of each AEP component as a function of stimulus type. Syllable /ba/ (stippled bar) elicited significantly longer latencies than 500 Hz tone burst (grid bar) across all AEP components. (B) Mean difference in the latencies of each AEP component as a function of noise condition. All latencies were significantly prolonged in babble (vertical striped bar) versus quiet (dotted bar) condition. The abscissa denotes the AEP components and the ordinate denotes the latency. Error bars represent ±2 standard deviations of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

The significant main effects of stimulus type and noise condition were found in the latencies of all AEP components. The data were collapsed across ONH and OHI groups. As shown in Figure 5.2-11 (A), syllable /ba/ elicited significantly longer latencies than 500 Hz tone burst across all AEP components for ONH and OHI groups, indicating that the acoustic features of the stimulus induce the changes in the latencies of all AEP components for ONH and OHI listeners. As shown in Figure 5.2-11 (B), the latencies of all AEP components were significantly prolonged in babble compared to in quiet for ONH and OHI groups, indicating that the noise masker induces the prolongations of the latencies of all AEP components for ONH and OHI listeners. The main effects were similar between outcomes produced by the effects of hearing loss (for ONH and OHI groups) and the effects of aging (for YNH and ONH groups).

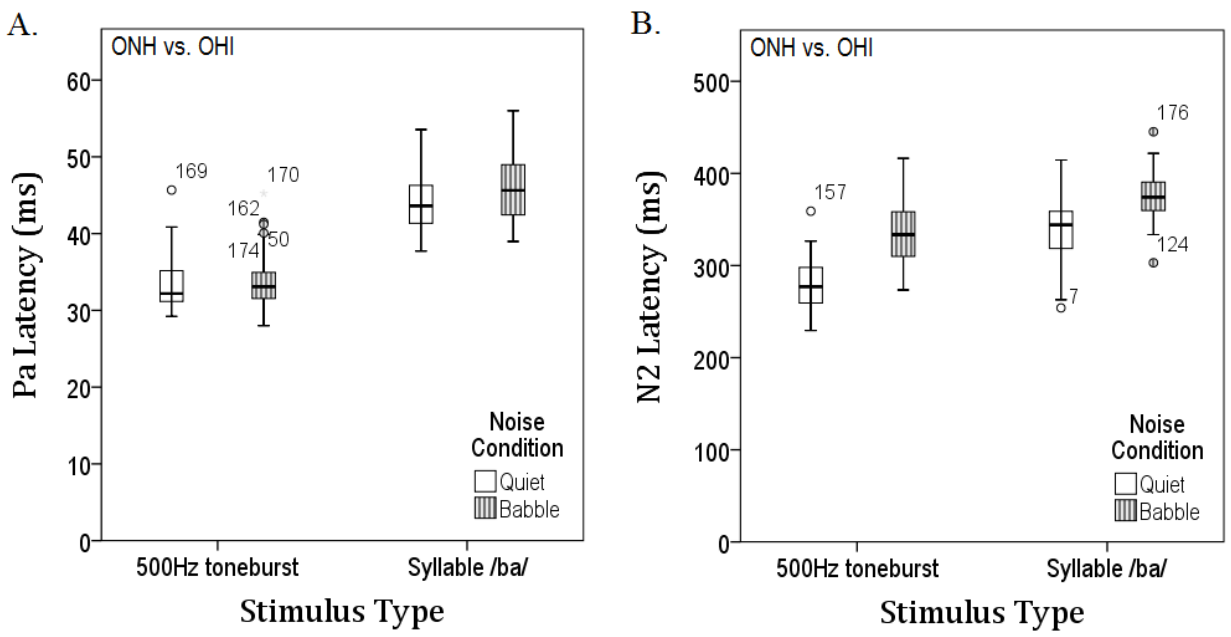


Figure 5.2-12. **Effects of interactions on the latencies for ONH and OHI groups**. Significant two-way interactions of stimulus type × noise condition. (A) Greater prolongations of Pa latencies in babble (gray box with vertical stripes) vs. quiet (open box) for syllable /ba/ than those for 500 Hz tone burst. (B) Greater prolongations of N2 latencies in babble vs. quiet for 500 Hz tone burst than those for syllable /ba/. The box represents the range of the middle 50% of responses. The top horizontal line represents the upper 25% of responses and the bottom horizontal line represents the lower 25% of responses. The thick horizontal line in the middle of the box represents the median. Circles represent mild outliers and asterisks represent extreme outliners.

In addition, significant two-way interactions were found in Pa and N2 latencies. Figure 5.2-12 graphically shows the interactions. Graph (A) represents the two-way interactions between stimulus type and noise condition on Pa latencies. There were greater prolongations in babble versus quiet for syllable /ba/ than those for 500 Hz tone burst. Graph (B) represents the two-way interactions between stimulus type and noise condition on N2 latencies. There were greater prolongations of N2 latencies in babble versus quiet for 500 Hz tone burst than those for syllable /ba/.

Post-hoc pairwise comparisons were conducted for the significant interactions using Bonferroni corrections to adjust the the alpha level (.05). According to the results of post-hoc analyses, Pa latencies elicited by syllable /ba/ exhibited significantly greater prolongations in babble ($p < .0001$) compared to those elicited by 500 Hz tone burst. Pa latencies in babble were significantly prolonged for syllable /ba/ versus 500 Hz tone burst ($p < .0001$) compared to those in quiet. N2 latencies elicited by 500 Hz tone burst exhibited significantly greater prolongations in babble ($p < .0001$) compared to those elicited by syllable /ba/. N2 latencies in quiet were significantly prolonged for syllable /ba/ versus 500 Hz tone burst ($p < .0001$) compared to those in babble.

5.2.5. Combined effects of aging and hearing loss on AEP amplitudes

To identify how the effects of aging on the AEP amplitudes change in combination with hearing loss, the combined effects of aging and hearing loss were examined for the amplitudes of each AEP component by testing group difference between YNH and OHI listeners, with tests of two-factor within-subject effects (stimulus type × noise conditions), using three-factor mixed ANOVA. Table 5.2-5 presents the summary of the ANOVA analyses on the amplitudes of each AEP component for YNH and OHI groups.

There were significant group differences between YNH and OHI groups, indicating that the combined effects of aging and hearing loss have significant impacts on the changes in the amplitudes of all AEP components for OHI compared with YNH group. As depicted in Figure 5.2-13, OHI group produced significantly enhanced amplitudes across all AEP components compared with YNH group, indicating that age-related hearing loss exhibits the significant age-related increases in the amplitudes of all AEP components for OHI relative to YNH group. As stated earlier, ONH group showed only significant age-related increases in Pa and N1 amplitudes compared with YNH group (Figure 5.2-1). Collectively, the combined effects may have stronger effects on the changes in the amplitudes than the effects of aging per se.

The ANOVA revealed significant main effects of stimulus type on Pa, N1, and N2 amplitudes. The data were collapsed across YNH and OHI groups. As depicted in Figure 5.2-14 (A), syllable /ba/ elicited significantly larger Pa and N1 amplitudes, and 500 Hz tone burst elicited significantly larger N2 amplitudes. P2 amplitudes were not significantly changed as a function of stimulus type. The main effects indicate that the acoustic features of the stimulus induce the changes in the amplitudes of Pa, N1, and N2 components.

Table 5.2-5.

Analysis on the combined effects of aging and hearing loss: ANOVA summary table for the amplitudes (μV) of Pa, N1, P2, and N2 as a function of stimulus type (500 Hz vs. /ba/), noise condition (Quiet vs. Babble), and listener group (YNH vs. OHI).

Source	*df*	Error	*F*	*p*-value
Pa				
Group	1	54	44.601	<.0001 *
Stimulus Type	1	54	43.600	<.0001*
Noise Condition	1	54	60.448	<.0001*
Stimulus x Noise	1	54	.993	.324
Stimulus x Group	1	54	1.940	.169
Noise x Group	1	54	.005	.944
Stimulus x Noise x Group	1	54	17.208	<.0001*
N1				
Group	1	54	20.729	<.0001*
Stimulus Type	1	54	49.083	<.0001*
Noise Condition	1	54	80.016	<.0001*
Stimulus x Noise	1	54	.402	.529
Stimulus x Group	1	54	3.924	.053
Noise x Group	1	54	17.361	<.0001*
Stimulus x Noise x Group	1	54	.508	.479
P2				
Group	1	54	4.578	.037*
Stimulus Type	1	54	.555	.460
Noise Condition	1	54	181.448	<.0001*
Stimulus x Noise	1	54	22.401	<.0001*
Stimulus x Group	1	54	6.555	.013*
Noise x Group	1	54	3.361	.072
Stimulus x Noise x Group	1	54	.458	.501
N2				
Group	1	54	6.562	.013*
Stimulus Type	1	54	14.501	<.0001*
Noise Condition	1	54	182.084	<.0001*
Stimulus x Noise	1	54	23.814	<.0001*
Stimulus x Group	1	54	1.887	.175
Noise x Group	1	54	6.391	.014*
Stimulus x Noise x Group	1	54	.001	.974

*Significant at $p < .05$

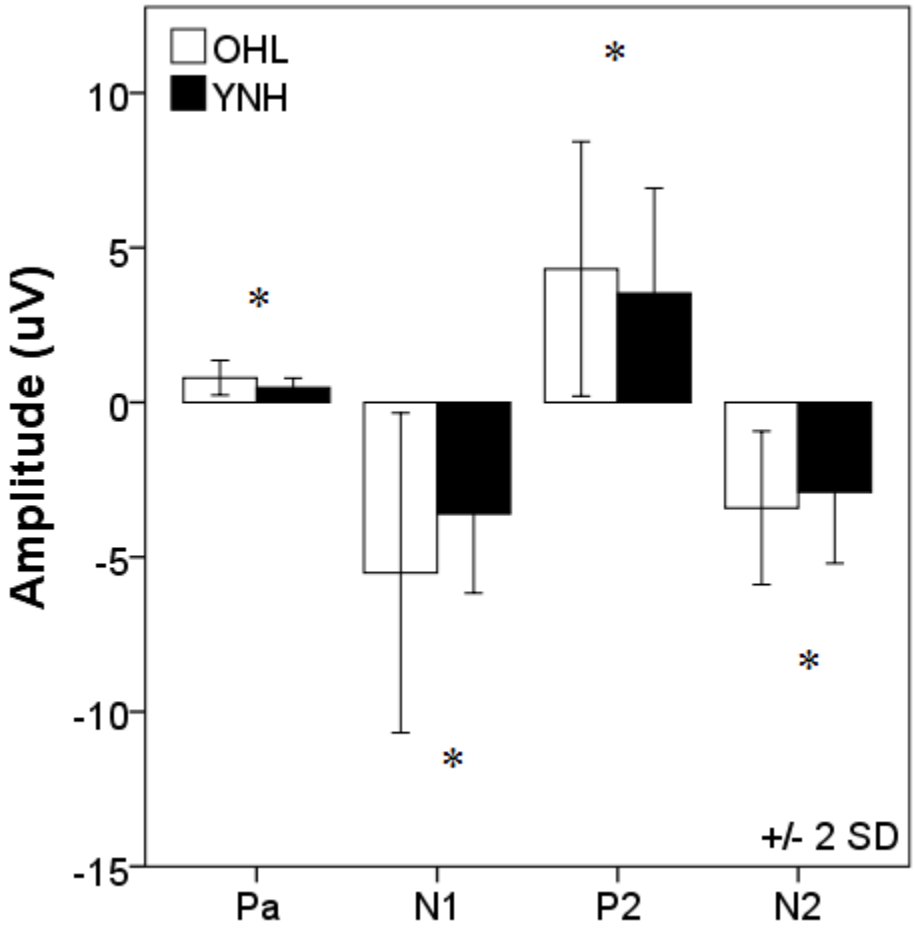


Figure 5.2-13. Group mean difference in the amplitudes of each AEP component. There were significant between-group differences for all AEP components, indicating the significant combined effects of aging and hearing loss on the amplitude enhancement. OHI group (older hearing-impaired adults, open bar) shows significantly enhanced amplitudes across all AEP components compared with YNH group (young normal-hearing adults, black bar). The abscissa denotes the AEP components and the ordinate denotes the amplitude. Error bars represent ±2 standard deviations of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

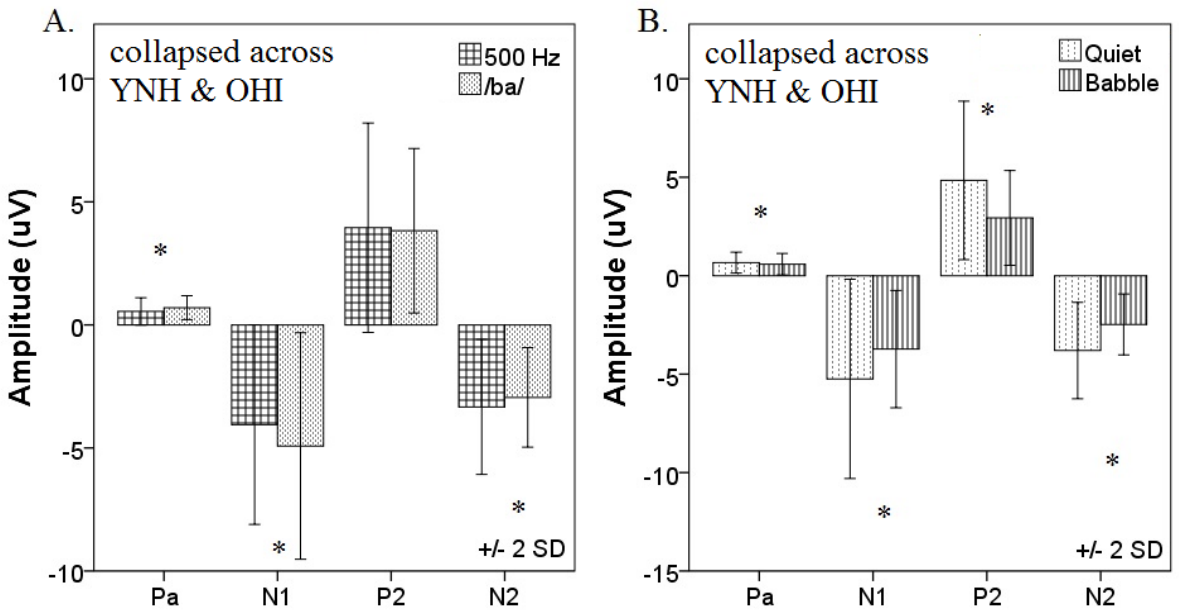


Figure 5.2-14. (A) Mean difference in the amplitudes of each AEP component as a function of stimulus type. Syllable /ba/ (stippled bar) elicited significantly larger Pa and N1 amplitudes and 500 Hz tone burst (grid bar) elicited significantly larger N2 amplitudes. (B) Mean difference in the amplitudes of each AEP component as a function of noise condition. Significantly larger amplitudes in quiet (dotted bar) than babble (vertical striped bar) across all AEP components. The abscissa denotes the AEP components and the ordinate denotes the amplitude. Error bars represent ±2 standard deviations of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

The main effects of stimulus type on amplitudes were similar between outcomes produced by the combined effects (for YNH and OHI groups) and the effects of hearing loss (for ONH and OHI groups). The main effects of stimulus type on amplitudes, however, were different between outcomes produced by the combined effects and the effects of aging (for YNH and ONH groups, Figure 5.2-2, A). There were also significant main effects of noise condition on the amplitudes of all AEP components. The data were collapsed across YNH and OHI groups. As shown in 5.2-14 (B), the amplitudes of all AEP components were significantly reduced in babble compared to in quiet, indicating that the noise masker induces the reductions of the amplitudes of all AEP components. The outcomes for the main effects of noise condition on the amplitudes

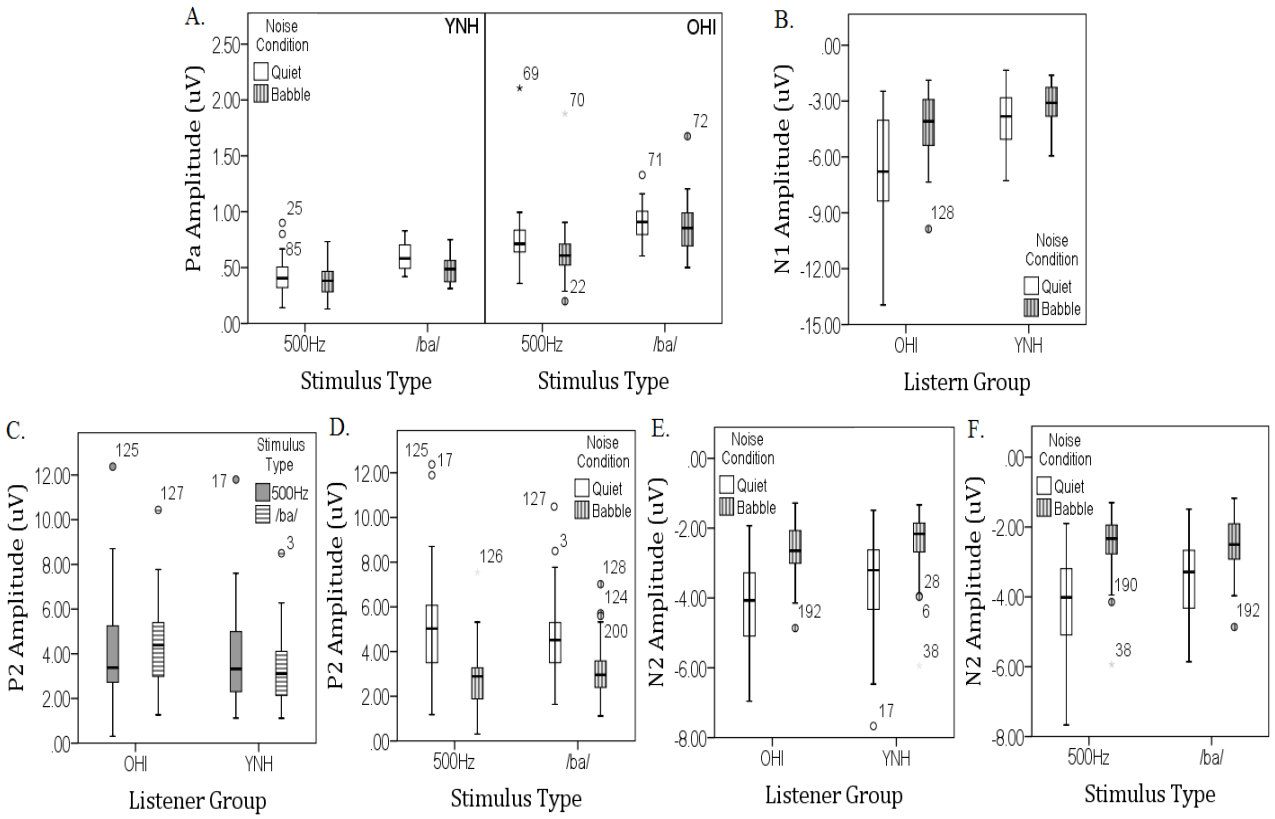


Figure 5.2-15. **Effects of interactions on the amplitudes for YNH and OHI groups**. (A) Three-way interactions of stimulus type × noise condition × group. For YNH group, greater reductions of Pa amplitudes in babble (gray box with vertical stripes) vs. quiet (open box) for syllable /ba/ than those for 500 Hz tone burst. For OHI group, greater reductions of Pa amplitudes in babble vs. quiet for 500 Hz tone burst than those for syllable /ba/. (B) Two-way interactions of listener group × noise condition. Greater reductions of N1 amplitudes in babble vs. quiet for OHI group than those for YNH group. (C) Two-way interactions of listener group × stimulus type. Greater increases in P2 amplitudes for 500 Hz tone burst (gray box) vs. syllable /ba/ (horizontal striped box) in YNH group and greater increases in P2 amplitudes for syllable /ba/ vs. 500 Hz tone burst in OHI group. (D) Two-way interactions of stimulus type × noise condition. Greater reductions of P2 amplitudes in babble vs. quiet for 500 Hz tone burst than those for syllable /ba/. (E) Two-way interactions of listener group × noise condition. Greater reductions of N2 amplitudes in babble vs. quiet for OHI group than those for YNH group. (F) Two-way interactions of stimulus type × noise condition. Greater reductions of N2 amplitudes in babble vs. quiet for 500 Hz tone burst than those for syllable /ba/. The box represents the range of the middle 50% of responses. The top horizontal line represents the upper 25% of responses and the bottom horizontal line represents the lower 25% of responses. The thick horizontal line in the middle of the box represents the median. Circles represent mild outliers and asterisks represent extreme outliners.

of all AEP components were similar among all listener groups, independent of the effcts of aging, hearing loss, or both.

In addition, the ANOVA revealed significant three-way interactions on Pa amplitudes and two-way interactions on N1, P2, and N2 amplitudes. Figure 5.2-15 illustrates the six interactions. Graph (A) represents the three-way interactions of stimulus type, noise condition, and listener group on Pa amplitudes. YNH group showed greater reductions of Pa amplitudes in babble versus quiet for syllable /ba/ than those for 500 Hz tone burst, whereas ONH group showed greater reductions of Pa amplitudes in babble versus quiet for 500 Hz tone burst than those for syllable /ba/. Graph (B) represents the two-way interactions of listener group and noise condition on N1 amplitudes. N1 amplitudes exhibited greater reductions in babble versus quiet for OHI group than those for YNH group. Graph (C) represents the two-way interactions of listener group and stimulus type on P2 amplitudes. YNH group showed greater increases in P2 amplitudes for 500 Hz tone burst versus syllable /ba/, whereas OHI group showed greater increases in P2 amplitudes for syllable /ba/ versus 500 Hz tone burst. Graph (D) represents the two-way interactions of stimulus type and noise condition on P2 amplitudes. P2 amplitudes exhibited greater reductions of P2 amplitudes in babble versus quiet for 500 Hz tone burst than those for syllable /ba/. Graph (E) represents the two-way interactions of listener group and noise condition on N2 amplitudes. N2 amplitudes exhibited greater reductions in babble versus quiet for OHI group than those for YNH group. Graph (F) represents the two-way interactions of stimulus type and noise condition on N2 amplitudes. N2 amplitudes exhibited greater reductions in babble versus quiet for 500 Hz tone burst than those for syllable /ba/.

Post-hoc pairwise comparisons were conducted for the significant interactions using Bonferroni corrections to adjust the alpha level (.05). The results of post-hoc analyses can be

described as follows. For Pa amplitudes, OHI group showed significantly greater reductions of Pa amplitudes in babble versus quiet for 500 Hz tone burst ($p < .0001$) than those for syllable /ba/, whereas YNH group showed significantly greater reductions of Pa amplitudes in babble versus quiet for syllable /ba/ ($p < .0001$) than those for 500 Hz tone burst. OHI group showed no significant reductions of Pa amplitudes elicited by syllable /ba/in babble versus quiet. OHI group showed significantly increased Pa amplitudes elicited by syllable /ba/ versus 500 Hz tone burst in babble ($p < .0001$) than those in quiet, whereas YNH group showed significantly increased Pa amplitudes elicited by syllable /ba/ versus 500 Hz tone burst in quiet ($p < .0001$) than those in babble. OHI group produced significantly enhanced Pa amplitudes compared with YNH group, irrespective of stimulus type or noise condition. The age-related enhancements of Pa amplitudes in OHI versus YNH group were significantly greater for syllable /ba/ in babble ($p < .0001$) than other comparisons of Pa amplitudes (i.e., syllable /ba/ in quiet, and 500 Hz tone burst in quiet and in babble). For N1 amplitudes, OHI group showed significantly greater reductions of N1 amplitudes in babble versus quiet ($p < .0001$) than did YNH group. For P2 amplitudes, YNH group showed significantly increased P2 amplitudes elicited by 500 Hz tone burst versus syllable /ba/ in quiet ($p = .001$), but no significant differences in P2 amplitudes between stimulus types in babble ($p = .731$). OHI group showed significantly increased P2 amplitudes elicited by syllable /ba/ versus 500 Hz tone burst in babble ($p = .002$), but no significant differences in P2 amplitudes between stimulus types in quiet ($p = .626$). The age-related enhancements of P2 amplitudes in OHI versus YNH group were significantly greater for syllable /ba/ in both quiet ($p = .002$) and babble ($p = .009$) than the counterparts for 500 Hz tone burst. P2 amplitudes elicited by 500 Hz tone burst were not significantly different between YNH and OHI groups in both quiet and babble. For N2 amplitudes, both YNH and OHI groups

showed significantly greater increases in N2 amplitudes elicited by 500 Hz tone burst versus syllable /ba/ in quiet [YNH ($p < .0001$), OHI ($p = .005$)] than those in babble. The age-related enhancements of N2 amplitudes in OHI versus YNH group were significantly greater for syllable /ba/ in quiet ($p = .001$) and in babble ($p = .047$) than those for 500 Hz tone burst. There were no significant differences in N2 amplitudes elicited by 500 Hz tone burst between YNH and OHI groups.

5.2.6. Combined effects of aging and hearing loss on AEP latencies

To identify how the effects of aging on the AEP latencies change in combination with hearing loss, the combined effects of aging and hearing loss were examined for the latencies of each AEP component by testing group difference between YNH and OHI listeners, with tests of two-factor within-subject effects (stimulus type × noise conditions), using three-factor mixed ANOVA. Table 5.2-6 presents the summary of the ANOVA analyses on the latencies of each AEP component for YNH and OHI groups.

There were significant group differences between YNH and OHI groups, indicating that the combined effects of aging and hearing loss have significant impacts on the changes in the latencies of all AEP components for OHI relative to YNH group. As depicted in Figure 5.2-16, OHI group produced significantly prolonged latencies of all AEP components compared with YNH group, indicating that age-related hearing loss exhibits the significant age-related prolongations of latencies across all AEP components in OHI relative to YNH group. The later the AEP components, the longer the age-related delay. The combined effects may have stronger effects on the changes in the latencies than the effects of aging per se. ONH group produced significantly prolonged Pa, P2, and N2 latencies compared with YNH group (Figure 5.2-4).

Table 5.2-6.

Analysis on the combined effects of aging and hearing loss: ANOVA summary table for the latencies (μV) of Pa, N1, P2, and N2 as a function of stimulus type (500Hz vs. /ba/), noise condition (Quiet vs. Babble), and listener group (YNH vs. OHI).

Source	*df*	Error	*F*	*p*-value
Pa				
Group	1	54	35.836	<.0001 *
Stimulus Type	1	54	245.024	<.0001*
Noise Condition	1	54	36.039	<.0001*
Stimulus x Noise	1	54	2.685	.107
Stimulus x Group	1	54	21.734	<.0001*
Noise x Group	1	54	.583	.449
Stimulus x Noise x Group	1	54	.625	.433
N1				
Group	1	54	8.952	.004*
Stimulus Type	1	54	358.678	<.0001*
Noise Condition	1	54	133.638	<.0001*
Stimulus x Noise	1	54	.017	.897
Stimulus x Group	1	54	2.850	.097
Noise x Group	1	54	.100	.754
Stimulus x Noise x Group	1	54	1.296	.260
P2				
Group	1	54	11.150	.002*
Stimulus Type	1	54	163.186	<.0001*
Noise Condition	1	54	149.113	<.0001*
Stimulus x Noise	1	54	.215	.645
Stimulus x Group	1	54	11.455	.001*
Noise x Group	1	54	4.688	.035*
Stimulus x Noise x Group	1	54	6.783	.012*
N2				
Group	1	54	82.340	<.0001*
Stimulus Type	1	54	153.726	<.0001*
Noise Condition	1	54	172.399	<.0001*
Stimulus x Noise	1	54	2.341	.132
Stimulus x Group	1	54	.669	.417
Noise x Group	1	54	.023	.880
Stimulus x Noise x Group	1	54	30.512	<.0001*

*Significant at $p < .05$

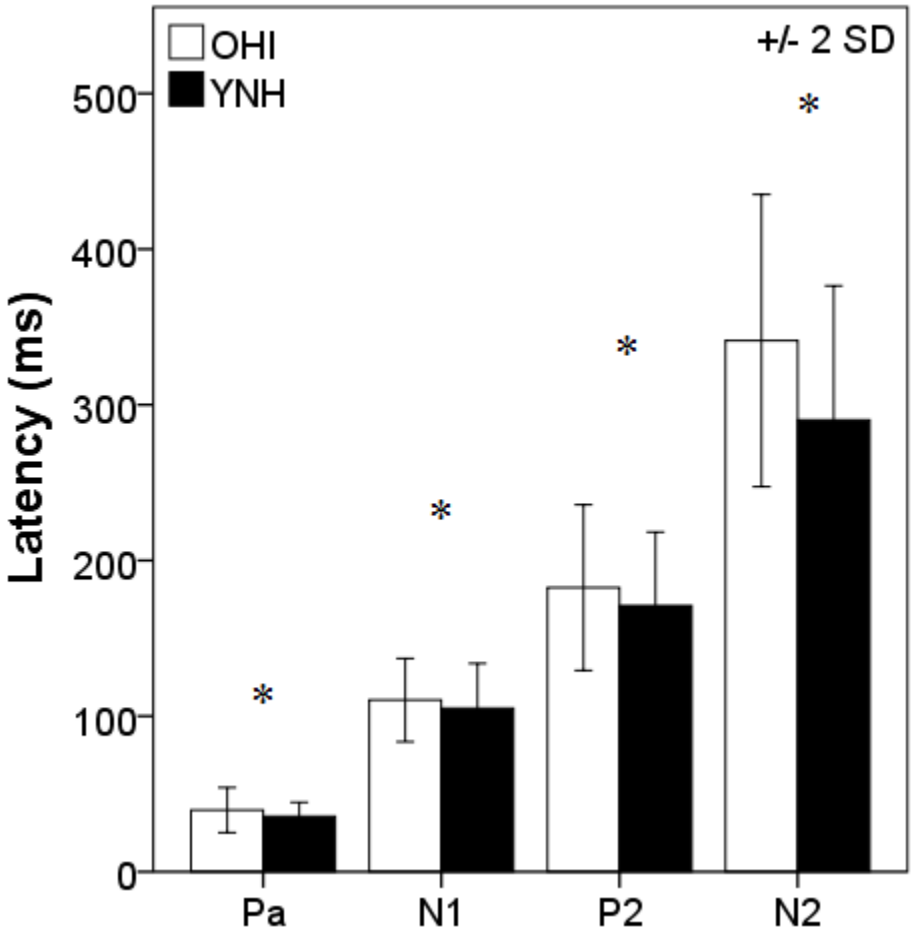


Figure 5.2-16. Group mean difference in the latencies of each AEP component. There were significant between-group difference in the latencies of all AEP components, indicating a significant combined effect of aging and hearing loss on latency prolongation. OHI group showed significantly prolonged latencies across all AEP components compared with YNH group. The abscissa denotes the AEP components and the ordinate denotes the latency. Error bars represent ±2 standard deviations of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

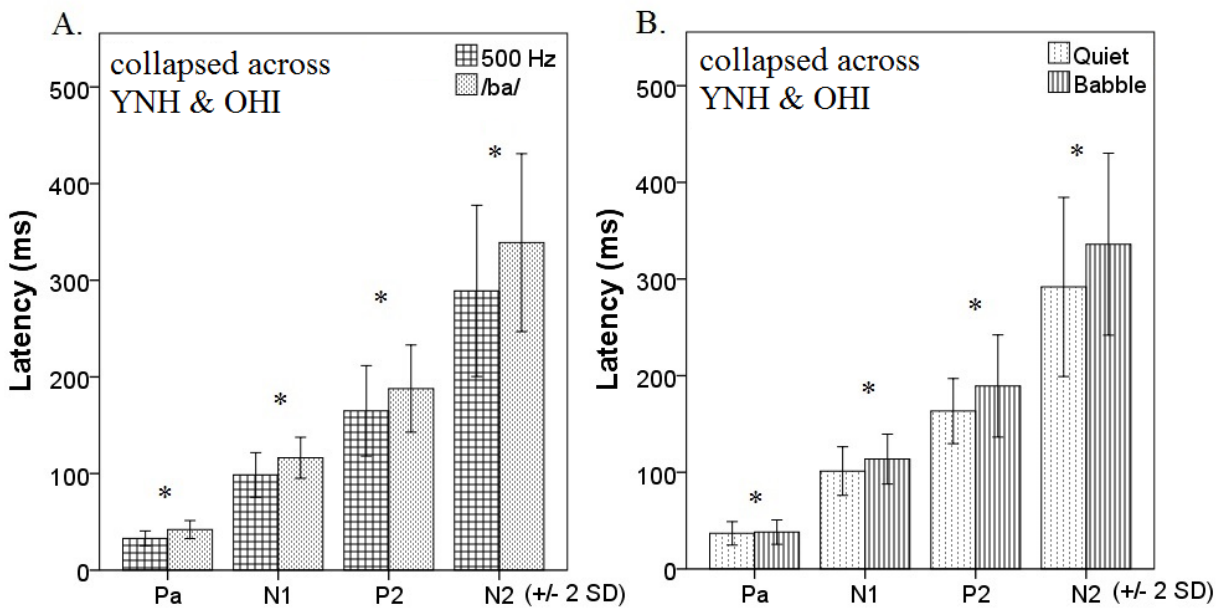


Figure 5.2-17. (A) Mean difference in the latencies of each AEP component as a function of stimulus type. Syllable /ba/ (stippled bar) elicited significantly longer latencies than 500 Hz tone burst (grid bar) across all AEP components. (B) Mean difference in the latencies of each AEP component as a function of noise condition. All latencies were significantly prolonged in babble (vertical striped bar) versus quiet (dotted bar) condition. The abscissa denotes the AEP components and the ordinate denotes the latency. Error bars represent ±2 standard deviations of the mean. Asterisks (*) indicate that the mean difference is significant at the .05 level.

The ANOVA revealed significant main effects of stimulus type and noise condition on the latencies of all AEP components. As depicted in Figure 5.2-17 (A), syllable /ba/ elicited significantly prolonged latencies across all AEP components compared to 500 Hz tone burst, indicating that the acoustic features of the stimulus affect the latencies of all AEP components. As depicted in Figure 5.2-17 (B), the latencies of all AEP components were significantly reduced in babble compared to in quiet, indicating that the noise masker induces the prolongations of the latencies of all AEP components. The outcomes for the main effects of both stimulus type and noise condition were similar in the latencies of all AEP components among three listener groups, independent of the effects of aging, hearing loss, or both.

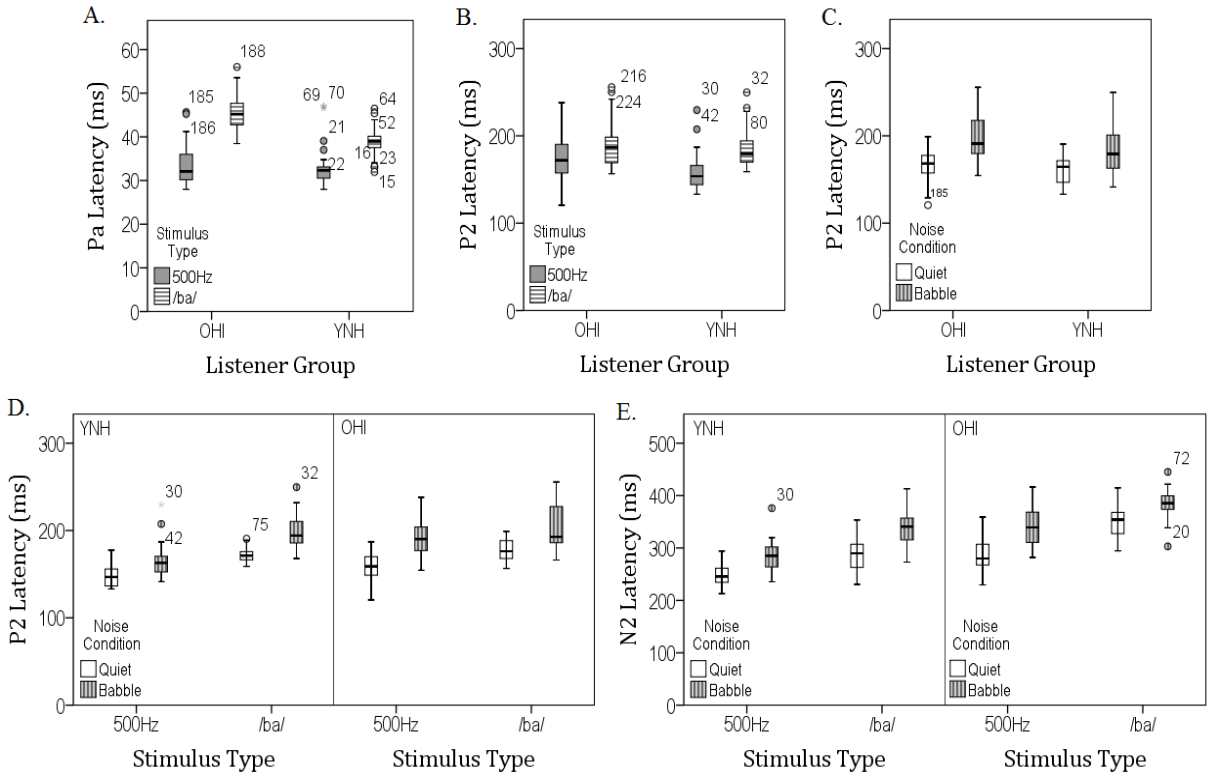


Figure 5.2-18. **Effects of interactions on the latencies for YNH and OHI groups:** (A) Two-way interactions of group × stimulus type on Pa latencies. Greater prolongations of Pa latencies for syllable /ba/ vs. 500 Hz tone burst in OHI group than the counterparts in YNH group. (B) Two-way interactions of group × stimulus type on P2 latencies. Greater prolongations of P2 latencies for syllable /ba/ vs. 500 Hz tone burst in YNH than the counterparts in OHI group. (C) Two-way interactions of group × noise condition on P2 latencies. Greater prolongations of P2 latencies in babble vs. quiet in OHI group than the counterparts in YNH group. (D) Three-way interactions of stimulus type × noise condition × group on P2 latencies. For YNH group, greater prolongations of P2 latencies in babble vs. quiet for syllable /ba/ than the counterparts for 500 Hz tone burst, and greater prolongations of P2 latencies for syllable /ba/ vs. 500 Hz tone burst in babble than the counterparts in quiet. For OHI group, greater prolongations of P2 latencies in babble vs. quiet for 500 Hz tone burst than the counterparts for syllable /ba/, and greater prolongations of P2 latencies for syllable /ba/ vs. 500 Hz tone burst in quiet than the counterparts in babble. (E) Three-way interactions of stimulus type × noise condition × group on N2 latencies. For YNH group, greater prolongations of N2 latencies in babble vs. quiet for syllable /ba/ than the counterparts for 500 Hz tone burst, and greater prolongations of N2 latencies for syllable /ba/ vs. 500 Hz tone burst in babble than the counterparts in quiet. For OHI group, greater prolongations of N2 latencies in babble vs. quiet for 500 Hz tone burst than the counterparts for syllable /ba/, and greater prolongations of N2 latencies for syllable /ba/ vs. 500 Hz tone burst in quiet than the counterparts in babble. The box represents the range of the middle 50% of responses. The top horizontal line represents the upper 25% of responses and the bottom horizontal line represents the lower 25% of responses. The thick horizontal line in the middle of the box represents the median. Circles represent mild outliers and asterisks represent extreme outliners.

In addition, there were significant two-way interactions on Pa and P2 latencies, and three-way interactions on P2 and N2 latencies. Figure 5.2-18 graphically shows the five interactions. Graph (A) represents the two-way interactions of listener group and stimulus type on Pa latencies. OHI group showed greater prolongations of Pa latencies elicited by syllable /ba/ versus 500 Hz tone burst than YNH group. Graph (B) represents the two-way interactions of listener group and stimulus type on P2 latencies. YNH group showed greater prolongations of P2 latencies elicited by syllable /ba/ versus 500 Hz tone burst than OHI group. Graph (C) represents the two-way interactions of listener group and noise condition on P2 latencies. OHI group showed greater prolongations of P2 latencies in babble versus in quiet than YNH group. Graph (D) represents the three-way interactions of listener group, stimulus type, and noise condition on P2 latencies. YNH group showed greater prolongations of P2 latencies in babble versus in quiet for 500 Hz tone burst than those for syllable /ba/, whereas OHI group showed greater prolongations of P2 latencies in babble versus in quiet for syllable /ba/ than those for 500 Hz tone burst. In addition, YNH group showed greater prolongations of P2 latencies elicited by syllable /ba/ versus 500 Hz tone burst in babble than those in quiet, whereas OHI group showed greater prolongations of P2 latencies elicited by syllable /ba/ versus 500 Hz tone burst in quiet than those in babble. Garph (E) represents the three-way interactions of listener group, stimulus type, and noise condition on N2 latencies. YNH group showed greater prolongations of N2 latencies in babble versus in quiet for syllable /ba/ than those for syllable /ba/, whereas OHI group showed greater prolongations of N2 latencies in babble versus in quiet for 500 Hz tone burst than those for syllable /ba/. In addition, YNH group showed greater prolongations of N2 latencies elicited by syllable /ba/ versus 500 Hz tone burst in babble than those in quiet, whereas

OHI group showed greater prolongations of N2 latencies elicited by syllable /ba/ versus 500 Hz tone burst in quiet than those in babble.

The post-hoc pairwise comparisons were conducted for significant main effects and interactions using Bonferroni corrections to adjust the alpha level (.05). The results of post-hoc analyses can be described as follows. For Pa latencies, OHI group demonstrated significantly prolonged Pa latencies elicited by syllable /ba/ versus 500 Hz tone burst ($p < .0001$), compared with those in YNH group. The age-related prolongations of Pa latencies in OHI versus YNH group were significantly greater for syllable /ba/ ($p < .0001$) than the counterparts for 500 Hz tone burst. There were no significant differences between YNH and OHI groups in Pa latencies elicited by 500 Hz tone burst. For P2 and N2 latencies, OHI group demonstrated significantly greater prolongations of P2 and N2 latencies for syllable /ba/ versus 500 Hz tone burst in quiet [P2 ($p < .0001$), N2 ($p < .0001$)] than those in babble. For OHI group, both P2 and N2 latencies elicited by 500 Hz tone burst exhibited significantly greater prolongations in babble [P2 ($p < .0001$), N2 ($p < .0001$)] than those elicited by syllable /ba/. However, YNH group demonstrated significantly greater prolongations of P2 and N2 latencies for syllable /ba/ versus 500 Hz tone burst in babble [P2 ($p < .0001$), N2 ($p < .0001$)] than those in quiet. For YNH group, both P2 and N2 latencies elicited by syllable /ba/ exhibited significantly greater prolongations in babble [P2 ($p < .0001$), N2 ($p < .0001$)] than those elicited by 500 Hz tone burst. The age-related prolongations of P2 latencies in OHI versus YNH group were significantly greater for 500 Hz tone burst in quiet ($p = .032$) and in babble ($p < .0001$) than the counterparts for syllable /ba/. P2 latencies elicited by syllable /ba/ were not significantly prolonged for OHI relative to YNH group in both quiet and babble. N2 latencies were significantly prolonged in OHI relative to YNH group, irrespective of stimulus type or noise

condition. The age-related prolongations of N2 latencies in OHI versus YNH group were significantly greater for syllable /ba/ in quiet than other comparisons of N2 latencies (i.e., syllable /ba/ in babble, and 500 Hz tone burst in quiet and in babble).

5.3. Intercorrelations between AMLRs and ALLRs

To identify the interrelationships between AEP components generated at the early and later stages of auditory processing in the central auditory system, we correlated AMLR Pa with each of ALLR components (N1, P2, and N2) using Pearson's correlation coefficients. Table 5.3-1 presents the correlations of amplitudes and latencies between all pairs of AEP components for each group.

As shown in Table 5.3-1, both OHI and ONH groups showed a significant positive correlation between Pa amplitudes and P2 amplitudes, and significant negative correlations between Pa amplitudes and N1 amplitudes or N2 amplitudes. However, YNH group showed only one significant negative correlation between Pa amplitudes and N1 amplitudes. Negative correlations come from negative values of N1 and N2 amplitudes. Both positive and negative correlations, therefore, indicate that enhanced Pa amplitudes are significantly associated with enhanced amplitudes of N1, P2, and N2. With respect to latencies, all listener groups showed all significant positive correlations between latencies of AMLR Pa and each of ALLR components, indicating that prolonged Pa latencies are significantly associated with prolonged latencies of N1, P2, and N2.

Table 5.3-1.

Correlations between AMLR Pa and each of ALLR components (N1, P2 and N2) by listener group.

		Pa of AMLRs					
ALLRs		Amplitude (μV)			Latency (ms)		
		YNH	ONH	OHI	YNH	ONH	OHI
	N (d*f*)	120	104	104	120	104	104
N1	Correlation	-.467*	-.417*	-.250*	.524*	.619*	.589*
	p-value	<.0001	<.0001	.010	<.0001	<.0001	<.0001
P2	Correlation	.174	.410*	.381*	.558*	.385*	.326*
	p-value	.057	<.0001	<.0001	<.0001	<.0001	<.001
N2	Correlation	-.103	-.291*	-.298*	.429*	.588*	.489*
	p-value	.262	.003	.002	<.0001	<.0001	<.0001

*Correlation is significant at the 0.01 level (2-tailed).

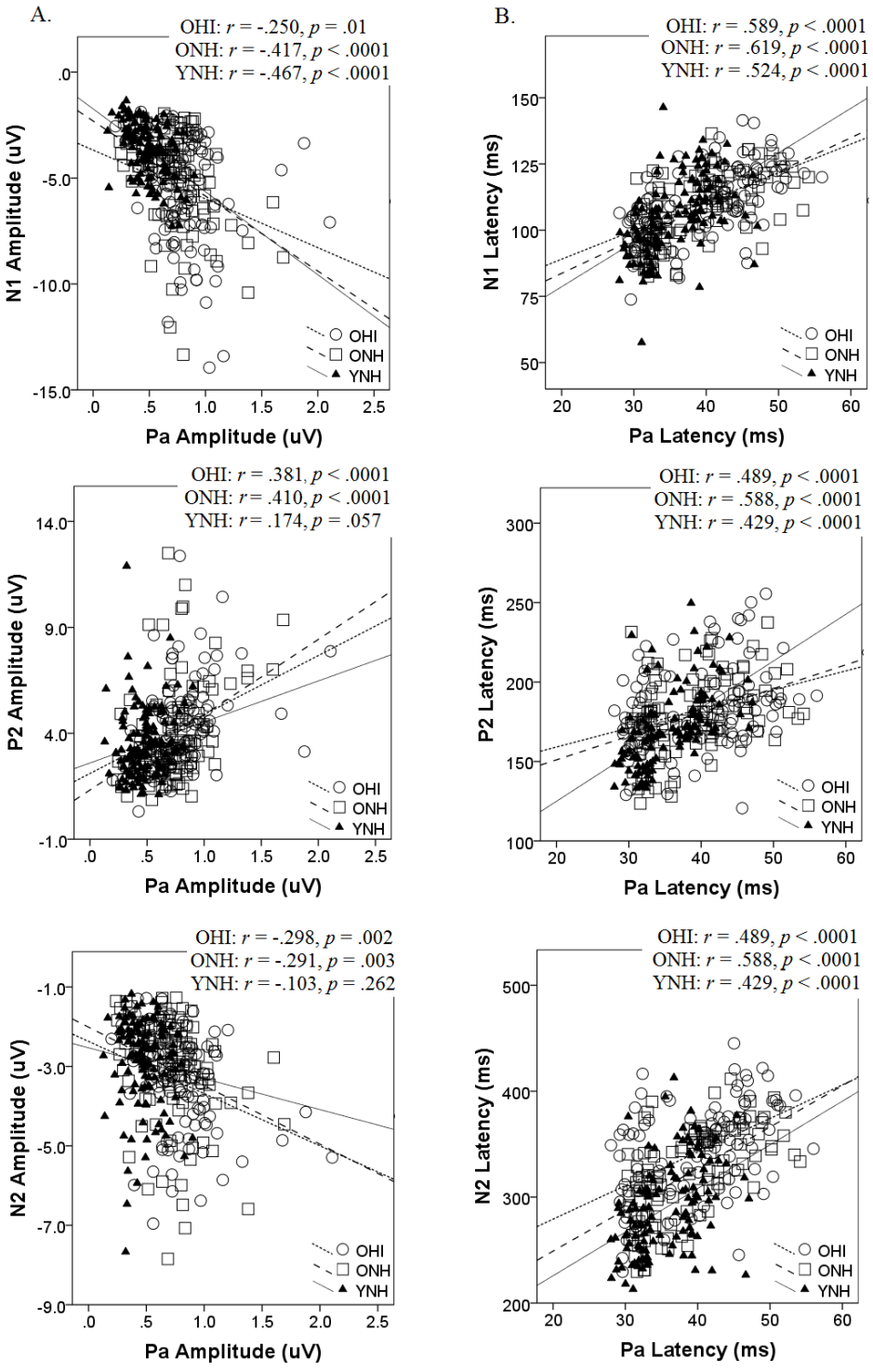


Figure 5.3-1. Relationships between Pa and each of ALLR components: (A) All significant correlations bewteen AEP amplitudes except for two pairs (i.e., Pa vs. P2 and Pa vs. N2) in YNH group. (B) All significant correlations between AEP latencies for all pairs in three groups. Open circles, open squares and filled triangles denote OHI listeners, ONH listeners, and YNH listeners, respectively. Dotted lines, dashed lines, and thin lines denote regression lines fitted to OHI listeners, ONH listeners and YNH listeners, respectively. Correlations are significant at the 0.01 level (2-tailed).

Figure 5.3-1 shows scatterplots to represent the relationship between AMLR Pa and ALLR components. Graph (A) plots Pa amplitudes against the amplitudes of each ALLR component classified by listener groups and graph (B) plots Pa latencies against the latencies of each ALLR component classified by listener groups. All scatterplots of relationships between latencies show significant positive relationships for all listener groups, indicating that prolonged Pa latencies may predict prolonged latencies of N1, P2, and N2. The scatterplot of Pa amplitudes against N1 amplitudes showed a significant negative relationship for all listener groups. The scatterplot of Pa amplitudes against P2 amplitudes showed a significant positive relationship for both OHI and ONH groups. The scatterplot of Pa amplitudes against N2 amplitudes showed a negative relationship for both older listener groups. Both ONH and OHI listeners demonstrated significant relationships beween amplitudes of Pa and all components of ALLRs, indicating that enhanced Pa amplitudes may predict enhanced amplitudes of N1, P2, and N2. However, YNH listeners demonstrated only significant relationship between Pa amplitudes and N1 amplitudes, indicating that larger Pa amplitudes correspond with larger N1 amplitudes.

5.4. Electrophysiological Correlates of R-SPIN-LP Scores

The group differences in R-SPIN-LP scores were evaluated for three listener groups using a one-way ANOVA. Table 5.4-1 presents means and standard deviations of R-SPIN-LP scores for three listener groups. The ANOVA analysis revealed a significant group difference in R-SPIN-LP scores (F (2, 79) = 40.767; $p < .0001$). Bonferroni post-hoc test was conducted to confirm where the group difference occurred. Post-hoc results revealed significant group differences between OHI and ONH groups ($p < .0001$), and between OHI and YNH groups ($p < .0001$). As depicted in Figure 5.4-1, OHI group produced significantly lower R-SPIN-LP scores than both ONH and YNH groups, indicating that OHI listeners are significantly poorer at perceiving speech in noise than both ONH and YNH groups. There was no significant difference in R-SPIN-LP scores between ONH and YNH groups.

Table 5.4-1.

Means and standard deviations of R-SPIN-LP scores for three listener groups.

Group	Means	Std. Deviations
OHI (N=26)	64	18.76
ONH (N=26)	86.46	6.70
YNH (N=30)	90.80	5.57

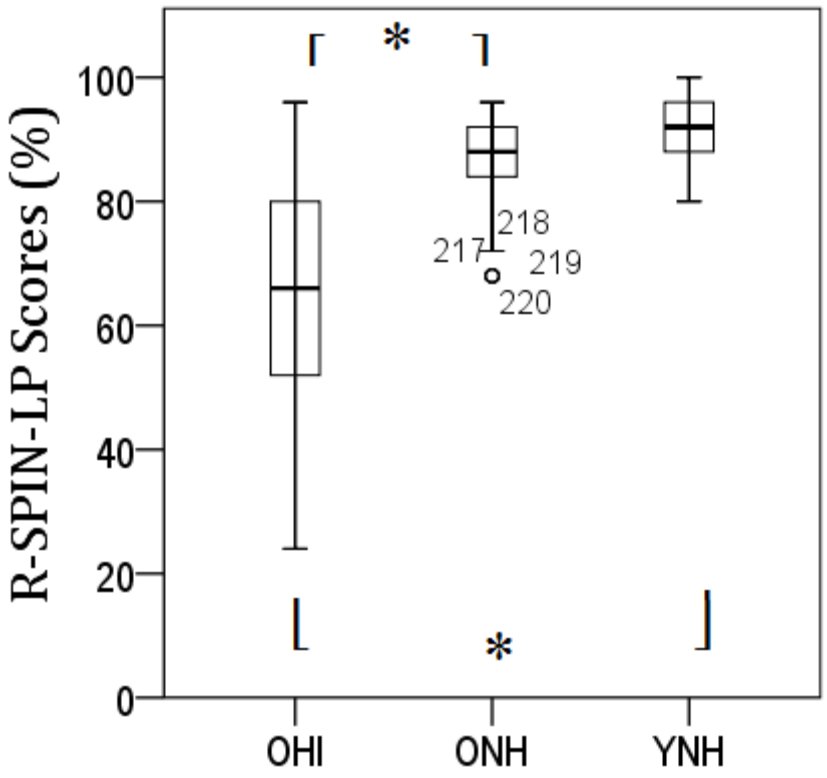


Figure 5.4-1. Comparisons of R-SPIN-LP scores among three listener groups. Significantly lower R-SPIN-LP scores in OHI than both ONH and YNH groups, with no significant difference in R-SPIN-LP scores between ONH and YNH groups. The box represents the range of the middle 50% of responses. The top horizontal line represents the upper 25% of responses and the bottom horizontal line represents the lower 25% of responses. The thick horizontal line in the middle of the box represents the median. Labeled circles represent outliners. Asterisks (*) indicate that the mean difference is significant at the .05 level.

To determine electrophysiological correlates of SIN perception in older listeners, the correlations of R-SPIN-LP scores with the amplitudes and latencies of each AEP component (i.e., Pa, N1, P2 and N2) were evaluated for both ONH and OHI listener groups. Table 5.4-2 provides Pearson's correlation coefficients for identifying significant relationships of R-SPIN-LP scores with the amplitudes and the latencies of each AEP component by listener group.

Table 5.4-2.

Correlations of R-SPIN-LP scores with amplitudes and latencies of each AEP component by listener group

		Amplitudes				Latencies			
R-SPIN-LP		Pa	N1	P2	N2	Pa	N1	P2	N2
YNH	*r*	.046	-.092	.122	-.140	-.103	.168	.233	.080
	p	.808	.629	.520	.461	.587	.375	.216	.675
ONH	*r*	-.630*	.199	-.391*	.273	.033	.350	.205	-.188
	p	.000	.330	.048	.178	.875	.079	.314	.357
OHI	*r*	-.574*	.10	-.207	.446*	-.034	.002	-.155	-.636*
	p	.002	.638	.310	.022	.869	.992	.448	.000

* Correlation is significant at the 0.05 level.

ONH group showed moderate-to-strong, significant negative correlations of R-SPIN-LP scores with Pa amplitudes and P2 amplitudes, indicating that reduced R-SPIN-LP scores are significantly related to enhanced Pa and P2 amplitudes in ONH listeners. OHI group showed a moderate, significant negative correlation of R-SPIN-LP scores with Pa amplitudes and a moderate, significant positive correlation of R-SPIN-LP scores with N2 amplitudes, indicating that reduced R-SPIN-LP scores are significantly related to enhanced Pa and N2 amplitudes in OHI listeners. The positve correlation between R-SPIN-LP scores and N2 amplitudes stems from negative values of N2 amplitudes. In addition, there was only one strong, significant negative correlation of R-SPIN-LP scores with N2 latencies in OHI group, indicating that reduced R-SPIN-LP scores are significantly related to prolonged N2 latencies in OHI listeners. There were no statistically significant correlations of R-SPIN-LP scores with latency measures in ONH group. YNH group demonstrated no significant correlations of R-SPIN-LP scores with any of the amplitude or latency measures.

To better understand relationship between SIN perception and electrophysiological responses, correlations of R-SPIN-LP scores with the amplitudes and latencies of AEP components were measured as a function of stimulus type and noise condition by group.

Figure 5.4-2 depicts the significant relationships between SIN perception and AEP amplitudes by plotting R-SPIN-LP scores against the amplitudes as a function of stimulus type and noise condition by listener group. ONH listeners showed strong, significant negative relationships of R-SPIN-LP scores with Pa amplitudes for syllable /ba/ in Quiet and Babble, and moderate, significant negative relationship with Pa amplitudes for 500 Hz tone burst in Quiet. Also, ONH listeners showed moderate, significant negative relationships of R-SPIN-LP scores with P2 ampltiudes for 500 Hz tone burst and syllable /ba/ in Quiet. In ONH listeners, age-

related reduction in SIN perception may be accounted for by age-related enhancement of the following amplitudes: (1) Pa amplitudes for 500 Hz tone burst in Quiet, (2) Pa ampltiudes for syllable /ba/ in both Quiet and Babble, (3) P2 amplitudes for syllable /ba/ in Quiet, and (4) P2 amplitudes for 500 Hz tone burst in Quiet. OHI listeners showed moderate, significant negative relationships of R-SPIN-LP scores with Pa amplitudes for 500 Hz tone burst and syllable /ba/, independent of noise condition. In addition, OHI listeners showed moderate, significant postivie relationships of R-SPIN-LP scores with N2 ampltiudes for 500 Hz tone burst in Babble and syllable /ba/ in Quiet. In OHI listeners, age-related reduction in SIN perception may be accounted for by the following amplitudes: (1) Pa amplitudes for 500 Hz tone burst in both Quiet and Babble, (2) Pa amplitudes for syllable /ba/ in both Quiet and Babble, (3) N2 amplitudes for 500 Hz tone burst in Babble, and (4) syllable /ba/ in Quiet. Collectively, these results indicate that age-related reduction in SIN perception may be better accounted for by the enhanced Pa amplitudes for syllable /ba/ in both ONH and OHI listeners.

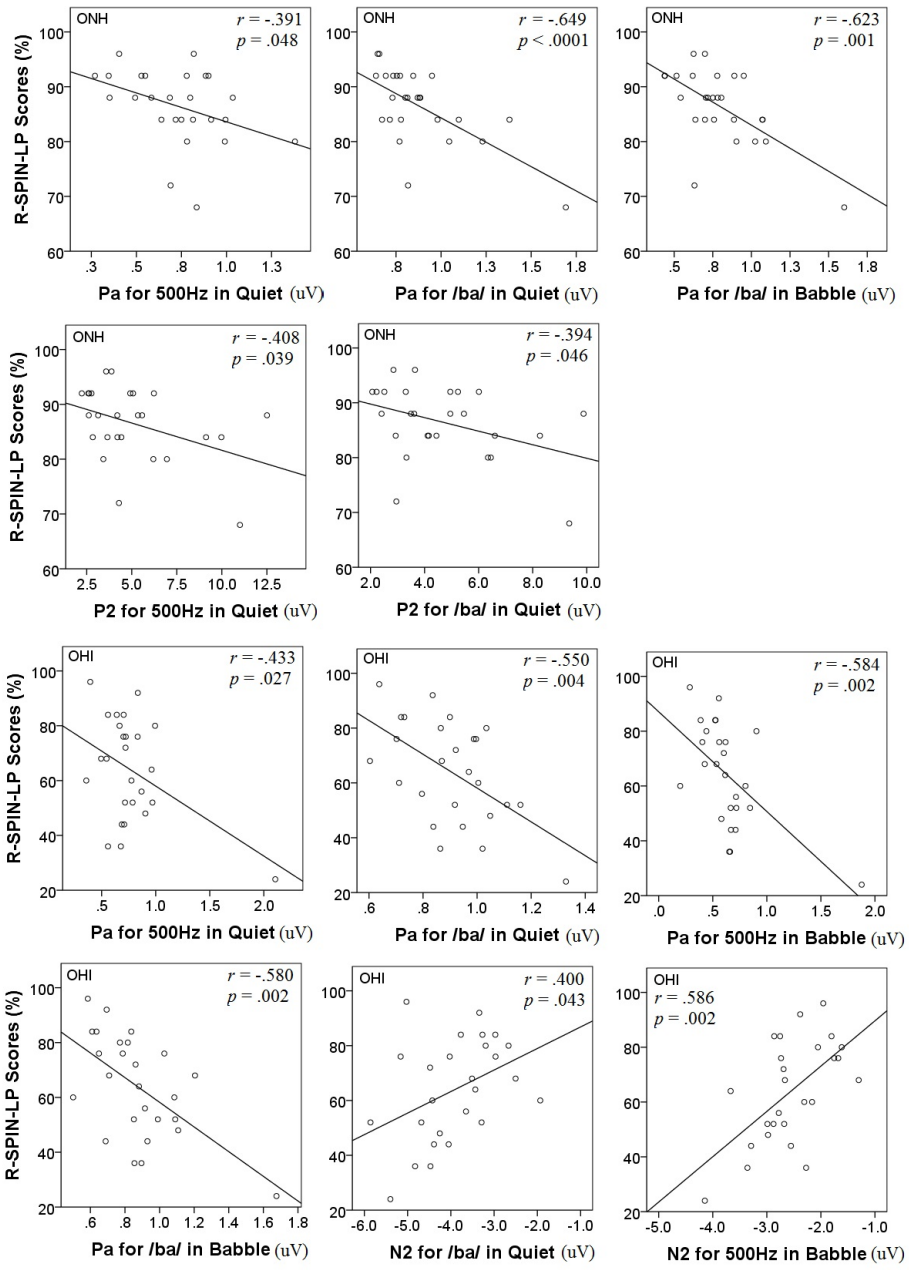


Figure 5.4-2. Scatterplots showing significant relationship between R-SPIN-LP scores and AEP amplitudes as a function of stimulus type and noise condition for ONH and OHI groups. The upper two panels show five significant negative correlations of R-SPIN-LP scores with the following amplitudes for ONH group: Pa amplitudes for 500 Hz tone burst in Quiet, Pa amplitudes for syllable /ba/ in Quiet and Babble, P2 amplitudes for 500 Hz tone burst in Quiet, and P2 amplitudes for syllable /ba/ in Quiet. The lower two panels show four significant negative and two significant positive correlations of R-SPIN-LP scores with the following amplitudes for OHI group: Pa amplitudes for 500 Hz tone burst in Quiet and Babble, Pa amplitudes for syllable /ba/ in Quiet and Babble, N2 amplitudes for syllable /ba/ in Quiet, and N2 amplitudes for 500 Hz tone burst in Babble. Significant relationships indicate that poorer R-SPIN-LP scores are significantly related to larger amplitudes of the corresponding components in ONH (i.e., Pa and P2) and OHI (i.e., Pa and N2) listeners. Correlations are significant at the .05 level.

Figure 5.4-3 depicts the significant relationship between SIN perception and AEP latencies by plotting R-SPIN-LP scores against the latencies as a function of stimulus type and noise condition by listener group. ONH group demonstrated a strong, significant negative relationship between R-SPIN-LP scores and N2 latencies for syllable /ba/ in the Babble, indicating that lower R-SPIN-LP scores are significantly related to longer N2 latencies for syllable /ba/ in the Babble for ONH listeners. While there was no significant relationship found between R-SPIN-LP scores and total N2 latencies (i.e., collapsed across stimulus types and noise conditions) in ONH listeners, their R-SPIN-LP scores were highly and significantly correlated with N2 latencies for syllable /ba/ in the Babble. Theses results indicate that the relationship between R-SPIN-LP scores and N2 latencies may be contingent on stimulus type and/or noise condition. In ONH listeners, reduced SIN perception may be better accounted for by delayed N2 latencies for syllable /ba/, speech sound, in the Babble. In OHI listeners, lower R-SPIN-LP scores were highly correlated with longer N2 latencies for syllable /ba/ in both Quiet and Babble, indicating that age-related reduction in SIN perception may be accounted for by age-related prolongation of N2 latencies for syllable /ba/, speech sound, regardless of whether or not the babble background is presented. Taken together, delayed N2 latencies elicited by speech sounds such as syllable /ba/, in the presence of the babble background, may serve as an electrophysiological indicator of reduced SIN perception with advancing age. Besides, enhanced Pa amplitudes for syllable /ba/ may also serve as electrophysiological index of age-related reduction in SIN perception in older listeners.

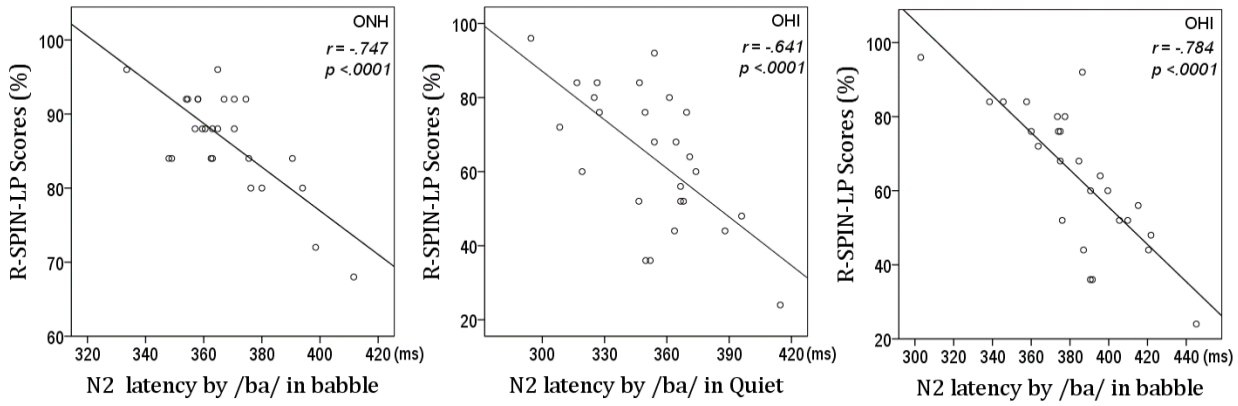


Figure 5.4-3. Scatterplots showing relationship between R-SPIN-LP scores and AEP latencies as a function of stimulus type and noise condition for ONH and OHI groups. Scatterplots of R-SPIN-LP scores against N2 latencies for syllable /ba/ in the Babble with the regression line fitted to the data of 26 ONH listeners (left graph), representing a significant negative relationship of R-SPIN-LP scores with N2 latencies for syllable /ba/ in Babble for ONH group. Scatterplots of R-SPIN-LP scores against N2 latencies for syllable /ba/ in Quiet (middle graph) and Babble (right graph) with the regression line fitted to the data of 26 OHI listeners, representing the significant correlations of R-SPIN-LP scores with N2 latencies for syllable /ba/ in Quiet and Babble for OHI group. Significant negative correlations indicate that poorer R-SPIN-LP scores are significantly related to more prolonged N2 latencies for syllable /ba/. Correlations are significant at the .05 level.

Chapter 6:

Discussion

6.1. Effects of Aging and Age-related Hearing Loss on AEP morphology

6.1.1. Major findings

The first hypothesis, which postulates the differential effects of aging and hearing loss on morphological changes in AEP responses, was examined by comparing three listener groups (i.e., YNH, ONH and OHI listeners) for the amplitudes and latencies of AMLRs and ALLRs (i.e., Pa, N1, P2 and N2) as a function of stimulus type (i.e., 500 Hz tone burst and syllable /ba/) and noise condition (i.e., Quiet and Babble)

The effects of aging produced significantly enhanced amplitudes of Pa and N1, and significantly prolonged latencies of Pa, P2, and N2 in ONH relative to YNH group. The effects of hearing loss produced only significantly prolonged N2 latencies in OHI relative to YNH group. The combined effects of aging and hearing loss produced significantly enhanced amplitudes and significantly prolonged latencies across all AEP components in OHI relative to YNH group, suggesting that the interplay between effects of aging and hearing loss may have a stronger impact on morphological changes in AEP responses, as compared to the separate effects of aging and hearing loss on AEP morphology. Age-related changes in AEP morphology become prominent in combination with hearing loss.

AEP morphology changes as a function of stimulus type and noise condition. For all listener groups, Pa and N1 amplitudes were significantly larger for syllable /ba/ than 500 Hz tone

burst, and N2 amplitudes were significantly larger for 500 Hz tone burst than syllable /ba/. P2 amplitudes were significantly larger for 500 Hz tone burst than syllable /ba/ in YNH and ONH groups but were not significantly different between stimulus types in OHI group. The changes in P2 amplitudes as a function of stimulus type may be affected by age-related hearing loss, while the effects of stimulus types on the changes in the amplitudes of Pa, N1, and N2 may be similar among groups, irrespective of aging and/or hearing loss. The amplitudes of all AEP components were significantly reduced in babble versus in quiet. With respect to changes in AEP latencies, syllable /ba/ elicited significantly longer latencies than 500 Hz tone burst across all AEP components for all listener groups, irrespective of aging and/or hearing loss. In line with the reduction of AEP amplitudes induced by the babble masker, the latencies of all AEP components were significantly prolonged in babble versus in quiet for all listener groups, indicating the effects of babble masker on the latency prolongation, irrespective of aging, hearing loss, or both. Prolonged latencies for speech stimulus, syllable /ba/, may reflect slower neural processing of complex acoustic signals like speech sound. Prolonged AEP latencies for syllable /ba/ relative to 500 Hz tone burst were more delayed than those for 500 Hz tone burst in Babble, indicating slower neural processing of speech sounds in speech-like background noise. Such a latency prolongation appears to be greater for the later components.

The age-related enhancements of Pa and N1 amplitudes were clearly observed in ONH relative to YNH group for both syllable /ba/ and 500 Hz tone burst in both babble and quiet, indicating that Pa and N1 amplitudes, which reflect early stages of auditory processing at subcortical and cortical levels, may be susceptible to the aging per se, compared to P2 and N2 amplitudes, which reflect later stage of auditory processing at multiple cortical levels. P2 and N2 amplitudes were, however, significantly enhanced in OHI relative to YNH group for syllable

/ba/ in both quiet and babble, indicating that the combination of aging and hearing loss, age-related hearing loss, may have stronger effects on the age-related increase in the amplitudes of all AEP components. In general, the longer the latencies of the AEP components, the more likely it is to reflect higher-order sensory processing of spectrotemporal features (Ceponiene et al., 2005). Significantly enhanced P2 and N2 amplitudes for syllable /ba/ in OHI listeners, independent of noise condition, indicate that age-related hearing loss may affect auditory sensory processing at multiple levels of central auditory pathway, in particular, for a speech sound comprised of complex acoustic features. Age-related morphological changes in the amplitudes of later components of cortical responses may be further compounded by the combined effects of aging and hearing loss, compared with the effects of aging per se. On the other hand, morphological variations related to hearing loss were not significantly different between ONH and OHI groups in the amplitudes of all AEP components.

With respect to age-related changes in AEP latencies, aging per se induced significantly prolonged AEP latencies of the following components in ONH relative to YNH group: (1) Pa latencies for syllable /ba/ in both quiet and babble, (2) P2 latencies for 500 Hz tone burst in babble, and (3) N2 latencies for both 500 Hz tone burst and syllable /ba/ in both quiet and babble. Age-related hearing loss has a stronger effect on the prolongations of AEP latencies in OHI relative to YNH group. Similar to the outcomes produced by the effects of ageing per se, OHI listeners produced significantly prolonged Pa latencies for syllable /ba/ in quiet and babble, significantly prolonged P2 latencies for 500 Hz tone burst in babble, and significantly prolonged N2 latencies for both 500 Hz tone burst and syllable /ba/ in both quiet and babble. Besides, OHI group showed additional prolongations of the following latencies: (1) N1 latencies for 500 Hz tone burst in both quiet and babble, and (2) P2 latencies for 500 Hz tone burst in quiet. N1

latencies, which reflect the earlier stage of cortical processing, may be less sensitive to age-related delays in auditory neural timing at the cortical level in ONH listeners, compared with the later components of cortical responses such as P2 and N2, which reflect later stages of cortical processing. N2 latencies, the last component of ALLRs, which is the later-occuring obligatory cortical response in the passive-listening paradigm, produced marked age-related prolongations. N2 latencies are more likely to reflect age-related delays in auditory neural timing in both ONH and OHI listeners, possibly reflecting the accumulated latency of age-related delays in synaptic transmission along the auditory pathway. ONH group showed significantly prolonged N2 latencies for syllable /ba/ in both quiet and babble, compared with YNH group. OHI group showed significantly prolonged N2 latencies for both 500 Hz tone burst and syllable /ba/ in both quiet and babble, compared with YNH group, indicating that age-related hearing loss may have stronger effects on the prolongations of N2 latencies than the effects of aging per se. Significant prolongation of N2 latencies in OHI listeners may reflect increased processing loads of sensory integration of spectrotemporal information. Age-related prolongation of N2 latencies may indicate the age-related slowing of processing speed (e.g., Harris et al., 2012), and the addition of hearing loss may compound slowed processing speed, manifested as increased prolongation of N2 latencies.

6.1.2. Age-related changes in each AEP component

In the present study, the age-related changes in AEP morphology have been demonstrated as enhanced amplitudes and prolonged latencies across all components of AMLRs and ALLRs. The age-related morphological changes became more intensified in combination with (age-related) hearing loss, when elicited at suprathreshold level by a taskless (stimulus-driven) passive recording paradigm at suprathreshold level. Some previous studies, in agreement with the present findings, support amplitude enhancement (e.g., Pfefferbaum et al., 1984; Amenedo & Diaz, 1998; Ford & Pfefferbaum, 1991; Tremblay et al., 2003) or latency prolongation (e.g., Goodin et al., 1978; Picton et al., 1984; Lenzi et al., 1989; Barrett et al., 1987; Tremblay et al., 2003; Lister et al., 2011) of cortical responses, associated with aging per se or age-related hearing loss. However, other studies have reported no age-related changes in amplitudes (e.g., Torre & Fowler, 2000; Brown et al., 1983; Picton et al., 1984; Barrett et al., 1987) or latencies (e.g., Brown et al., 1983; Ford & Pfeffebaum et al., 1991; Woods, 1992; Polich, 1997; Amenedo & Diaz, 1998). As such, conflicting results of studies on age-related electrophysiological changes may be due to methological differences. For example, the obligatory (exogenous) potentials of task-irrelevant features are dependent on stimulus charactersistics without regard to the subjects's attention to stimuli in a passive listening condition (i.e., ignoring a train of a repeating stimulus - homogenous paradigm). The obligatory AEP responses in the present study, which have been recorded using repeating stimuli in the passive listening condition, are different from endogenous (event-related) potentials that are recored in an active listening condition such as an oddball paradigm task, in which cognitive variables such as attention and stimulus context effects (e.g., target/standard discrimination task) are allocated. The components of ALLRs, which are likely to have both exogenous and endogenous chanracersitics, are altered

differentially in response to the attended and ignored stimulus, while the waveform morphology of AMLRs that are predominantly exogenous are not changed by paying attention to the stimulus. In general, the longer the latency of the AEP, the more likely it is to have endogenous influences. That is, attention has stronger endogenous effects on later AEPs, such as N2 component. Prior studies of auditory attention (Picton et al., 1971; Picton & Hillyard, 1974) have demonstrated how paying attention to stimuli has a greater effect on cortical AEPs and little to no effect on earlier evoked potentials up to AMLRs. N1 and P2 amplitudes were consistently and significantly enhanced in the elderly relative to young adults during unattended and attended listening conditions (Alain & Woods, 1999; Amenedo & Diaz, 1999; Ceponiene et al., 2008), with significantly prolonged P2 latencies and no or little prolonged N1 latencies (e.g., Picton et al., 1984; Iragui et al., 1993; Tremblay et al., 2003, 2004), in agreement with our findings which showed significant age-related enahncment of N1 and P2 ampltiudes, with significant age-related prolongation of P2 latencies. General findings of N2 component, however, are significantly diminished or absent N2 amplitudes (e.g., Chao & Knight, 1997; Bertoli & Probst, 2005; Ceponiene et al., 2008) and significantly prolonged N2 latencies (e.g., Iragui et al., 1993; Ceponeien et al., 2008) in the elderly, compared with young adults, in the attended condition. These previous findings showing the diminution of N2 amplitude with advancing age are not consistent with the present findings which showed significantly enhanced N2 amplitudes in OHI listeners and slightly but insignificantly enhanced N2 amplitudes in ONH listeners, possibly resulting from the following major methodological differences: listening condition, electrode location, stimulus intensity, and stimulus type. The present results are recorded in the passive listening condition, in which listeners ignored repeating stimuli and watched a mute movie, in order to minimize the effects of attention on stimulus processing. Further, it is known that N2

amplitude increases when sensory processing is "disconnected" from perceptuo-cognitive processing, for example, during sleep (Paavilainen et al., 1987) or when inhibitory capacities are immature, as in young children (Ceponiene et al., 2005), similar to increased overall electroencephalogram (EEG) amplitudes during relaxed vs. alert states (e.g., predominance of alpha vs. beta rhythm, respectively) (Ceponiene et al., 2008). In the same vein, N2 enhancment associated with age-related hearing loss for the passively elicited cortical AEP components may reflect the diminished capacity of central inhibition in automatic stages of auditory processing, separate from attention-related processing. Differences in N2 amplitudes contingent on the involvement of attention to listening task, that is to say, age-related enhancement in a passive homogenous paradigm vs. age-related diminution in an active oddball paradigm, may indicate that exogenous (i.e., externally driven, involutary, bottom-up) and endogenous (i.e., internally driven, voluntary, top-down) responses at the later stage of auditory processing indexed by the N2 are more likely to reflect distinct neural mechanisms that affect auditory processing in different ways. Age-related inefficiency of automatic (bottom-up) auditory processing may be modified by cognitive operations, such as allocation of attention or memory, by switching to top-down controlled process (for a review, see Alain et al., 2004). At this later stage of auditory processing, N2 could be an index of proactive control processes (Harris et al., 2012) as a stage of sensory processing preceding P3 that indexes cognitive processing.

Speech sounds, in addition to tonal sounds which have been typically recorded in previous research, were recorded at suparthrehold intensity level for reducing the confounding effects of audibility differences due to hearing loss on morphological alterations. N2 component is barely distinguishable from background activity but is rather prominent in the waveform when tied to a high enough stimulus intensity. Provided that attention is not actively engaged in the

listening condition, N2, which is dominated by exogenous characteristics, is dependent on the physical characteristics of stimulus, such as stimulus intensity. In particular, suprathreshold stimulation overexcites stimulus-evoked neural activity in the aging auditory system, in which the strength of inhibitory synapses is scaled down and the strength of excitatory synapses is scaled up to compensate for sensory deprivation following age-related cochlear degeneration, thereby resulting in central gain enhancement (e.g., Salvi et al., 1990; Qiu et al., 2000; Eggermont, 2017; Salvi et al., 2017). Suprathreshold stimulation is more likely to reveal age-related functional changes in central auditory system. In fact, several studies (Qiu et al., 2000; Salvi, Wang, & Ding, 2000; Chen et al., 2015) have proved that suprathreshold local field potential amplitudes in the medial geniculate body, auditory cortex, and lateral amygdala increased rapidly and, in turn, exceeded normal level of amplitudes despite the reduced sensory input, in contrast to the reduced amplitude of the compound action potentials roughly proportional to the reduced cochlear output. The paradoxical increase in suprathreshold amplitudes at higher auditory centers, despite the reduction in the output of the cochlea, indicates that neural amplification involved in central gain gradually increases from peripheral to more central auditory loci (e.g., Lu et al., 2011; Chen et al., 2015).

Historically, cortical AEP components have been recorded using nonspeech sounds such as short or long tonal stimuli in aging research. Though the number of AEP studies that use speech sounds is growing, little is yet known about age-related differences in AEP results on neural processing of speech sounds which contain time-varying spectral properties. Indeed, most of the above-mentioned studies used tonal sounds to elicit AEP responses, demonstrating equivocal findings on age-related differences in AEP morphology. In the present study, age-related differences in the later portion of obligatory cortical responses as indexed by P2 and N2

components of ALLRs became more pronounced in response to syllable /ba/ rather than 500 Hz tone burst, as shown in the significant age-related enhancement of amplitudes for syllable /ba/ in older adults with age-related hearing loss. These present results provide the evidence substantiating the importance of speech sound as a stimulus for identifying age-related changes in AEP morphology, in particular, at the later stage of auditory processing. Along with significant age-related enhancement of P2 and N2 amplitudes for syllable /ba/ in OHI relative to YNH group, the significant prolongation of N2 latencies in OHI relative to YNH group provides further evidence supporting the importance of speech sound as a stimulus to evaluate auditory processing in older adults, in line with a theoretical account of age-related slowdown of processing speed.

In previous studies, another major contributor to equivocal findings on age-related changes in AEP morphology is the electrode location. A number of studies have reported the AEP results arising from different electrode locations or multiple electrode configurations, which yielded inconsistent findings across different electrode locations in electrophysiological studies of aging human auditory system. Some authors have reported a significant interaction between age and electrode location for cortical AEP components. Anderer et al. (1996) reported that N1 and P2 latencies were dependent on electrode position, demonstrating increased N1 latency posteriorly and increased P2 latency anteriorly with advancing age. However, N2 latency was consistently increased at 17 different locations including Cz, Fz and Pz with advancing age. Concerning age-related changes of N2, Iragui et al. (1993) found an increase in the amplitude and the latency at Cz and Pz, but Enoki et al. (1993) reported a decrease in the amplitude at Fz. Iragui et al. (1993) reported more pronounced N1 amplitude at lateral sites (T5, T6) and more pronounced P2 amplitude at central sites (C3, C4), with no significant age-dependent effects on

N1 and P2 amplitudes. However, N1 and P2 latencies have been reported to be significantly increased at midline sites (Cz, Pz) with advancing age. The significance of electrode locations in the assessment of age-related electrophysiological changes in central auditory system converges with age-related shifts in topographic maps, which reflect age-dependent changes in generator activity caused by age-related functional reorganization of central brain network. Indeed, several authors (Friedmane et al., 1993; Iragui et al., 1993; Anderer et al., 1996) have reported that frontal scalp activity shifted and spread to more central and lateral foci for the longer latency cortical component indexed by N2 in older adults, as compared with more forntal activity in young adults. N2 amplitudes were increased at the central and parietal electrode sites and decreased at the frontal site with advancing age, as compared with more pronounced N2 amplitudes at the frontal site in young adults. N2 component is generally thought to arise from the frontal lobes, limbic system, or other obscure subcortical strucutres. Ditributed neural activity over the frontal, central, and parietal regions at and around the midline (Cz, Pz) for N2 component may reflect age-relatd shifts in N2 generator activity, possibly associated with cortical neuroplasticity due to age-related declines in frontal lobe function. In line with their findings, significantly enhanced N2 amplitudes associated with age-related hearing loss in our findings, which have been recorded at Cz electrode location, may also reflect age-related functional changes in N2 generator activity probably caused by age-related alteration of frontal cortical activity. Additionally, significant age-related prolongation of N2 latency may reflect delayed integrative processing of sensory information at higher-order cortical areas, as a result of increasing difficulties and efforts in synchronizing neural acitivies across widely distributed cortical areas rather than frontally focused neural activities, which were observed in young adults

(e.g., Friedman et al., 1993). Neurophysiological mechanism underlying age-related changes in AEP morphology will be discussed in later sessions.

6.1.3. Effects of physical stimulus parameters on AEP morphology

The effects of stimulus types on AEP amplitudes and latencies are attributed to different spectrotemporal characteristics of tone burst (simple and brief nonspeech signal) versus consonant-vowel (CV) syllable (acoustically complex speech signal). Spectrotemporal characteristics of the stimulus include, but are not limited to, duration, rise time (i.e., stimulus onset), intensity, frequency and interstimulus interval.

In the present study, the significant difference in AEP latencies as a function of stimulus type (500 Hz tone burst vs. syllable /ba/) may result from the difference in the overall stimulus duration and the rise time. For example, if stimulus duration is decreased, particularly shorter than 30ms, and rise time is short and more rapid, the latencies decrease. In this study, the respective stimulus durations were 20ms of 500 Hz tone burst and 115 ms of syllable /ba/. The rise time of 500 Hz tone burst was 5ms, with more rapid stimulus onset; on the other hand, the rise time of syllable /ba/ was around 30-40 ms, which accorded with the time of amplitude envelope rise slope that includes the time of stop release and time of maximum amplitude of sound envelope. AEP latencies were significantly prolonged for syllable /ba/ relative to 500 Hz tone burst in both Quiet and Babble, irrespective of the effects of aging and/or hearing loss, possibly resulting from longer stimulus duration and increased rise time for syllable /ba/ relative to 500 Hz tone burst, consistent with the previous findings that AEP latencies increased with increasing stimulus rise time (Kodera et al., 1979). In particular, little is known about recordings of AMLRs in response to speech signials. The age-related latency prolongation of AMLRs

remains controversial to date. Therefore, it may be worthy of note that age-related difference in Pa latencies was found for speech stimulus, syllable /ba/. The significantly prolonged Pa latencies for syllable /ba/ relative to 500 Hz tone burst in the Babble may occur because of spectrotemporal features of syllable /ba/ that contain double sound onsets, the first of which has an increased rise time relative to a brief onset of 500 Hz tone burst. In addition, the acoustic complexity of speech sound may result in a delayed and less synchronized neural discharge especially in the presence of babble noise, more adversely affected by the interaction with fluctuating background noise.

The significant differences in AEP amplitudes as a function of stimulus type may result from differences in interstimulus interval and spectra compositions between stimulus types. 500 Hz tone burst consists of one tone for the center frequency of 500Hz, with constant energy density for stimulus duration, and syllable /ba/ consists of multiple frequency bands, with spectral energy reduction in the later portion of the stimulus. There were differences in the interstimulus interval between 500 Hz tone burst (1400 ms) and syllable /ba/ (1300 ms). Increasing the interstimulus interval serves to enhance later AEP components such as P2 (e.g., Hari et al., 1982). The dense spectral region with more energy in the earlier portion of /ba/ stimulus may contribute to larger amplitudes of early AEP components such as Pa and N1, while spectral energy reduction in the later portion of syllable /ba/ and shorter interstimulus interval than 500 Hz tone burst may result in the reduced amplitudes of later AEP components such as P2 and N2.

The present findings, which showed larger Pa and N1 amplitudes for syllable /ba/ and larger P2 and N2 amplitudes for 500 Hz tone burst, were comparable to the findings of previous investigators. In previous studies, tonal stimuli versus speech stimuli, in general, resulted in

shorter P1-N1-P2 latencies with equivocal findings of the amplitude change. Eulitz et al. (1995) reported significantly longer N1 peak latencies for synthetic German vowels versus 1000Hz tone and no significant differences in N1 amplitudes between speech and tonal stimuli. Tiitinen et al. (1999) recorded N1-P2 responses to both 535 Hz tonal and synthetic vowel stimuli and found significantly larger N1-P2 amplitudes and significantly longer N1 latency in response to the vowel versus the tonal stimulus. P2 latencies were reported to be significantly shorter when elicited by the tonal versus vowel stimulus. Ceponiene et al. (2001) found smaller amplitudes and longer latencies of N250 (equivalent to N2) in response to the vowel token versus tones. In a follow-up study, Ceponiene et al. (2005) reported larger N1 and P2 amplitudes when evoked by the complex tonal stimulus comprised of five sinusoidal tones versus the syllable. According to the findings of Swink and Stuart (2012), the latencies of P1-N1-P2 components were significantly shorter when evoked by 723 Hz tone burst versus vowel stimulus. With respect to P1-N1-P2 amplitudes, P1 component was significantly smaller when evoked by the tone burst versus the speech stimulus, whereas N1 and P2 components were significantly larger when evoked by the tone burst versus the speech stimulus. Altogether, the tonal stimulus consistently elicited shorter latencies of cortical responses (i.e., P1, N1, P2 and N2) compared with the speech stimulus. In addition, their results showed that P1 and N1 amplitudes were significantly larger in response to the speech versus the tonal stimulus and P2 and N2 amplitudes were significantly larger in response to the tonal versus the speech stimulus, with equivocal findings of N1 amplitudes.

In the present study, the amplitudes of all AEP components were significantly reduced in Babble relative to Quiet for all three groups. The latencies of all AEP components were significantly prolonged in Babble versus Quiet for all listener groups. These results agree well

with previous studies on the effects of noise masking on cortical responses (e.g., Nousak & Stapells, 2005; Whiting et al.,1998), which demonstrated increase in the latencies and decrease in the amplitudes of AEP components including Pa, N1, P2, N2 and P3 with increasing masker level.

The morphological changes in cortical responses in the presence of masking noise are involved in both peripheral and central physiological mechanisms. Peripheral mechanisms include mechanical suppression (i.e. nonlinearity) in the cochlea and auditory-nerve fibers which underlies frequency selectivity and CF (characteristic frequency)-specific threshold elevation (Costalupes et al., 1984; Ruggero et al., 1992), excitation of nerve fibers by the noise which increases their baseline discharge rate and reduces the response to the tone (Smith. 1979), and adaptation to the continuous noise which compresses the neural response by reducing the saturation discharge rate of nerve fiber response to the tone (Delgutte, 1990; Ruggero, 1992). With increasing noise level, the baseline discharge rate increase, and the saturated discharge decreases (Costalupes et al., 1984; Palmer, 1995). Nousak & Stapells (2005) have shown the masker effects in evoked potential peaks, in which masked ABR and AMLR amplitudes were reduced and became smaller with increasing noise level, reflecting the decrease in both the effective stimulus level and the number and synchrony of neuroelectric sources contributing to the neural responses as masker level increases. In central auditory mechanism, the dynamic balance between excitation and inhibition shapes the responses of central neurons to signals in noise, shifting the rate-level functions to higher levels at a faster rate than that observed in the auditory periphery (e.g., Gibson et al., 1985; Arle & Kim, 1991). At both the inferior colliculus and cortex, the suppression effects of neural responses to the tone is reduced in noise and the reduction of the saturated firing rate is smaller (Rees & Palmer, 1988; Phillips, 1990), resulting

in the enhancement of neural processing in central auditory neulei, which may be facilitated by inhibitory effects. Such central enhancement or facilitory effects may be affected by the levels of signals and noise masker (Burkard & Hecox, 1983a; Burkard & Palmer, 1997), as manifested by enhanced electrophysiological responses to higher signals relative to the level of noise masker. Furthermore, central enhancement effects become prominent with advancing age, because of age-related alteration of inhibitory effects, a disrupted balance between inhibition and excitation.

Signal levels (i.e., stimulus intensities) and signal-to-noise ratio (i.e., the difference between the signal level and the background noise level) may determine signal processing in the presence of background noise (e.g., Martin & Boothroyd, 2000; Billings et al., 2009). With respect to the effects of signal-to-noise ratio on AEP morphology, it has been reported that the interplay between suprathreshold signal levels (e.g., at least 20-30 dB above threshold) and signal-to-noise ratios have strong effects on morphological changes in cortical evoked responses for the aged population, leading to a rapid increase in the amplitudes and decrease in the latencies at the higher signal levels and higher signal-to-noise ratios (e.g., Phillips, 1987; Wang, et al., 2002; McCullagh & Shinn, 2013; Billings et al., 2015). In the aging auditory system, increased neural activity associated with age-related functional compensation may be intensitifed by suprathreshold stimulation and at higher signal-to-noise ratios. The enhanced amplitudes of cortical evoked responses in the aged population, in particular, for those who have age-related hearing loss, at high stimulus levels (e.g., Pfefferbaum et al., 1984; Amenedo & Diaz, 1999; Tremblay et al., 2003; Nousk & Stapells, 2005; Harris et al., 2007) reflect neural amplification related to the increased central gain (for a review, see Eggermont, 2017). In line with this idea, the results of the present study, which showed larger amplitudes of all AEP components in both

Quiet and Babble for both ONH and OHI groups than YNH group, may be accounted for by age-related increase in central gain or neural amplification at the suprathreshold level and at higher signal-to-noise ratio.

In this study, the reduced amplitudes of all AEP components in Babble versus Quiet for all listener groups may result from the decreased audibility and disturbed neural synchrony which are caused by the decrease in signal levels due to a noise masker, indicating the significant masking effects of background noise. The reduction in the amplitudes induced by the noise masker is consistent with previous findings that the masked cortical evoked responses produced smaller amplitudes than the non-masked responses (e.g., Martin et al., 1996; Nousak & Stapells, 2005; McCullagh & Shinn, 2013). However, the age-related difference in the masked amplitudes of cortical evoked responses is equivocal. Billings et al. (2015) demonstrated larger amplitudes of P1, P2, and N2 for young normal-hearing adults than older adults with either normal hearing or age-related hearing loss, at the signal levels of 50-80 dB SPL in the presence of a variety of noise levels, resulting in signal-to-noise ratios ranging from -10 to +35 dB. N1 amplitudes, however, were more enhanced in older adults with age-related hearing loss than both older and young adults with normal hearing sensitivity in whom N1 amplitudes were similar. In contrast, McCullagh & Shinn (2013) demonstrated significantly larger N1 and P2 amplitudes for older adults with age-related hearing loss than young normal-hearing adults at the signal level of 50 dB SL and SNRs of +20 and +10 dB. Kim et al. (2012) also demonstrated slightly larger N1-P2 amplitudes for older adults with audiometrically normal hearing than young normal-hearing adults at the signal levels of 90-100 dB SPL and at signal-to-noise ratio of +30 dB. Nousak & Stapells (2005) demonstrated that masked Pa amplitudes were enhanced and approached or exceeded normal values only at the highest stimulus level of 90 dB nHL and at the signal-to-

noise ratio of + 50 dB. In line with previous finings, the present results also demonstrated significantly larger amplitudes of cortical responses, designated as Pa, N1, P2, and N2, in Babble at the signal level of 90 dBA Leq (i.e., equivalent to 100 dB peak SPL) and at signal-to-noise ratio of + 25 dB for both OHI and ONH groups than YNH group, with slightly but insignificantly larger amplitudes of all AEP components in OHI than ONH group. One of major factors on these inconsistent findings in previous studies may be a signal level because a wide variety of threshold configuration for those who have age-related hearing loss may determine actual signal-to-noise ratios. The signal levels sufficiently higher than hearing thresholds (i.e., minimum audibility) may determine the appropriate signal-to-noise ratios for the aged population with hearing loss because hearing threshold levels may stand in for the background noise level and, in turn, produce smaller than the intended signal-to-noise ratios (for a review, see Billings, et al., 2015). In the previous studies (McCullagh & Shinn, 2013; Kim et al., 2012), increased amplitudes of cortical response to signals in noise for older adults were obtained at the signal levels of at least 30-50 dB above the poorest thresholds in the audiometric configuration and at comparable signal-to-noise ratios (i.e., +25 dB), indicating that the age-related difference in the amplitudes of cortical evoked responses may be dependent on the signal levels in the presence of background noise. The present results, which showed increased AEP amplitudes to suprathreshold signals in Babble for OHI and ONH listeners, confirm the effects of signal levels on age-related enhancement in amplitudes of cortical evoked responses in background noise.

On the other hand, the general effects of masking on the latencies of cortical responses are that the latencies increase with increasing masker level, because the reduced signal audibility due to increments in masker level may result in threshold shifts of similar magnitude of increments in masker level; therefore, decreases in latency occur with increasing signal-to-noise

ratio (Billings et al., 2009). Significantly increased N1 and P2 latencies in background noise were demonstrated in young normal-hearing listeners (e.g., Billings et al., 2009; McCullagh, Musiek, &Shinn, 2012). The age-related prolongation in the latencies of auditory cortical responses in the presence of background noise has been previously reported by some investigators, consistent with the present findings. Bertoli et al. (2005) reported longer P2 latencies at signal-to-noise ratio of 0 dB for elderly listeners with/without hearing loss compared with young normal listeners. However, there was no significant difference in P1 and N1 latencies between elderly and young listeners. McCullagh & Shinn (2013) demonstrated significantly increased P2 latencies at signal-to-noise ratios of 0, +10 and +20 dB versus in Quiet for older adults with audiometrically normal hearing at 500Hz and 1000Hz tones compared with young normal hearing adults. Their results showed no significant difference in N1 latencies at all signal-to-noise ratios (i.e., 0, +10, +20, and Quiet) between older and young listeners. Billings et al. (2015) and McCullagh et al. (2012) reported significantly prolonged N1 and P2 latencies at the poorer signal-to-noise ratios (e.g., -5, 0, and +5) in both older and young adults. The present study also showed no significant difference in N1 latencies in both Quiet and Babble at signal-to-noise ratio of +25 dB between ONH and YNH groups but significantly prolonged N1 latencies in both Quiet and Babble for OHI compared with YNH group. Pa and N2 latencies were significantly delayed in both Quiet and Babble for both ONH and OHI compared with YNH group. P2 latencies were significantly delayed in Babble for ONH group and significantly delayed in both Quiet and Babble for OHI group, as compared with YNH group. Consistent with previous findings, there was no significant difference in N1 latencies between older and younger listeners with audiometrically normal thresholds; in addition, there were sgnificantly prolonged

P2 latencies in noise for older adults with/without hearing loss compared with young normal-hearing adults.

Potential neurophysiological mechanisms underlying masking effects (i.e., background noise) on the latencies of cortical responses may be the decrease in the number of recruited neurons and disturbance in neural synchrony of multiple synaptic activities contributing to neural resources (for a review, see Eggermont 2007). Furthermore, age-related delays in the latencies may be due to a decrease in conduction rate along auditory nerve synapses, increased neural refractory period, and age-related breakdown of myelin (Papanicolaou, Loring, & Eisenberg, 1984; Peters, 2002), all of which contribute to age-related changes in neural synchrony, leading to a disruption in the normal timing of sequential events in neuronal circuits and slowing neural processing, particularly in the presence of noise.

In the present study, Pa latencies were significantly prolonged in both Quiet and Babble in both ONH and OHI groups compared with YNH group, inconsistent with the previous findings reported by Nousak & Stapells (2005). The potential reasons for the difference in these findings may reside in the stimulus type. Based on post-hoc results of this study, Pa latencies were significantly prolonged for syllable /ba/ in both Quiet and Babble for both ONH and OHI groups compared with YNH group. However, Pa latencies were not significantly different for 500 Hz tone burst in both Quiet and Babble between both older groups and YNH group. On the other hand, Nousak & Stapells (2005) recorded Pa latencies in response to 1 kHz tone burst for normal-hearing participants aged 24 to 55 years, demonstrating that the masked Pa latencies approached those of the non-masked responses at the signal levels of 80 and 90 dB nHL in the presence of masking noise at the levels of 40 and 60 dB nHL.

Previous researches have reported little or no effects of aging on the latencies of the early cortical AEP components such as P1 and N1 (e.g., Pfefferbaum et al., 1979, 1980; Papanicolaou, Loring, & Eisenberg, 1984; McCullagh & Shinn, 2013). However, the present results are equivocal in that there was no significant age-related delay in N1 latencies even in the Babble condition but significantly delayed Pa latencies in both Quiet and Babble for ONH and OHI groups compared with YNH group, indicating the significant effects of either aging per se or age-related hearing loss on Pa latencies, the earlier cortical component than N1. These equivocal outcomes may result from methodological differences such as recording parameters, for example, stimulus presentation rate, acoustic features, and analysis time window. Pa latencies of AMLRs were recorded at faster presentation rate (11.1/s) in the shorter analysis time window, separately from recordings of ALLRs in which all AEP components were simultaneously recorded at slower presentation rate (.71/s) in the longer analysis time window. However, it cannot be excluded that Pa latencies for the speech stimulus may reflect age-related difference in the early stage of cortical processing. Investigators have reported the age-related delays in cortical responses at faster presentation rate (e.g., Tremblay, Billings, & Rohila, 2004), due to increased recovery cycle of neural activity in the aging auditory system (Papanicolaou, Loring, & Eisenberg, 1984), which requires a longer refractory period of time for subsequent stimulus-induced activity (Tremblay, Billings, & Rohila, 2004; McCullagh & Shinn, 2013), thereby having a more adverse impact on synchronized neural activity of time-varying speech sounds. In this study, the age-related prolongation of Pa latencies for syllable /ba/ may be also related to the increased neural refractory period in the aging auditory system.

6.2. Age-related Changes in Interrelationships between Neuroelectric Activities

Aging, often accompanied by hearing loss, has adverse impacts on sound processing along the ascending auditory pathways and within the auditory cortices. Recent studies (e.g., Anderson et al., 2014; Schoof & Rosen, 2016) have demonstrated the age-related changes in auditory processing at both subcortical and cortical levels. For example, distorted or exaggerated sensory encoding was observed at subcortical and cortical stages of auditory processing in the aging auditory system (e.g., Bidelman et al., 2014). Subcortical- and cortical evoked responses originate from different auditory resources, reflecting distinct neural processing. The relationship between neural encodings of sounds at corical and subcortical levels is still in question.

To delineate interrelationships of neuroelectric responses between subcortical and cortical levels in hierarchical processing of auditory information, the amplitudes and latencies of AMLR Pa component were correlated with the amplitudes and latencies of ALLR components (N1, P2, and N2). Pa component is involved in neuroelectric responses from not only a part of auditory cortex but also multiple subcortical structures such as inferior colliculus, reticular formation, medial geniculate body, and thalamocortical pathway, reflecting neural processing in subcortical auditory structures. On the other hand, N1 and P2 components are primarily involved in neuroeletric responses from multiple cortical regions in temporal lobe such as supratemporal primary auditory cortex (i.e., Heschl's gyrus, planum temporale), auditory association areas, and superior temporal gyrus, and tempora-parietal cortex, reflecting cortical processing across multiple cortical areas in temporal lobe. N2 component reflects later stage of

cortical processing than N1 and P2, which is involved in neuoelectric responses from frontal lobes and limbic system.

The present results showed that enhanced Pa amplitudes were significantly correlated with enhanced ampiltudes of N1, P2, and N2 components in ONH and OHI listeners. These findings may suggest significant relationship between neuroelectric responses at subcortical and cortical levels. In other words, the early stage of auditory sensory processing occurring at subcortical levels or lower levels of neural processing may be related to the later stage of auditory processing occurring at cortical levels or higher levels of neural processing. Of note, the relationship between subcortical and cortical neural processing was not found in the ampltiudes for YNH listeners, with the exception of the relationship between Pa and N1 amplitudes, which may possiblely be attributed to overlaps between the domains of the multiple neural generators of Pa and N1 components.

The age-related group difference in relationship between auditory sensory processings at subcortical and cortical levels may be associated with age-related down-regulation of GABAergic function for the compensation of diminished auditory inputs presumably caused by age-related cochlear degeneration. Notwithstanding a reduced cochler output, neural activities from the higher levels of the central auditory system are paradoxically enhanced at suprathrehsold intensities (e.g., Salvi et al., 2000; Auerbach et al., 2014). Such an increase in the central neural activities to compensate for the loss of sensory inputs is referred to as central gain enhancement. The compensatory enhancement of central gain is predominantly attributed to increased ratio of excitation/inhibition in central auditory networks, by which the strength of excitatory synapses is scaled up and the strength of inhibitory synapses is scaled down. Increased redundancy in neuroelectric activites, which may possibly result from compensatory

enhancement of central gain in the aging auditory system, may underlie the amplitude-based interrelationships between lower- and higher levels of ascending auditory pathway.

The previous studies (e.g., Edinger et al., 1975; Alexander et al., 1976) have argued that the prefrontal cortex exerts inhibitory control over multiple subcortical and cortical regions. Knight et al. (1989) reported the functional relationship between AMLR Pa component and frontal cortical areas, suggesting that enhanced Pa ampltiudes index the loss of inhibitory control mediated by prefrontal function which is responsible for regulating primary auditory cortical activity. In animal model, it has been shown that blocking a prefronto-thalamic mechanism resulted in increased primary auditory evoked responses in the cat (e.g., Skinner & Yingling, 1976). Enhanced Pa amplitudes may reflect gating deficits of sensoy input to the auditory cortices, implemented by the prefrontal-thalamo-cortical loops, where the prefrontal function regulates thalamo-reticular inhibitory control of sensoty input to cortex (e.g., Kraus et al., 1982; Wood et al., 1988). Further evidence linking frontal lobe dysfuction and enhanced AMLRs is provided by the finding that elderly subjects with the highest percentage of errors on the Wisconsin Card Sorting Test, a putative measure of frontal lobe function, tended to generate larger amplitudes of AMLR components (Chao & Knight, 1995a, b). Taken together, all these data suggest that age-related deficits in inhibitory control within central auditory networks are linked to declining prefrontal gating, postulating ineffective top-down modulation of sensory regions by prefrotal cortex (Knight et al., 1999; Kok, 1999).

By the same token, given the normal inhibitory control of the gating mechanism, it is most likely that the irrelevant neural information lessens by the aid of efficient top-down modulation (e.g., selective attention). What is more, irrelevant neural information may be filtered out by local auditory interneurons, traveling through subcortical auditory centers to

higher cortical networks in healthy young adults. Indeed, animal models demonstrated that neural representations are typically reduced in redundancy between each successive stage of auditory processing (Chechik et al., 2006). Redundancy reduction along the ascending auditory pathway may be a generic organization principle of neural systems, allowing for easier readout of auditory information in higher auditory centers (e.g., auditory cortex) (Chechik et al., 2006). In line with this idea, our findings that subcortical encoding as indexed by Pa ampltiudes are not significantly related to higher-order cortical encoding as indexed by P2 and N2 in YNH listeners, may suggest redundancy reduction in the transfer of information between functional stages (i.e., lower- and higher-level brain function) of the central auditory pathway in young healthy adults. It may be postulated that higher-order cortical processing stations are more likely to be independent of early sensory encodings in subcortical auditory centers in a healthy auditory system.

These results are at odds with our other findigns from older listener groups. Both ONH and OHI groups showed significant positive correlations between the amplitudes of Pa and all late-latency components (i.e., N1, P2, and N2), indicating that age-related alterations of early sensory auditory processing may interrelate with successive stages of later-occurring auditory processing. The amplitude-based interrelationships between subcortical (lower) and cortical (higher) levels of the ascending auditory pathway in older listeners may reflect a higher redundancy in the transfer of neural information between successive stages of auditory processing in the aging auditory system. The increased informational redundancy at higher (cortical) level of auditory processing may impede the process which extracts relevant information in neural signals and encodes them independently (for a review, see Chechik et al., 2006), because the over-redundancy in neural activites leads to sensory overload with irrelevant

information. A large increase in the informational redundancy may impede neural coherence and synchronization of thalamo-cortical network in the aging auditory system (for a review, see Ceponiene et al., 2008; Bidelman et al., 2014), interfereing with sensory processing and the flow of neural information (Schneider, et al., 2002).

The age-related changes in the transfer of neural information along the ascending auditory pathway involve concomitant functional reorganization at subcortical and cortical levels of central auditory system. Age-related increase in the redundancy of neural representations between functional levels (subcortical vs. cortical) of auditory pathway may result in different strategies for auditory processing at higher-order cortical representations in older listeners against younger listeners, such as top-down compensation.

The aging per se may be necessary and sufficient in inducing age-related changes in interrelationship of neural activites between subcortical and cortical auditory centers, admitting that hearing loss may exacerbate age-related changes in central auditory function and system. The neural mechanism underlying amplitude-based interrelationship beween neuroelectric responses in the successive stations of the ascending auditory pathway (subcortical- and cortical levels) may be mediated by functional reorganization of inhibitory contral network in the central auditoy system.

Latency-based interrelationships of neuroelectric responses between AMLR Pa and ALLR components were similar among YNH, ONH, and OHI groups. The results showed the moderate-strong positive correlations between Pa latencies and N1, P2 and N2 latencies for all three groups, indicating that prolonged AMLR Pa latencies may predict prolonged latencies of ALLR components in all listener groups. In other words, neural timing at subcortical levels

significantly affects auditory timing at cortical levels. Spectrotemporal information is transferred from lower auditory stations and modulated on the way to the auditory cortical aresas. The integrity of spectrotemporal information is dependent on precise phase locking and synchronized neural firing, all of which are responsible for neural precision and sharpening of frequency tuning, accomplished through activation of inhibitory sidebands (Williams & Fuzessery, 2011). Auditory information coded in many nuclei and by numerous brainstem neuronal types converges on the inferior colliculus, in which temporal information is processed and represented for transmission to the cortex, higher auditory centers. Inferior colliculus, one of major auditory centers in the midbrain, may act like the functional hubs for temporal coding of sound gaps, AM (i.e., amplitude modulation), and FM (i.e., frequency modulation), which are important features for speech perception, especially in the presence of temporally fluctuating noise.

The age-related declines in GABAergic and glycinergic inhibition alter subcortical encoding of rapidly changing spectrotemporal information such as dynamic formant transitions, because of the following deficits possibly caused by the disturbance of neural functions in subcortical auditory nuclei and structures: reduced frequency selectivity, deteriorated phase-locking, a loss of periodicity coding, temporal jitter, a lack of neural response consistency, a decrease in the synchrony of neural firing, delayed neural recovery, and decreased spectral magnitude (Moore, 2008; Anderson et al., 2012). As a result, diminished temporal precision leads to timing delays in subcortical neural responses, manifested by prolonged latency peak. Age-related delays in subcortical temporal precision may be a major contributor to suprathreshold temporal processing deficits, which underlies age-related declines in SIN perception (e.g., Andersion, 2012). Age-related subcortical timing delays continue up to cortical auditory region, resulting in overall slowing of neural processing and thereby demanding longer

temporal integration windows in older adults. The precise subcortical response timing is sustained by the balanced excitatory and inhibitory subcortical neural networks.

Age-related hearing loss (i.e., presbycusis) may demand even longer temporal windows to integrate neural activites, due to more broadly distributed neural networks related to neuroplasticity (e.g., Friedman et al., 1993). Collectivley, neurons encode sound timing elements progressively as one ascends the auditory pathway from auditory nerve fibers, passing through subcortical areas like inferior colliculus, to auditory cortical areas. Young healthy listeners with normal temporal processing ability (e.g., precise spike timing, accurate phase-locking, synchronous neural firing) preserve temporal fidelity in neural signaling through successive subcortical relay stations to auditory cortical areas, as confirmed by the present findings of latency-based interrelationships between subcortical and cortical levels in younger listeners. On the other hand, age-related declines in temporal fidelity give rise to subcortical timing delays, which are progressively transmitted to auditory cortical areas and even increase neural timing delays, accompanied by the accumulation of delays in synaptic transmission across multiple cortical areas. In the present study, both ONH and OHI groups showed the significant positive relationships between the latencies of Pa and other cortical components (i.e., N1, P2, and N2), indicating that age-related subcortical timing delays may account for age-related changes in processing speed at cortical levels. Neural timings as indexed by peak latencies may underlie latency-based interrelationship between subcortical and cortical auditory structures.

The latency-based interrelationships between neuroelectric activites at early (subcortical) auditory processing and later stages of cortical processing were found in all listener groups, irrespective of aging, hearing loss, or both; however, the amplitude-based interrelationships between neuroelectric activities at subcortical auditory processing and later stages of cortical

processing (P2, and N2) were only found in older listener groups. These different patterns between the latency-based and the amplitude-based interrelationships in listener groups may result from different neural mechanisms underlying amplitudes and latencies, respectively. For instance, ampltiudes are more related to energy of neural activities and more reactive to intensified spectral density as measured by height or depth of a peak, whereas latencies reflect neural timing as measured by the time of appearance of a peak. Therefore, latencies and amplitudes of subcortical and coritcal responses may engage in different neurophysiological mechanisms underlying age-related changes in AEP morphology. This notion is in line with the previous finding that age-related compensatory increase in central gain may not alter spike timing code, that is, temporal fidelity, while the enhanced central gain may facilitate a rapid and complete recovery of sensitivity to diminished afferent inputs (Chambers et al., 2016). The increased central gain can lead to hypersynchrony (for a review, Auerbach et al., 2014), accompanied by increased hyperactivity, as manifested by enhanced amplitudes, but did not alter the speed of neural processing, retaining slow neural processing and coexisting with delayed latency due to long duration of firing action potentials (Deyo & Lytton, 1997).

Age-related functional alteration in the central auditoy system is associated with age-related breakdown of excitatory-inhibitory balance, predominantly via GABAergic pathway. Age-related changes in inhibitory control would be either the consequence of normal aging process or the compensatory central changes secondary to cochlear damage or both. The age-related loss of peripheral afferent input following cochlear damage/degeneration include, but are not limited to outer and inner hair cells, loss of auditory (cochlear) nerve fibers, spiral ganglion neuron loss, and stria vascularis atrophy. These age-related changes in the lower levels of the ascending auditory pathway may lead to pre- and postsynaptic compensatory down-regulations

of GABAergic inhibition in the higher stations of the auditory pathway (Betts et al., 2007), mediated by homestatic processes (Turrigiano, 2007) in multiple auditory regions. The weak neural signals may be progressively amplified as they are relayed to higher auditory centers, eventually leading to neural hyperactivity in the high-order auditory processing, facilitated by increased central gains (e.g., Chambers et al., 2016). Altogether, age-related changes in the amplitude-based interrelationships may be involved in age-related loss of GABA-mediated inhibition, modulated by central neuroplasticity.

Individuals with age-related synaptic/neuronal loss at the level of the cochlear nerve, who have intact cochlear mechanics and hair cell functions, can have difficulty with auditory temporal coding, despite audiometrically normal hearing. In fact, age-related loss of auditory neural fibers has an adverse effect on the precision of neural synchronization and spike timing precision across neural assemblies at multiple levels along auditory pathways, possibly due to a reduction in the speed of transmission of action potentials in individual fibers (Chritoper et al., 2014). Some recent studies using electroencephalogaphy revealed that listeners with poor subcortical temporal coding had poor cortical sensitivity to changes in interaural time differences (Bharadwaj et al., 2015), perhaps suggesting cascading effects (Tallal et al., 1993), which start with neural desynchronization at the level of cochlear nerve and proceed slowly to the higher cortical levels of temporal auditory processing. Similar to typical presbycusis manifested by hearing threshold elevation associated with hair cell losses, cochlear deaffrentation associated with the loss of auditory/cochlear nerve fibers (e.g., loss of synapses, demyelinated peripheral terminals of nerve fibers, loss of spiral ganglion neurons) may also result in reduced neural outputs. The predominant auditory dysfunction caused by age-related loss of auditory nerve fibers may be age-related degradation in temporal precision and fidelity, which may be a major

contributor to age-related changes in the latency-based interrelationships between successive stages of auditory processing.

Cochlear deafferentation primarily caused by age-related degeneration of cochlear nerve fibers may also increase central gain, in line with central gain hypothesis. Little is known about the relations among central gain, cochlear deafferentation, and hearing threshold elevation. To date, only a few studies have argued that central gain was substantially increased in even mild loss of inner hair cells (Salvi et al., 1990; 2000). The results demonstrated that the local potentials were larger in auditory cortex than subcortical structures such as inferior colliculus and medial geniculat body, regardless of the amount of threshold elevation, indicating that the amount of cochlear degeneration and the degree of threshold elevation may not account for the magnitude of increase in central gain. Age-related changes in compensatory central gains may be affected by other hidden problems, such as genetic susceptibility, degree of aging (e.g., neurotransmitter metabolism, brain changes) and interactions in all possible combinations between the above-mentioned variables. Indeed, in an animal model, it has been shown that maximum amplitude enhancement of AMLRs may be dependent on interindividual differences in the biochemical mechanisms that reugulate brain metabolic activity, neurotransmitter release, re-uptake and binding to the receptors on post-synptic membranes in the auditory centers (Popelar et al., 2008). Individual differences in age-related neurophysiological changes may affect a multifaceted process of central neuroplasticity in the aging auditory system, contributing to interindividual differences in age-related electrophysiological changes. The large interindividual differences in older listeners have been commonly reported by AEP studies of aging, in agreement with our data set, which is illustrated by scatterplots in Figure 5.3-1.

6.3. Electrophysiological Correlates of Speech-in-Noise Perception

In the present study, neural correlates of age-related declines in SIN perception were determined by correlating middle-and late latency responses with R-SPIN-LP scores, behavioral measurement of SIN perceptual ability, for ONH and OHI listeenrs. In line with the present findings that lower R-SPIN-LP scores corresponded to enhanced amplitudes of Pa, P2 and N2 components for both older listener groups, age-related declines in SIN perception may be significantly related to age-related increase in suprathreshold amplitudes of Pa component, which reflects thalamocortical ativities, with contributions from subcortical auditory structures such as inferior colliculus, and age-related increase in suprathreshold amplitudes of P2 and N2 components, which reflect neural activities in multiple cortical areas including lateral temporal, fronto-central, central, and frontal cortices, with conritutions from limbic system. In particular, Pa amplitudes were related to R-SPIN-LP scores in both ONH and OHI groups, regardless of the presence of hearing loss; additionally, the relationship with P2 amplitudes was only found in ONH group and the relationship with N2 amplitudes was only found in OHI group. Suprathreshold amplitudes of Pa component may be a better indicator of age-related change in SIN perception for older listeners, as compared with suprathreshold amplitudes of P2 and N2 components. Strong relationship between reduced Pa amplitudes and poorer R-SPIN-LP scores may suggest that age-related alteration of subcortical neural responses are significantly related to reduced SIN perception with advancing age, confirming and extending the previous findings of age-related deficits in subcortical processing of speech cues in noise (Anderson et al., 2011; Anderson et al., 2012; Anderson et al., 2013; Bidelman et al., 2014; Schoof & Rosen, 2016). In our data set, stimulus types and noise conditions appear to have no effects on the relationship between the amplitudes and R-SPIN-LP scores in this study. We cannot exclude, however, the

possibility that the interactions between acoustic features of stimulus and Babble noise may affect the relationship between R-SPIN-LP scores and the amplitudes. The group differernce in the relationship of R-SPIN-LP scores with P2 ampltiudes for ONH listeners versus N2 amplitudes for OHI listeners may be in part due to difference in cortical map reorganization consequent on hearing loss.

Age-related declines in SIN perception begin with neuronal degeneration of cochlea at early stage of auditory pathway, which includes a loss of outer hair cell function, as reflected in elevated hearing thresholds, altered loudness perception and reduced frequency selectivity, and a loss of inner hair cells and auditory neural fibers (e.g., synapse dysfuncton, spiral ganglion cell death and demyelination), as reflected in reduced neural synchrony, reduced precision of phase locking to spectral peaks or individual cycles of the stimulus waveform (Young & Sachs, 1979) and delayed neural timing. Such peripheral auditory changes trigger and even intensify functional alteration and reorganization in central auditory networks to compensate for auditory deprivation, thereby resulting in amplified neural coding of overall amplitude envelolpe (ENV) which leads to "relative" deficit in temporal fine structure (TFS) coding (Zhong et al., 2014). Acoutic information contain two types of temporal cues in speech segments, each of which can be conveyed by a slowly varying ENV (i.e., relatively slow variations in amplitude over time) superimposed on a more rapid TFS (i.e., rapid oscillations with rate close to the center frequency of the band). Both ENV and TFS, which are responsible for temporal precision in neural coding, are represented in the timing of neural discharge. The coherence of the temporal envelope across frequency channels helps to perceptually bind together different acoustic constituents of an "object" in the auditory scene (Elhilali et al., 2009; Shamma et al., 2011), enabling listeners to parse the incongruous mixture of sounds. In particular, TFS information plays an important role

in the detection of frequency modulation responsible for coding of pitch and speech formants (e.g., transitions), and listening in the dips of the fluctuating background sound (Moore, 2008), significantly contributing to speech intelligibility in noise. A loss of sepctrotemporal coding fidelity, which results from age-dependent neurophysiological changes associated with both auditory deafferenation and compensatory increase in central gain, leads to poor sensory coding of suprathreshold acoustic features important for speech understanding in cocktail-party situations. This phenomenon is referred to as suprathreshold processing deficits (e.g., Reed et al., 2009; Ruggles et al., 2011; Kortlang et al., 2016), and common perceptual deficits experienced by older adults (e.g., Ruggles et al., 2011; Shamma, 2011), regardless of whether or not hearing loss is present. Older adults with audiometrically normal hearing thesholds may still have obscure auditory dysfunction, perhaps caused by various forms of degenerative changes in cochlea, for example, cochlear neuropathy, which leads to difficulties with temporal coding of suprathreshold sounds, similar to older adults with hearing loss, presbycusis. Even if audibility and loudness perception are restored by suitable compensation strategies, suprathreshold processing deficits may persist, because deficits in temporal coding fidelity of sound waveform still remain. A wide range of individual differences in older adults' ability to understand speech in background noise may be accounted for by individual differences in suprathreshold processing deficits. In the present study, it is shown that age-related increase in suprathreshold amplitudes of subcortical-cortical neural responses is significantly related to decreased behavioral performance on SIN percepton in older listeners, indicating electrophysiological correlates of age-related changes in SIN perception and subcortical-cortical encoding to suprathreshold signals. These results provide electrophysiological evidence for age-related deficits in suprathreshold auditory processing. Large interindividual differences in suprathreshold neural

processing in correlation with age-related declines in SIN perception are observed in our data set (Figure 5.4-2).

With regard to relationship between R-SPIN-LP scores and latencies of AMLRs and ALLRs, it is shown that lower R-SPIN-LP scores are significantly related to age-related prolongation of N2 latencies in response to syllable /ba/ for both older groups, with no relationships beween R-SPIN-LP scores and latencies for YNH group. While lower R-SPIN-LP scores of OHI group were strongly related to prolonged N2 latencies elicited by speech stimulus, syllable /ba/, in Quiet and in Babble, lower R-SPIN-LP scores of ONH group were only significantly related to prolonged N2 latencies for syllable /ba/ in Quiet but not in Babble, indicating that hearing loss may have stronger effects on the relationship between SIN perception and N2 latencies, later-occurring neural responses, which reflect neural processing speed of higher-order, multiple cortical sites. N2 latencies elicited by speech or speech-like sounds may serve as an objective neural index of SIN perception in older adults.

The time course of long-latency response reflects the accumulation of temporal changes in neural synchrony that travels through auditory pathways from auditory-nerve fibers to multiple cortices including auditory cortical areas. The magnitude of increase in peak latency may reflect the degree of efficiency in the information flow in the corresponding neural network. The increase in the peak latency is relatively small at shorter latencies of early AEP components and almost twice as large at longer peak latencies. Age-related declines in neural synchrony at periphery and slowed neuronal oscillation in cortical networks may exert a negative impact on temporal precision/acuity, interfereing with the ability to process rapid acoustic changes such as TFS information. Recent studies suggest a close relationship between age-related deficits in auditory temporal processing and slowdown in processing speed (e.g., Harris et al., 2012; Harris

& Dubno, 2017). Processing speed generally decline with advancing age, in conjunction with age-related declines in neural oscillatory activity at subcortical and cortical regions including age-related changes in fiber tracts. For example, with advancing age, the increase in slow-wave alpha activity occur, resulting in a shift to lower-dominated alpha frequency (e.g., Klimesch et al., 1996) and the change in alpha phase (i.e., slow oscillatory brain phase) (Henry & Obleser, 2012; Strauß et al., 2015). Alpha oscillations contribute to contextualizing temporal frames for neural interactions via the timing of functional inhibition and facilitation, allowing more efficient integration of time information within and across brain regions. Age-related slowing of alpha oscillatory activity, thus, leads to inefficient neural processing and modulate reaction time to auditory sensory processing, in association with slowed processing speed (e.g., Klimesch, 1999; Klimesch et al., 1996). Along with age-related declines in neural synchrony, slower cortical oscillations have additive effects on larger windows of temporal integration, suggesting a significant contribution of slowed processing speed to age-related deficits in auditory temporal processing (Harris & Dubono, 2017). N2 latencies may reflect processing speed associated with auditory temporal processing in that N2 generators are involved in structural and functional cortical networks that participate in higher-order auditory sensory processing (Bekker et al., 2005; Jonkman et al., 2007; Lavric et al., 2007). Taken all together, significant relationship between age-related prolongation of N2 latencies for speech sounds, syllable /ba/, and poorer SIN perception in older adults indicates the age-related slowdown of processing speed associated with auditory temporal processing, which is critical to understanding speech in the presence of temporally fluctuating background noise. Prolonged N2 latencies may be taken as electrophysiological correlates of age-related declines in SIN perception.

6.4. Conclusions

In sum, three hypotheses were addressed by testing three listener groups (i.e., YNH, ONH, and OHI) to evaluate suprathreshold amplitudes and latencies of each AEP component (i.e., Pa, N1, P2 and N2) as a function of stimulus type (500 Hz tone burst, syllable /ba/) and noise condition (in quiet vs. in babble). The major findings of this study can be summarized as follows:

1. Aging and hearing loss may have differential effects on morphological changes in AEP responses.

(1) Aging (YNH versus ONH) has a significant effect on suprathreshold amplitudes of Pa and N1 and suprathreshold latencies of Pa, P2 and N2. ONH group produced significantly enhanced Pa and N1 amplitudes and significantly prolonged Pa, P2 and N2 latencies as compared with YNH group. Syllable /ba/ elicited larger Pa and N1 amplitudes, and 500 Hz tone burst elicited larger P2 and and N2 amplitudes. The amplitudes of all AEP components were significantly reduced in babble versus in quiet. Pa and N1 amplitudes are more susceptible to the aging process in the central auditory system, compared to P2 and N2 amplitudes. Syllable /ba/ elicited significantly prolonged latencies of all AEP components compared with 500 Hz tone burst, with significant prolongations of latencies across all AEP components in babble versus in quiet. Age-related latency prolongations became more prominent in babble, reflecting slower neural processing in speech-like background noise.

(2) Hearing loss (ONH versus OHI) has no significant effect on suprathreshold amplitudes of all AEP components and has a significant effect on N2 latencies. OHI

group showed slightly but insignificantly enhanced amplitudes of all AEP components and significantly prolonged N2 latencies as compared with ONH group. Syllable /ba/ elicited significantly larger Pa and N1 amplitudes, and 500 Hz tone burst elicited significantly larger N2 amplitudes. There was no significant difference in P2 amplitudes as a function of stimulus type. Both ONH and OHI groups showed significant reductions of amplitudes across all AEP components in babble versus in quiet. Similar to outcomes produced by the effects of aging, syllable /ba/ elicited significantly prolonged latencies of all AEP components compared to 500 Hz tone burst, with significant prolongations of latencies across all AEP components in babble versus in quiet. The significant prolongation of N2 latencies in OHI listeners may indicate that hearing loss has more adverse effects on sensory integrative processing of spectrotemporal information which occurs at higher-order auditory cortical areas, compared to aging per se. The age-related prolongations of latencies reflect age-related slowing of processing speed, possibly exacerbated by the addition of hearing loss.

(3) Significant age-related changes in the ampltiudes and latencies were exacerbated for all AEP components in combination with the effects of hearing loss, indicating stronger effects of age-related hearing loss on age-related changes in AEP morphology. OHI group showed significantly enhanced amplitudes and prolonged latencies across all AEP components, compared with YNH group. The interplay between effects of aging and hearing loss may have stronger impacts on the amplitudes and latencies of subcortical and cortical responses. Syllable /ba/ elicited significantly larger Pa and N1 amplitudes and 500 Hz tone burst elicited significantly larger N2 amplitudes. P2 amplitudes elicited by syllable /ba/ were not significantly different from those elicited by 500 Hz tone burst,

indicating that acoustic features of the stimulus have no significant effects on the changes in P2 amplitudes. The effects of stimulus types on the changes in the amplitudes were similar between outcomes produced by the effects of hearing loss and the combined effects, but different from outcomes by the effects of aging, indicating that hearing loss may moderate the effects of stimulus types on P2 amplitudes. The amplitudes were significantly reduced and the latencies were significantly prolonged across all AEP components in babble versus in quiet. N2 latencies may be a stronger marker of age-related delays in auditory neural timing, exhibiting more significant prolongations, particularly in response to speech stimulus like syllable /ba/. Age-related hearing loss induced more prolonged N2 latencies in OHI relative to YNH group than aging per se in ONH relative to YNH group. The prolonged N2 latencies may better reflect age-related declines in speed of spectrotemporal processing in older adults, both those who have audiometrically normal hearing and those who have age-related hearing loss.

2. There may be functional interrelaionships between AEP responses occurring at early (i.e., Pa, lower) and later (N1, P2, and N2, higher) stages of auditory processing in the aging auditory system.

(1) In both ONH and OHI listeners, enhanced Pa amplitudes corresponded with enhanced ampiltudes of N1, P2, and N2 components, suggesting that the early stage of auditory processing occurring at subcortical levels may be related to the later stage of auditory processing occurring at higher-order cortical regions. The underlying mechanism of significant relationship between subcortical and cortical responses in the aging auditory system may be associated with age-related down-regulation of GABAergic function. Over-redundancy of neural information, possibly due to

compensatory enhancement of central gain, which leads to sensory overload with irrelevant information, impeding segregation of auditory information into distinct components that belong to different auditory objects. On the other hand, YNH listeners showed no amplitude-based interrelationships between neuroelectric responses at subcortical and cortical levels, with the exception of the interrelationships between Pa and N1 amplitudes, resulting from the decrease in informational redundancy along successive stations of the ascending auditory pathway in younger listeners. Neural representations at higher processing stations may become independent of early sensory encoding at lower processing stations in the normal (young) auditory system.

(2) Latency-based interrlationships between Pa and late-latency components were similar among YNH, ONH, and OHI groups, indicating that prolonged Pa latencies corresponded with prolonged latencies of N1, P2, and N2 components in all listener groups. Age-related subcortical timing delays continue up to higher cortical stations of auditory pathway, resulting in longer temporal integration windows in older adults. Age-related subcortical timing delays may account for age-related changes in processing speed at cortical levels. The amplitude-based and the latency-based interrelationships between neuroelectric responses in subcortical and cortical auditory pathway may reflect different neural mechanisms underlying age-related changes in AEP morphology.

3. Age-related varations in AEP responses may have neural correlates of age-related declines in SIN perception.

(1) Lower R-SPIN-LP scores were significantly correlated with enhanced amplitudes of Pa, P2 and N2 components in both ONH and OHI groups, indicating the

electrophysiological correlates of age-related reduction of SIN perception. The reduced R-SPIN-LP scores in older listeners may be accounted for by age-related increase in suprathreshold amplitudes of Pa component, and age-related increase in suprathreshold amplitudes of P2 and N2 components. Age-related loss of sepctro-temporal coding fidelity leads to poor sensory coding of suprathreshold acoustic features essential for speech understanding in cocktail-party situations, which is referred to as suprathreshold processing deficits. Older adults with audiometrically normal hearing thesholds may also have difficulties with temporal coding of suprathreshold sounds. Suprathrehsold temporal processing deficits may be a major contributor to age-related declines in SIN perception. Our findings showed that age-related increases in suprathreshold amplitudes of subcortical-cortical neural responses were significantly related to decrases in behavioral performance on SIN percepton in older listeners. These results serve as electrophysiological evidence of age-related deficits in suprathreshold auditory processing.

(2) Lower R-SPIN-LP scores are significantly correlated with age-related prolongations of N2 latencies for syllable /ba/ in both ONH and OHI listeners, indicating the electrophysiological correlates of age-related reduction of SIN perception. Age-related declines in neural synchrony and slower cortical oscillatory activities lead to slowing of processing speed, which is a major contributor to age-related deficits in auditory temporal processing. Prolonged N2 latencies may reflect age-related slowing of temporal processing speed, which may be a major contributor to age-related deficits in temporal fidelity. Temporal fidelity is critical to speech understanding in temporally fluctuating background noise. Taken together, age-related prolongations of N2 latencies elicited by

syllable /ba/ may serve as an electrophysiological index of age-related declines in SIN perception.

References

Adler G., Adler J. (1989). Influence of stimulus intensity on AEP components in the 80 to 200 millisecond latency range. Audiology, 28(6), 316-24.

American Speech-Language-Hearing Association (ASHA) Task Force on Central Auditory Processing Development. (1996). Central auditory processing: current status of research and implications for clinical practice. Am J Audiol. 5, 41-54.

Alain, C., & Woods, D. L. (1999). Age-related changes in processing auditory stimuli during visual attention: evidence for deficits in inhibitory control and sensory memory. Psycho. Aging 14, 507-519.

Alain, C., Roye, A., & Arnott, S. R. (2013). Middle- and long-latency evoked potentials: what are they telling us on central auditory disorders? In: G.G. Celesia (Eds.), Handbook of Clinical Neurophysiology: Disorders of Peripheral and Central Auditory Processing.Vol.10, Elsevier B. V., 177-199.

Alcaini, M., Giard, M. H., Thevenent, M., & Pernier, J. (1994). Two separate frontal components in the N1wave of the human auditory evoked response. Psychophysiology, 31(6), 611-615.

Amenedo E., & Diaz, F. (1999). Effects of aging on middle-latency auditory evoked potentials: A cross-sectional study. Biol Psychiatr, 43, 210-219.

ANSI S3.5. (1969). American national standard methods for the calculation of the articulation index. New York: ANSI.

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

Anderson, S., Parbery-Clark, A., White-Schwoch, T., & Kraus, N. (2012). Aging affects neural precision of speech encoding. J. Neurosci. 32, 14156-14164.

Anderson, S. Parbery-Clark, A., White-Schwock, T., Drehobl, S., & Kraus, N. (2014). Effects of hearing loss on the subcortical respresentation of speech cues. J. Acoust. Soc. Am. 133(5), 3030-3038.

Anderson, S., White-Schwoch, T. W., Parbery-Clark, A., & Kraus, N. (2013). Reversal of age-related neural timing delays with training. PNAS 110(11), 4357-4362.

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

Anderer, P., Paschual-Marqui, R. D., Semlitsch, H.V. & Saletu, B. (1998). Differential effects of normal aging on sources of standard N1, target N1 and target P300 auditory event-related brain potentials revealed by low resolution electromagnetic tomography (LORETA). Electroencephalography and Clinical Neurophysiology, 108(2), 160-174.

Appell, J., Kertesz, A., & Fisman, M. (1982). A study of language functioning in Alzheimer patients. Brain and Language, 17, 73-91.

Arle, J. E., & Kim, D. O. (1991). Simulations of cochlear nucleus neural circuitry: Excitatory-inhibitory response-area types I-IV. J Acoust Soc Am. 90(6), 3106-21.

Atcherson, S. R., Gould H. J., Pousson, M. A., & Prout, T. M. (2006). Long-term stability of N1 sources using low-resolution electromagnetic tomography. Brain Topography, 19(1-2), 11-20.

Atienza, M., Cantero, J. L., & Dominguez-Marin, E. (2002). The time course of neural changes underlying auditory perceptual learning. Learn. Mem. 9, 138-150.

Auerbach, B. D., Rodrigues, P. V., & Salvi, R. J. (2014). Central gain control in tinnitus and hyperacusis. Frontiers in Neurology 5, 1-21.

Azumi, T. Nakashima, K., & Takahashi, K. (1995). Aging effects on auditory middle latency responses. Electroencephalogr Clin Neurophysiol, 35, 397-401.

Barnet A. B. (1975). Auditory evoked potentials during sleep in normal children from ten days to 3 years of age. Electroenceph clin Neurophysiol. 39(1), 29-41.

Barrett, G., Neshige, R., Shibasaki, H. (1987). Human auditory and somatosensory event-related potentials: effects of response condition and age. Electroencephalogr. Clin. Neurophysiol. 66, 409-419.

Baumann, S. B., Rogers, R. L., Papanicolaou, A. C., et al. (1990). Intersession replicability of dipole parameters from three components of the auditory evoked magnetic field. Brain Topogr 3, 311-319.

Bayles, K. A., & Tomoeda, C. K. (1983). Confrontation naming impairment in dementia. Brain and Language, 19, 98-114.

Bee, M. A., & Klump, G. M. (2004). Primitive auditory stream segregation: A neurophysiological study in the songbird forebrain. Journal of Neurophysiology, 92, 1088-1104.

Bertoli, S. & Probst, R. (2005). Lack of standard N2 in elderly participants indicates inhibitory processing deficit. Neuroreport, 28, 16(17), 1933-7.

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. Journal of the Association for Research in Otolaryngology, 6, 207-222.

Best, V., Gallun F. J., Carlile, S., & Shinn-Cunningham, B. G. (2007). Binaural interference and auditory grouping. J Acoust Soc Am 121, 1070-1076.

Betts, L. R., Sekuler, A. B., & Bennett, P. J. (2007). The effects of aging on orientation discrimination. Vision Res. 47, 1769-1780.

Bharadwaj, H. M., Verhulst, S., Shaheen, L., Liberman, M. C., & Shinn-Cunningham, B. G. (2014). Cochlear neurophathy and the coding of supra-threshold sound. Frontiers in Systems Neuroscience 8 (26), 1-18.

Bhattacharya J. (2001). Reduced degree of long-range phase synchrony in pathological human brain. Acta Neurobiol Exp, 61, 309-318.

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

Bilger, R. C., Nuetzel, M. J., Rabinowitz, W. M., & Rzeckowski, C. (1984). Standardization of a test of speech perception in noise. J Speech Hear Res, 27, 32-48.

Billings, C. J., Tremblay, K. L., Stecker, G. C., & Tolin, W. M. (2009). Human evoked cortical activity to signal-to-noise ratio and absolute signal level. Hearing Research, 254, 15-24.

Billings, C. J. Penman, T. M., McMillan, G. P., & Ellis, E. M. (2015). Electrophysiology and perception of speech in noise in older listeners: Effects of hearing impairment and age. Ear & Hearing, 36(6), 710-722.

Bioacoustics, & Biomechanics, National Research Council, Commission on Behavioral & Social Sciences & Education, Washington, DC. (1988). Speech understanding and aging. Journal of the Acoustical Society of America, 83, 859-895.

Borgers, C., Epstein, S., Kopell, N. J. (2005). Background gamma rhythmicity and attention in cortical local circuits: A computational study. Proc Natl Acad Sci USA, 102, 7002-7007.

Bregman, A.S., & McAdams, S. (1994). Auditory scene analysis: The perceptual organization of sound. Journal of the Acoustical Society of America, 95, 1177-1178.

Briggs, F., Mangun, G. R., & Usrey, W. M. (2013). Attention enhances synaptic efficacy and the signal-to-noise ratio in neural circuits. Nature 499, 476-480.

Brokx, J. P., & Nooteboom, S. (1982). Intonation and the perceptual separation of simultaneous voices. Journal of Phonetic, 10, 23-26.

Bronkhorst, A. (2000). The cocktail party phenomenon: A review of research on speech intelligibility in mulitiple-talker conditions. Acta Acustica, 86, 117-128.

Brown, W. S., Marsh, J. T., & LaRue, A. (1983). Exponential electrophysiological aging: P3 latency. Lectroencephalogr Clin Neurophysiol, 55, 277-285.

Broyd, S.J., et al. (2005). The effect of methylphenidate on response inhibition and the event-related potential of children with attention deficit/hyperactivity disorder. Int J Psychophysiol. 58(1), 47-58.

Burkard, R. & Hecox, K. (1983). The effect of broadband noise on the human brainstem auditory response. I. Rate and intensity effects. J. Acoust Soc Am, 74(4), 1204-1213.

Burkard, R. & Pamer, A. (1997). Responses of chopper units in the ventral cochlear nucleus of the anaesthetized guinea pig to clicks-in-noise and click trains. Hear Res, 110, 234-250.

Buchwald, J. S. et al. (1992). Midlatency auditory evoked responses: P1 abnormalities in adult autistic subjects. Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 84(2), 164-171.

Burger, R. M., & Pollak, G. D. (1998). Analysis of the role of inhibition in shaping responses to sinusoidally amplitude-modulated signals in the inferior colliculus. Journal of Neurophysiology, 80, 1686-1701.

Canning, S. J. D., Leach, L., Stuss, D., Ngo, L., & Black, S. E. (2004). Diagnostic utility of abbreviated fluency measures in Alzheimer disease and vascular dementia. Neurology, 62, 556-562.

Caspary, D. M., Milbrandt, J. C., & Helfert, R. H. (1995). Central auditory aging: GABA changes in the inferior colliculus. Exp Geront, 30(3-4), 349-60.

Caspary, D. M., Schatteman, T. A., & Hughes, L. F. (2005). Age-related changes in the inhibitory response properties of dorsal cochlear nucleus output neurons: role of inhibitory inputs. Journal of Neuroscience, 25(47), 10952-10959.

Caspary, D., Ling, L., Turner, J. G., & Hughes, L. F. (2008). Inhibitory neurotransmission, plasticity and aging in the mammalian central auditory system. Journal of Experimental Biology, 211, 1781-1791.

Ceponiene, R., Alku, P., Westerfield, M., Torki, M., & Townsend, J. (2005). ERPs differentiate syllable and nonphonetic sound processing in children and adults. Psychophysiology 42(4), 391-406.

Ceponiene R., Rinne T., & Naatanen R. (2002). Maturation of cortical sound processing as indexed by event-related potentials. Cli Neurophysiol, 113(6), 870-82.

Ceponiene, R., Shestakova, A., Balan, P., Alku, P., Yiaguchi, K., & Naatanen, R. (2001). Children's auditory event-related potentials index sound complexity and "speechness". International Journal of Neuroscience, 109, 245-260.

Ceponiene, R., Westerfield, M., Torki, M., & Townsend, J. (2008). Modality-specificity of sensory aging in vision and audition: Evidence from event-related potentials. Brain Research, 1215, 53-68.

CHABA. (1988). Speech understanding and aging. Working Group on Speech Understanding and Aging. Committee on Hearing, Bioacoustics, and Biomechanics, Commission on behavioral and Social Sciences and Education, National Research Council. J Acoust. Soc. Am. 83, 859-895.

Chambers, A. Resnik, J., Yuan, Y. Whitton, J. P., Edge, A. S., & Liberman, M. C. (2015). Central gain restores auditory processing following near-complete cochlear denervation. Neuron 89, 867-879.

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

Chao, L. L., & Knight R. T. (1995a). Human prefrontal cortex gates distracting sensory inputs. Soc Neurosci Abstr 21, 476

Chao, L. L., & Knight R. T. (1995b). Human prefrontal lesions increase distractibility to irrelevant sensory input. NeuroReport 6, 1605-1610.

Chao, L. L. & Knight R. T. (1997). Prefrontal deficits in attention and inhibitory control with aging. Central Cortex 7 (1), 63-69.

Y-C., Li Xi., Liu, L., Wang, J., Lu, C-Q., et al. (2015). Tinnitus and hyperacusis involve hyperactivity and enhanced connectivity in auditory-limbic-arousal-cerebellar network. eLife, 4, e06576. http://doi.org/10.7554/eLife.06576.

Chechik, G., Anderson, M., Bar-Yosek, O., Young, E., Tishby, N., & Nelken, I. (2006). Reduction of information reducdancy in the ascending auditory pathway. Neuron 51, 359-368.

Chen, C.Y., et al. (2005). Neural correlates of impulsive-violent behavior: an event-related potential study. Neuroreport, 16, 1213-1216.

Chertkow, H., & Bub, D. (1990). Semantic memory loss in dementia of Alzheimer's type. Brain, 113, 397-417.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. Journal of the Acoustical Society of America, 25, 975-979.

Coats, A. C. (1978). Human auditory nerve action potentials and brainstem evoked responses. Acta Otolaryngol. 104:709-717.

Cohen, D., & Wu, S. (1980). Language and cognition. Ann Rev Gerontol Geriatr. 1, 71-96.

Corso, J. F. (1982). Sensory processes and perception in aging. In: Vudik, A. (Ed.), Lectures on Gerontology, pp. 441-479, Academic Press, London, 1982.

Corso, J. F. (1984). Auditory processes and aging: Significant problems for research. Exp Aging Res. 10(3), 171-173.

Costalupes, J. A., Young, E. D., & Gibson, D. J. (1984). Effects of continuous noise backgrounds on rate response of auditory nerve fibers in cat. J. Neurophysiol, 51, 1326-1344.

Courchesne, E. (1978). Neurophysiological correlates of cognitive development: changes in long-latency event-related potentials from childhood to adulthood. Electroencephalography and Clinical Neurophysiology, 45(4), 468-482.

Crowley K. E., & Colrain I. M. (2004). A review of the evidence for P2 being an independent component process: age, sleep and modality. Clinical Neurophysiology, 115, 732-744.

Cummings, J. L., Benson, D.F., Hill, M.A., & Read, S. (1985). Aphasia in dementia of the Alzheimer type. Neurology, 35, 394-397.

Darwin, C. J., & Hukin, R. W. (2000). Effectiveness of spatial cues, prosody, and talker characteristics in selective attention. Journal of the Acoustical Society of America, 107, 970-977.

Davis, H., Deatherage, B. H., Eldredge, D. H., & Smith, C. A. (1958). Summating potentials of the cochlea. American Journal of Physiology, 195(2), 251-261.

Delgutte, B. (1990). Physiological mechanisms of psychophysical masking: observations from auditory-nerve fibers. J Acoust. Soc. Am. 87, 791-809.

Desmedt, J. E., & Cheron, G. (1981). Non-cephalic reference recording of early somatosensory potentials to finger stimulation in adult or aging normal man: differentiation of widespread N18 and contralateral N20 from the prerolandic P22 and N30 components. Electroenceph. Clin. Neurophysiol, 52, 533-570.

Deyo, S. N., Wytton, W. W. (1997). Inhibition can disrupt hypersynchrony in model meuronal networks. Prog. Nero-Psychopharmocol. & Biol. Psychiat. 21, 735-750.

Desmedt, J. E., & Debecker, J. (1979). Wave form and neural mechanism of the decision P350 elicited without pre-stimulus CNV or readiness potential in random sequences of near-threshold auditory clicks and finger stimuli. Electroencephalography and Clinical Neurophysiology, 47(6), 648-670.

Deouell, L. Y., Bentin, S., & Giard, M. H. (1998). Mismatch negativity in dichotic listening: Evidence for interhemispheric differences and multiple generators. Psychophysiology, 35, 355-365.

Doll, T., & Hanna, T. (1997). Directional cueing effects in auditory recognition, in Binaural and Spatial Hearing in Real and Virtual Environments. In R.H. Gilkey & T. R. (Eds.), Anderson; Erlbaum, Hillsdale, NJ.

Durlach et al. (2003). Informational masking: conteracting the effects of stimulus uncertainty by decreasing target-masker similarity. J. Acoust. Soc. Am. 114(1), 368-379.

Elliott, L. (1995). Verbal auditory closure and the speech perception in noise (SPIN) test. Journal of Speech & Hearing Research, 38(6), 1363-1377.

Edwards, C. J., Leary, C. J., & Rose, G. J. (2008). Mechanisms of long-interval selectivity in midbrain auditory neurons: Roles of excitation, inhibition, and plasticity. J Neurophysiol, 100, 3407-3416.

Eggermont J.J. (2000). Neural responses in primary auditory cortex mimic psychophysical, across-frequency-channel, gap-detection thresholds. J Neurophysiol, 84(1), 453-63.

Eggermont, J. J., Ponton, C. W., Don, M., Warning, M. D., & Kwong, B. (1997). Maturational delays in cortical evoked potentials in cochlear implant users. Acta Otolaryngologia, 117, 161-163.

Eggermont, J. J. (2007). Electric and magnetic fields of synchronous neural activity. In R. F. Burkard, M. Don, J. J. Eggermont (Eds). Auditory Evoked Potentials (pp, 3-21). Philadelphia: Lippincott Williams & Wilkins.

Eggermont, J. J. (2017). Effects of long-term non-traumatic noise exposure on the adult central auditory system. Hearing problems without hearing loss. Hearing Research 352, 12-22.

Enoki, H., Sanada, S., Yoshinaga, H., Oka, E., & Ohtahara, S. (1993). The effects of age on the N200 component of auditory event-related potentials. Cognition Brain Research 1, 161-167.

Erwin, R. J., & Buchwald, J. S. (1986). Midlatency auditory evoked responses: Differential effects of sleep in the human. Electroencephalography and Clinical Neurology, 65(5), 383-392. PubMed.

Eulitz, C., Diesch, E., Pantev, C., Hampson, S., & Elbert, T. (1995). Magnetic and electric brain activity evoked by the processing of tone and vowel stimuli. Journal of Neuroscience, 15, 2748-2755.

Falkenstein, M., Koshlykova, N. A., Kiroj, V. N., Hoormann, J., & Hohnsbein, J. (1995). Late ERP components in visual and auditory Go/Nogo tasks. Electroenephalography and Clinical Neurophysiology, 96, 36-43.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (1999). ERP components in Go/Nogo tasks and their relation to inhibition. Acta Psychologica, 101, 267-291.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (2002). Inhibition-related ERP components: variation with modality, age, and time-on-task. Journal of Psychology, 16(3), 167-175.

Ford, J. M., Pfefferbaum, A. (1991). Event-related potentials and eyeblink responses in automatic and controlled processing effects of age. Electroencephalogr. Clin. Neurophysiol. 78, 361-377.

Friedman, D., Simpson, G., & Hamberger, M. (1993). Age-related changes in scalp topography to novel and target stimuli. Psychophysiology 30, 383-396.

Frisina, R. D. (2001). Possible neurochemical and neuroanatomical base of age-related hearing loss-Presbycusis. Semiars in Hearing, 22, 213-225.

Frisina, S. T, et al. (2006). Characterization of hearing loss in Type II diabetics. Hearing Research, 211 (1-2), 103-113.

Frisina, et al. (2001). Auditory temporal processing during aging. In: P. Hof, C. Mobs (Eds.) Functional Neurobiology of Aging. New York: Academic, 565-580.

Frisina, R. D. (2001). Possible neurochemical and neuroanatomical bases of age-related hearing loss-presbycusis. Semin Hear, 22, 213-225.

Frisina, R. D. (2001). Subcortical neural coding mechanisms for auditory temporal processing. Hear Res, 158, 1-27.

Frisina, D. R., & Frisina, R. D. (1997). Speech recognition in noise and presbycusis: Relations to possible neural mechanisms. Hear Res, 106, 95-104.

Freyman, R., Helfer, K., McCall, D., & Clifton, R. (1999). The role of perceived spatial separation in the unmasking of speech. J. Acoust. Soc. Am. 1016, 3578-3587.

Fujikawa, S. & Weber, B. (1977). Effects of increased stimulus rate on brainstem electric response (BER) audiometry as a function of age. J. Amer. Audiol. Soc., 3, 147-150.

Giard, et al. (1994). Dissociation of temporal and frontal components in the human auditory N1 wave: A scalp current density and dipole model analysis. Electroencephalography and Clinical Neurophysiology, 92(3), 238-252.

Gibson, D. J., Young, E. D., & Costalupes, J.A. (1985). Similarity of dynamic range adjustment in auditory nerve and cochlear nuclei. J. Neuophysiol, 53, 940-958.

Gordon-Salant, S., & Fitzgibbons, P. J. (1997). Selected cognitive factors and speech recognition performance among young and elderly listeners. J Speech Lang Hear Res, 40, 423-431.

Gates, G. A., Cooper, J. C., Kannel, W. B., & Miller, N. J. (1990). Hearing in the Elderly: The Framingham Cohor, 1983-1985, Part I. Basic Audiometric Test Results. Ear and Hearing, 11(4), 247-256.

Gates, G.A., Karzon R.K., Garcia P, et al. (1995). Auditroy dysfunction in aging and senile dementia of the Alzheimer's type. Arch Neurol. 52:626-634.

Gates, G. A., Schmid, P., Kujawa S. G., Nam, B. D., & Agostino, R. (2000). Longitudinal threshold changes in older men with audiometric notches. Hear Res, 141, 220-228.

Gates, G.A., & Mills, J. H. (2005). Presbycusis. Lancer, 366:1111-20.

Gates, G. A. (2009). Central Auditory Processing in Presbycusis: an Epidemiologic Perspective. Hearing Care for Adults, 47-52.

Gates, G. A. et al. (2010). Executive dysfunction and presbycusis in older persons with and without memory loss and dementia. Cogn Behav Neurol, 23(4), 218-223.

Gates, G. A. (2012). Central presbycusis: an emerging view. Otolaryngology-Head and Neck Surgery, 147(1), 1-2.

Gerken, G. (1996). Central tinnitus and lateral inhibition: an auditory brainstem model. Hear. Res. 97, 75-83.

Gerken, G., Simhadri-Sumithra, R., & Bhat, K. (1986). Increase in central auditory responsiveness during continuous tone stimulation or following hearing loss. In: Salvi, R.D., Henderson R.P., Hamernik, V. Colletti (Eds.), Applied and Basic Aspects of Noise Induced Hearing Loss. Plenum Press, New York; 198-211.

Gerken, G., Hesse, P., & Wiorkowski, J. (2001). Auditory evoked responses in control subjects and in patients with problem-tinnitus. Hear. Res. 157, 52-64.

Goff, E. R., Allison, T., & Vaughan, H. G. Jr. (1978). The functional neuroanatomy of event related potentials. In E. Callway, P. Tueting, & S. H. Koslow (Eds), Event-related potentials in man (pp.1-79). New York: Academic Press.

Goodin, D. S., Squires, K. C., Henderson, B. H., & Starr, A. (1978). Age-related variation in evoked potentials to auditory stimuli in normal human subjects. Electroenceph. Clin. Neurophysiol., 44, 447-458.

Halgren, E., Marinkovik, K., Chauvel, P. (1998). Generators of late cognitive potentials in auditory and visual oddball tasks. Electroencephalogr Clin Neurophysiol, 106, 156-164.

Halgren, E. et al. (1980). Endogenous potentials generated in the human hippocampal formation and amygdala by infrequent events. Science, 210 (4471), 803-805.

Hall, J. W. III (2007). New Handbook of Auditory Evoked Responses. Boston: Allyn & Bacon.

Hall, J. C. (1999). Gabaergic inhibition shapes frequency tuning and frog. J Comp Physiol, 185, 479-491.

Hari, R. (1990). The neuromagnetic method in the study of the human auditory cortex, In the study of the human auditory cortex, In Grandori, F. Hoke, M., Romani, G.L.(Eds.), Auditory Evoked Magnetic Fields and Potentials, Advances in Audiology, Vol. 6 (pp. 222-282), Karger, Basel.

Hari et al. (1984). Responses of the primary auditory cortex topitch changes in a sequence of tone pips: Neuromagnetic recordings in man. Neuroscience Letters, 50(1-3), 127-132.

Hari R., Hamalainen H., Hamalainen M., Kekoni J., Sams M., & Tiihonen J. (1990). Separate finger representations at the human second somatosensory cortex. Neuroscience, 37(1), 245-9.

Hari, R., Kaila, K., Katila, T., Tuomisto, T., & Varpula, T. (1982). Interstimulus interval dependence of the auditory vertex response and its magnetic counterpart: Implications for their neural generation. Electroencephalography and Clinical Neurophysiology, 54, 561-556.

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 & Hearing, 33(3), 330-339.

Harris K.C., Mills J.H., Dubno, J.R. (2007). Electrophysiologic correlates of intensity discrimination in cortical evoked potentials of younger and older adults. Hear Res, 228, 58-68.

Harrison, J., Buchwald, J., & Kaga, K. (1986). Cat P300 present after primary auditory cortex ablation. Electroencephalography and Clinical Neurophysiology, 63(2), 180-187.

Harkrider A. W. (2012). Middle latency responses. In S. R. Atcherson & T. M. Stoody (Eds.), Auditory Electrophysiology (pp121-135). New York: Thieme

Harkrider, A. W., Plyer, P. H., & 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.

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, 2153-2164.

Harris, K. C., & Dubno, J. R. (2017). Age-related deficits in auditory temporal processing: unique contributions of neural dyssynchrony and slowed neuronal processing. Neurobiology of Aging 53, 150-158.

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, 330-339.

Hashimoto, I., Mashiko, T., Yoshikawa, K., Mizuta, T., Imada, T., & Hayashi, M. (1995). Neuromagnetic measurements of the human primary auditory response. Electroenceph. Clin. Neurophysiol., 96, 348-356.

He, N., Mills, J. H., Ahlstrom, J. B., Dubno, J. R. (2008). Age-related differences in the temporal modulation transfer function with pure-tone carriers. JASA 124(6), 3481-3849.

Helfer, K. S., & Vargo, M. (2009). Speech recognition and temporal processing in middle-aged women. J Am Acad Audiol, 20, 264-271.

Heinrich, A., Schneider, B. A, & Craik, F. I. (2007). Investigating the influence of continuous babble on auditory short-term memory performance. Q J Exp Psychol 61:735-751.

Hickox, A. E., & Liberman, J. C. (2014). Is noise-induced cochlear neuropathy key to the generation of hyperacusis or tinnitus? Journal of Neurophysiology, 111, 552-564.

Hodges, J. R., Salmon, D. P., & Butters, N. (1992). Semantic memory impairment in Alzheimer's disease: Failure of access or degraded knowledge? Neuropsychologia, 30. 301-314.

Humes, L. E., Watson, B. U., Christensen, L. A., Cokely, C. G., Halling, D. C., & Lee, L. (1994). Factors associated with individual differences in clinical measures of speech recognition among the elderly. Journal of Speech & Hearing Research, 37, 465-474.

Hyde, M. (1997). The N1 response and its applications. Audiol Neurootol, 2, 281-307.

Ibrahim, R. (2012). The role of temporal fine structure cues in speech perception. Open Access Dissertations and Theses. Paper 6904. http://digitalcommons.mcmaster.ca/opendissertations/6904

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, 10-22.

Jerger, J. (1973). Audiological findings in aging. Adv. Otorhinolaryngol. 20, 115-124.

Jerger, J. & Musiek, F. (2000). Report of the consensus conference on the diagnosis of auditory processing disorders in school-aged children. J. Am Acad Audiol, 11, 467-474.

Jerger, J., Oliver, T., Chmiel, R. (1988). Auditory middle latency response: a perspective. Seminars in Hearing 9, 75-86.

Jerger, J., Jerger, S., Oliver, T., & Pirozzolo, F. (1989). Speech understanding in the elderly. Ear & Hearing, 10, 79-89.

Jerger, J., Johnson, K., Jerger, S., et al. (1991). Central auditory processing disorders: a case study. J Am Acd Audiol, 2, 36-54.

Joris, P. X., & Yin, T. (1991). Responses to amplitude-modulated tones in the auditory nerve of the cat. J. Acoust. Soc. Am. 91(1), 215-232.

Karayanidis, F. Andrews, S., Ward, P.B. (1995). ERP indices of auditory selective attention in aging and parkinson's disease. Psychophysiology 32, 335-350.

Kausler, S. H. (1988). Cognition and aging. In: Shadden B. B., (ed.) Communication Behavior and Aging: A Sourcebook for Clinicians. Baltimore: Williams & Wilkins, 79-106.

Kiefer, M., Marzinzik, F., Weisbrod, M., Scherg, M., & Spitzer, M. (1998). The time course of brain activations during response inhibition. NeuroReport, 9, 765-770.

Kiehl, K.A., Laurens, K.R., Duty, T.L., Forster, B. B., & Liddle, P. F. (2001). Neural sources involvedin auditory target detection and novelty processing: An event-related fMRI study. Psychophysiology, 38(1), 133-142.

Kileny, P., Paccioretti, D., & Wilson, A. F. (1987). Effects of cortical lesions on middle-latency auditory evoked responses (MLR). Electroencephalogr Clin Neurophysiol, 66, 108-120.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Res. Brain Res. Rev. 29, 169-195.

Klimesch, W., Doppelmayr, M., Schimke, H., & Pachinger, T. (1996). Alpha frequency, reaction time, and the speed of processing information. J. Clin. Neurophysiol. 13, 511-518.

Knight R. T., Hillyard S. A., Woods D. L., & Neville H. J. (1980). The effects of frontal and temporal-parietal lesions on the auditory evoked potential in man. Electroenceph clin Neurophysiol, 50(1-2), 112-24.

Knight, R. T., Staines, W. R., Swick, D., Chao, L. L. (1999). Prefrontal cortex regulates inhibition and excitation in distributed neural networks. Acta. Psychol. (Amst) 101 (2-3), 159-178.

Kewley-Port, D., Burkle, T. Z., & Lee, J. H. (2007). Contribution of consonant versus vowel information to sentence intelligibility for young normal-hearing and elderly hearing-impaired listeners. J. Acoust. Soc. Am. 122 (4), 2365-2375.

Kidd, G. J., Mason, C., Deliwala, P., Woods, W., & Colburn, H. (1994). Reducing informational masking by sound segregation. J. Acoust. Soc. Am. 95, 3475-3480.

Kidd, G. J., Mason, C., & Rohtla, T. (1995). Binaural advantage for sound pattern identification, J. Acoust. Soc. Am. 98, 1977-1986.

Kim, J. R., Ahn, S. Y., Jeong, S. W., et al. (2012). Cortical auditory evoked potential in aging: effects of stimulus intensity and noise. Otol Neurotol, 33, 1105-1112.

Kodera, K., Hink, R. F., Yamada, O., & Suzuki, J-I. (1979). Effects of rise time on simultaneously recorded auditory-evoked potentials from the early, middle and late ranges. Audiology, 18, 395-402.

Kok, A. (1999). Varieties of inhibition: manifestations in cognition, event-related potentials and aging. Acta. Psychol. (Amst) 101 (2-3), 129-158.

Konrad-Martin, D., Dille, M. F., McMillan, G., Griest, S., McDermott, D., Fausti, S. A., et al. (2012). Age-relaetd changes in the auditory brainstem response. J. Am. Acad. Audiol. 23, 18-35.

Kortlan, S., Mauermann, M., & Ewert, S. D. (2016). Suprathreshold auditory processing deficits in noise: effects of hearing loss and age. Hearing Research 331, 27-40.

Kraus, N., & Nicol, T. (2009). Auditory evoked potentials. Encyclopedia of Neuroscience, pp 214-218.

Kraus, N., & McGee, T. (1994). Mismatch negativity in the assessment of central auditory function. American Journal of Audiology, 3(2), 39-51.

Kraus, N., et al. (1993). Mismatch negativity in school-age children to speech stimuli that are just perceptibly different. Electroencephalography and Clinical Neurophysiology, 88(2), 123-130.

Kraus, N., Ozdamar, O., Hier, D., & Stein, L. (1982). Auditory middle latency responses (MLRs) in patients with cortical lesions. Electroencephalography and clicnial Neurophysiology 54, 275-287.

Kraus, N., Smith, D. I., Reed, N. L., Stein, L. K., & Cartee, C. (1985). Auditory middle latency responses in children: effects of age and diagnostic category. Electroenceph. Clin. Neurophysiol. 62, 343-351.

Kropotov J. D., Alho K., Naatanen, R., et al. (2000). Human auditory cortex mechanisms of preattentive sound discrimination. Neurosci Lett, 280, 87-90.

Kujala, T., Kallio, J., Tervaniemi, M., & Naatanen, R. (2001). The mismatch negativity as an index of temporal processing in audition. Clinical Neurophysiology, 112(9), 1712-1719.

Kushnerenko E., Ceponiene R., Balan P., Fellman V., & Naatanen R. (2002). Maturation of the auditory change detection response in infants: a longitudinal ERP study. Neuroreport, 13(15), 1843-8.

Kutas, M., McCarthy, G., & Donchin, E. (1977). Augmenting mental chronometry: the P300 as a measure of stimulus evaluation time. Science, 197 (4305), 792-795.

Kutas, M., & Hillyard, S. A. (1983). Event-related brain potentials to grammatical errors and semantic anomalies. Mem Cognit, 11, 539-550.

Lenzi, A., Chiarelli G., Sambataro, G. (1989). Comparative study of middle-latency responses and auditory brainstem responsese in elderly subjecst. Audiology, 28, 144-151.

Liberman, M. C., & Kujawa, S. G. (2017). Cochlear synaptopathy in acquired sensorineural hearing loss: manifestations and mechanisms. Hearing Research 349, 138-147.

Lidestam, B., Holgersson, J., & Moradi, S. (2014). Comparison of informational vs. energetic masking effects on speech reading performance. Frontiers in Psychology, 5, 639-646.

Liegeois-Chauvel, C, Musolino, A., Badier, J. M., Marquis, P., & Chauvel, P. (1994). Evoked potentials recorded from the auditory cortex in man: Evaluation and topography of the

middle latency components. Electroencephalography and CLincial Neurophysiolography and Clinical Neurophsysiology, 92(3), 204-214.

Lin, H. W., Furman, A. C., Kujawa, S. G., & Liberman, M. C. (2011). Primary neural degeneration in the guinea pig cochlea after reversible noise-induced threshold shift. Journal of the Association for Research in Otolaryngology 12 (5), 605-616.

Lisker, L. & Abramson, A. S. (1970). The voicing dimension: Some experiments in comparative phonetics. In: Proceedings of the VI international congress of phonetic sciences. Academia, Prague, pp.563-567.

Lister, J. J., Maxfield, N. D., Pitt, G. J., & Gonzalez, V. B. (2011). Auditory evoked response to gaps in noise; older adults. International Journal of Audiology, 50, 211-225.

Lopez-Otin, C., Blasco, M.A., Partridge, L., Serrano, M., & Kroemer, G. (2013). The hallmarks of aging. Cell, 153(6), 1194-1217.

Lu, J., Lobarinas, E., Deng, A., Goodey, R., Stolzberg, D., Salvi, R. J., & Sun W. (2011). GABAergic neural activity involved in salicylate-induced auditor ycortex gain enhancement. Neuroscience 189, 187-198.

Lutfi, R. A. (1990). How much masking is informational masking? J. Acoust. Soc. Am. 88(6), 2607-2610.

Maiste, A. C., Wiens, A. S., Hunt, M. J., Scherg, M., & Picton, T. (1995). Event-related potentials and the categorical perception of speech sounds. Ear and Hearing, 16, 67-89.

Martin, B. A., Sigal, A., Kurtzberg, D., & Stapells, D. R. (1996). The effects of decreased audibility produced by high-pass noise masking on cortical event-related potentials to speech sounds /ba/ and /da/. J. Acoust. Soc. Am., 101(3), 1585-1599.

Martin, B. A., Tremblay, K. L., & Stapells, D. R. (2007). Principles and applications of cortical auditory evoked potentials. In R. F. Burkard, M. Don, & J. J. Eggermont (Eds). Auditory Evoked Potentials-Basic Principles and Clinical Application (pp482-507). Lippincott Williams & Wilkins.

McCallum, W. C., & Curry, S. H. (1980). The form and distribution of auditory evoked potentials and CNVS when stimuli and responses are lateralized. In H.H. Kornhuber & L. Deecke (Eds.), Progress in brain research: Motivation, motor and sensory processes of the brain. Electrical potentials, behavior and clinical use (Vol. 54, pp. 767-775). New Work: Elsevier.

McCarthy, G. et al., (1981). Intracranial recordings of event related potentials in humans engaged in cognitive tasks. Society for Neuroscience Abstracts, 8, 976.

McCullagh, J. & Shinn, J. B. (2013). Auditory cortical processing in noise in younger and older adults. Hearing, Balance and Communication, 11, 182-190.

McGreer, E. G., & McGreer, P. L. (1976). Neurotransmiter metabolism I the aging brain. In: R.D. Terry and E. Gershon (Eds.), Neurobiology of Aging. Raven Press, New York, 389 ff.

Madden, D. J., & Langley, L. K. (2003). Age-related changes in selective attention and perceptual load during visual search. Psychol Aging 18, 54-67.

Martin, A., & Fedio, P. (1983). Word production and comprehension in Alzheimer's disease: The breakdown of semantic knowledge. Brain and Language, 19, 124-141.

Marvel, J. B., Jerger, J. F., & Lew, H. L. (1992). Asymmetries in topographic brain maps of auditory evoked potentials in the elderly. J Am Acd Audiol 3:361-368.

Makela, J. P., Hamalainen, M. Hari, R., & McEvoy, L. (1994). Whole-head mapping of middle-latency auditory evoked magnetic fields. Electroenceph. Clin. Neurophysiol., 92, 414-421.

Mason, S. M., & Mellor, D. H. (1984). Brainstem, middle latency and late cortical evoked potentials in children with speech and language disorders. Electroenceph. Clin. Neurophysiol. 59: 297-309.

Meddis, R., & O'Mard, L. (1997). A unitary model of pitch perception. Journal of the Acoustical Society of America, 102, 1811-1820.

Mehraei, G., Hickox, A. E., & Bharadwaj, H. M. et al. (2016). Auditory brainstem response latency in noise as a marker of cochlear synaptopathy. Journal of Neuroscience 36 (13), 3755-3764.

Michelini , S. Arslanlls, J. H., Schmiedt, R. A., Schulte, B. A., & Dubno, J. R. (2006). Age-related hearing loss: A loss of voltage, not hair cells. Seminars in Hearing 27, 228-336.

Michelini, S., Arslan, E., Prosser, S., & Pedrielli, F. (1982). Logarithmic display of auditory evoked potentials. Journal of Biomedical Engineering, 4, 62-64

Micheyl, C., Tian, B., Carlyon, R. P., & Rauschecker, J. P. (2005). Perceptual organization of tone sequences in the auditory cortex of awake macaques. Neuron, 48, 139-148.

Moller, A. R. (2006). Hearing: anatomy, physiology, and disorders of the auditory system (2nd ed.). Amsterdam: Academic Press.

Moore, B. C. (2008). The role of temporal fine structure processing in pitch perception, masking, and speech perception for normal-hearing and hearing-impaired people. JARO 9, 399-406.

Moore, B. C., Peters, R. W., & Glasberg, B. R. (1985). Thresholds for the detection of inharmonicity in complex tones. Journal of the Acoustical Society of America, 77, 1861-1867.

Moore, B. C. J., Glasberg, B. R., & Stoev, M. (2011). The influence of age and high-frequency hearing loss on sensitivity to temporal fine structure at low frequencies. J. Acoust. Soc. Am. 131 (2), February 2012.

Morgan, D. E., Kamm, C. A., & Velde, T. M. (1981). From equivalence of the speech perception in noise (SPIN) test. J. Acoust. Soc. Am. 69(6).

Munjal, S. K., Panda, N.K., & Pathak, A. (2010). Relationship between severity of traumatic brain injury (TBI) and extent of auditory dysfunction. Brain Injury, 24(3), 525-532.

Musiek, F. E., Baran, J. A., & Shinn, J. (2004). Assessment and remediation of an auditory processing disorder associated with head trauma. Journal of the American Academy of Audiology, 15(2), 117-132.

Nadol, J. B. (1989). Anatomy and pathology of presbycusis, the aging ear: Current concepts of the etiology, pathophysiology, diagnosis, and rehabilitation of presbycusis. In: The Aging Ear (pp. 1-7). St. Louis, Washington University School of Medicine, 1989.

Naatanen, R. (1992). Attention and brain function. Hillsdale, NJ: Lawrence Erlbaum.

Naatanen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. Behav Brain Sci, 13, 201-288.

Naatanen R., & Picton T. (1987). The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. Psychophysiology, 24(4), 375-425.

Naatanen, R., & Picton, T. W. (1986). N2 and automatic versus controlled processes. In: W. C. McCallum, R. Zappoli, & F. Denoth (Eds.), Cerebral psychophysiology: Studies in event-related potentials (Electroencephalography and Clinical Neurophysiology. Supplement, 38, pp.169-186). Amsterdam: Elsevier.

Naatanen, R., Simpson, M., & Loveless, N. E. (1982). Stimulus deviance and evoked potentials. Biological Psychology, 14, 53-98.

Naatanen, R., Gaillard, A. W., & Mantysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. Acta Psychologica, 42(4), 313-329.

Nousak, J. K. & Stapells (2005). Auditory brainstem and middle latency responses to 1kHz tones in noise-masked normally-hearing and sensorineurally hearing-impaired adults. International Journal of Audiology, 44, 331-344.

Oates, P. A., Kurtzberg, D., & Stapells, D. R. (1991). Effects of sensorineural hearing loss on cortical event-related potential and behavioral measures of speech-sound processing. Ear.Hear, 23, 399-415.

Ober, B. A., Dronkers, N. F., Koss, E., Delis, D. C., & Friedland, R. P. (1986). Retrieval from semantic memory in Alzheimer-type dementia. Journal of Clinical and Experimental Neuropsychology, 8, 75-92.

O'Donnell, B. F. et al. (2004). Neural Synchronization deficits to auditory stimulation in bipolar disorder. Neurophysiology, Basic and Clinical, 15(8), 1369-1372.

Owen, J. H. (1981). Influence of acoustical and linguistic factors on the SPIN test difference score. J. Acoust. Soc. Am. 70(3), 678-682.

Paavilaimen et al. (1991). Right hemisphere dominance of different mismatch negativities. Electroencephalogr Clin Neurophysiol, 78, 466-479.

Paavilainen, P., Camman, R., Alho, K., Reinikainen, K., Sams, M., & Naatanen, R. (1987). Event-related potentials to pitch change in an auditory stimulus sequence during sleep. In: Johnson, R. J., Rohrbaugh, J. W., Parasuraman, R. (Eds.), Current Trends in Event-Related Potential Research (EEG Suppl. 40). Elsevier Science Publishers, Amsterdam, pp. 246-255.

Pachana, N. A., Boone, K. B., Miller, B. L., Cummings, J. L., & Berman, N. (1996). Comparison of neuropsychological functioning in Alzheimer's disease and frontotemporal dementia. Journal of the International Neuropsychological Society, 2, 505-510.

Paetau R., Ahonen A., Salonen O., & Sams M. (1995). Auditory evoked magnetic fields to tones and pseudowords in healthy children and adults. J Clin Neurophysiol, 12(2), 177-85.

Palmer, A. R. (1995). Neural signal processing. In B. C. J. Moore (Ed.), Hearing (pp. 75-121). New York: Academic Press.

Pang E. W., & Taylor M. J. (2000). Tracking the development of the N1 from age 3 to adulthood: an examination of speech and non-speech stimuli. Clin Neurophysiol, 111(3), 388-97.

Parikh, G., & Loizou, P.C. (2005). The influence of noise on vowel and consonant cues. Journal of the Acoustical Society of America, 118, 3894-3888.

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

Pascual-Marqui, R. D., Michel, C. M., & Lehmann, D. (1994). Low resolution electromagnetic tomography: A new method for localizing electrical activity in the brain. International Journal of Psychophysiology, 18(1), 49-65.

Paludetti, G., Maurizi, M., D'alatri, L., & Galli, J. (1991) Relationships between middle latency auditory responses and speech discrimination tests in the elderly. Acta Otol, 476, 105-109.

Patel, S. H., & Azzam, P. N. (2005). Characterization of N200 and P300: selected studies of the event-related potential. International Journal of Medical Sciences 2(4), 147-154.

Pekkonen, E., Huotilainen, M., Virtranen, J., Sinkkonen, J., Rinne, T., Ilmoniemi, R. J., & Naatanen, R. (1995). Age-related functional differences between auditory cortices: a whole-head MEG study. NeuroReport 6, 1803-1806.

Peters, A. (2002). The effects of normal aging on myelin and nerve fibers: a review. J. Neurocytol. 31,581-93

Pfefferbaum, A. Ford, J. M., Roth, W. T., Hopkins, W. F., & Kopell, B. S. (1979). Event-related potential changes in healthy aged females. Electroencephalogr Clin Neurophysiol, 46, 81-86.

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

Pfefferbaum, A., Ford, J. M., Wenegrat, B. G., Roth, W. T., & Kopell, B. S. (1984). Clinical application of the P3 component of event-related potentials. I. Normal aging. Electroencephalogr Clin Neurophysiol, 59, 85-103.

Phillips, D. P. (1987). Stimulus intensity and loudness recruitment: Neural correlates. J. Acoust Soc Am, 82(1), 1-12.

Phillips, D. P. (1990). Neural representation of sound amplitude in the auditory cortex: effects of noise masking. Behavioral Brain Research, 37, 197-214.

Picton, T. W. et al. (1999). Intracerebral sources of human auditory-evoked potentials. Audiology and Neuro-Otology, 4(2), 64-79.

Picton, T. (1995). The neurophysiological evaluation of auditory discrimination. Ear and Hearing, 16, 1-5.

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

Picton, T. W. & Hillyard, S. A. (1974). Human auditory evoked potentials: 2. Effects of attention. Electroencephalography and Clinical Neurophysiology, 36(2), 191-199.

Picton, T., Hillyard, S., Krusz, H., & Galambos, R. (1974). Human auditory evoked potentials, I: Evaluation of components. Electroencephalogr Clin. Neurophysiol, 36(2), 179-190.

Picton, T. W., Hillyard, S. A., Galambos, R., & Schiff, M. (1971). Human auditory attention: A central or peripheral process? Science, 173(994), 351-353.

Plyer, P. N., & Hedrick, M. S. (2002). The effects of stimulus presentation level on stop consonant identification in normal and hearing-impaired listeners. J. Am. Acad. Audiol, 13, 154-159.

Ponton, C. W., & Eggermont, J.J. (2001). Of kittens and kids: Altered cortical maturation following profound deafness and cochlear implant use. Audiology and Neuro-Otology, 6(6), 363-380.

Ponton, C. W., Don, M., Eggermont, J. J., et al. (1996a). Auditory system plasticity in children after long periods of complete deafness. Neuroreport, 8, 61-65.

Ponton, C. W., Don, M., Eggermont, J. J., et al. (1996b). Maturation of human cortical auditory function: differences between normal-hearing children and children with cochlear implants. Ear Hear, 17, 430-437.

Ponton C. W., Eggemont J. J., Kwong B., & Don M. (2000b). Maturation of human central auditory system activity: evidence from multi-channel evoked potentials. Clin Neurophysiol, 111(2), 220-36.

Pollack, I. (1975). Auditory informational masking. J. Acoust. Soc. Am. Suppl. 1, 57,S5.

Popelar, J., Grecova, J., Rybalko, N., & Syka, J. (2008). Comparison of noise-induced changes of auditory brainstem and middle latency response amplitudes in rats. Hearing Research 245, 82-91.

Popelar, J., Syka, J., & Berndt, H. (1987). Effect of noise on auditory evoked responses in awake guinea pigs. Hear. Res. 26, 239-247.

Praamstra, P., Hagoort, P., Maassen, B., & Crul, T. (1991). Word deafness and auditory cortical function: A case history and hypothesis. Brain, 114(Pt 3), 1197-1223.

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

Qiu, C., Salvi, R., Ding, D., & Burkard, R. (2000). Inner hair cell loss leads to enhanced response amplitudes in auditory cortex of unanesthetized chinchillas: evidence for increased system gain. Hear Res., 139, 153-171.

Rauschecker, J. P. (2005). Neural encoding and retrieval of sound sequences. Ann. N. Y. Acad. Sci. 1060. 125-135.

Reed, C. M., Braida, L. D., Zurek, P. M. (2009). Review of the literature on temporal resolution in listeners with cochlear hearing impairment: a critical assessment of the role of suprathreshold deficits. Trends Amplif. 13(1), 4-43.

Rees, A. & Palmer, A. R. (1988). Rate-intensity fuctions and their modification by broadband noise for neurons in the guinea pig inferior colliculus. J. Acoust. Soc. Am. 83, 1488-1498.

Reite, M., Teale, P., Zimmerman, J., Davis, K., & Whalen, J. (1988). Source location of a 50 ms latency auditory evoked field component. Electroanalysis, 70, 490-498.

Rich, M. M., & Wenner, P. (2007). Sensing and expressing homeostatic synaptic plasticity. Trends Neurosci. 30, 119-125.

Ries, P. W. (1994). Prevalence and characteristics of persons with hearing trouble: United States, 1990-91. Vital Health Stat 10; 188:1-75.

Rif J., Hari R., Hamalainen M. S., & Sams M. (1991). Auditory attention affects two different areas in the human supratemporal cortex. Electroenceph clin Neurophysiol, 79(6), 464-72.

Rinne, T., Alho K., Ilmoniemi, R. J., et al. (2000). Separate time behaviors of the temporal and frontal mismatch negativity sources. Neuroimage, 12, 14-19.

Ritter, W. (1982). Manipulation of event-related potential manifestations of information processing stages. Science, 218, 909-910.

Rosen, W. G. (1980). Verbal fluency in aging and dementia. Journal of Clinical Neuropsychology, 2, 135-146.

Richer, F., Johnson, R. A., & Beatty, J. (1983). Sources of late components of the brain magnetic response. Society for Neuroscience Abstracts, 9, 656.

Roth W. T., Ford J. M., Lewis S. J., & Kopell B. S. (1976). Effects of stimulus probability and task-relevance on event-related potentials. Psychophysiology, 13, 311-7.

Roup, C. M., Wiley, T. L., Safady, S. H., & Stoppenbach, D. T. (1998). Tympanometric Screening Norms for Adults. American Journal of Audiology. 7, 1-6

Royall, D. R., Lauterbach, E. C., Cummings, J. L., et al. (2002). Executive control function: a review of its promise and challenges for clinical research. A report from the committee on Research of the American Neuropsychiatric Association. J Neuropsychiatry Clin Neurosci. 14, 377-405.

Ruggero, M. A. (1992). Physiology of the auditory nerve. In A.N. Popper & R. R. Fay (eds.). The Mammalian Auditory Pathway: Neurophysiology. New York: Springer-Verlag, p. 3493.

Ruggles, D., Bharadwaj, H., & Shinn-Cunningham, B. G. (2011). Normal hearing is not enough to guarantee robust encoding of suprathreshold featues important in everyday communication. Proc. Natl. Acad. Sci. USA 108, 15516-15521.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. Psychol Rev 103, 403-28.

Salvi, R. J., Saunders, S. S., Gratton, M. A., Arehole, S., & Powers, N. (1990). Enhanced evoked response amplitudes in the inferior colliculus of the chinchilla following acoustic trauma. Hearing Research, 50, 245-258.

Salvi, R., Sun, W., Ding, D., & Chen, G. et al. (2017). Inner hair cell loss disrupts hearing and cochlear function leading to sensory deprivation and enhanced central auditory gain. Frontiers in Neuroscience 10, 621-635.

Salvi, R. J., Wang, J., & Ding, D. (2000). Auditory plasticity and hyperactivity following cochlear damage. Hear. Res. 147, 261-274.

Sayles, M., & Winter, I. M. (2008). Ambiguous pitch and the temporal representation of inharmonic iterated rippled noise in the ventral cochlear nucleus. Journal of Neuroscience, 28, 11925-11938.

Schaette, R., & McAlpine, D. (2011). Tinnitus with a normal audiogram: Physiological evidence for hidden hearing loss and computational model. Journal of Neuroscience, 31, 13452-13457.

Scherg, M., & Von Cramon, D. (1986). Evoked dipole source potentials of the human auditory cortex. Electroencephalography and Clinical Neurophysiology, 65(5), 344-360.

Scherg, M., & Von Cramon, D. (1985). Two bilateral sources of the late AEP as identified by a spatio-temporal dipole model. Electroencephalography and Clinical Neurophsyiology, 62(1), 32-44.

Scherg, M., Hari, R., & Hamalainen, M. (1989). Frequency-specific sources of the auditory N19-P30 detected by a multiple source analysis if evoked magnetic fields and potentials, In Williamson, S.J., Hoke, M., Stroink, G., and Kotani, M. (Eds.), Advances in Biomagnetism (pp. 97-100). Plenum Press, New York.

Scherg, M., Vajsar, J., & Picton, T.W. (1989). A source analysis of the late human auditory evoked potentials. J Cogn Neurosci, 1, 336-355.

Schmiedt R. A. (2010). The physiology of cochlear presbycusis. The Aging Auditory System, Springer Handbook of Auditory Research, 34, 9-38.

Schneider, A., & Pichora-Fuller, M. K. (2001). Age-related changes in temporal processing: implications for speech perception. Seminars in Hearing, Volume, 22(3), 227-239.

Schneider, B.A., Daneman, M., Pichora-Fuller, M. K. (2002). Listening in aging adults: from discourse comprehension to psychoacoustics. Can. J. Exp. Psychol. 56, 139-152.

Schoof, T., & Rosen, S. (2016). The role of age-related declines in subcortical auditory processing in speech perception in noise. JARO 17, 441-460.

Schroger, E. (1993). Event-related potentials to auditory stimuli following transient shifts of spatial attention in a Go/Nogo task. Biological Psychology, 36, 183-207.

Schuknecht, H. F. (1964). Further observation on the pathology of presbycusis. Arch Otolaryngol, 80, 369-382.

Schuknecht H. F. (1974). Presbycusis. In: Pathology of the Ear. Cambridge, MA: Harvard University Press.

Schuknecht H. F. & Gacek M. R. (1993). Cochlear Pathology in presbycusis. Ann Otol Rhinol Laryngol, 102, 1-16.

Schum, D. J. & Matthews, L. J. (1992). SPIN test performance of elderly hearing-impaired listeners. J Am Acad Audiol, 3, 303-307.

Seki, S. & Eggermont, J. (2003). Changes in spontaneour firing rate and neural synchrony in cat primary auditory cortex after localized tone-induced hearing loss. Hearing Research, 180, 28-38.

Setzen, G. et al. (1999). Central deafness in a young child with moyamoya disease: Paternal linkage in a Caucasian family-two case reports and a review of the literature. International Journal of Pediatric Otorhinolaryngology, 48(1), 53-76.

Shamma, S. A., Elhilali, M., & Micheyl, C. (2011). Temporal coherence and attention in auditory scene analysis. Trends Neurosci. 34, 114-123.

Shinn-Cunningham, B. G., & Best, V. (2008). Selective attention in normal and impaired hearing. Trends in Amplification, 12, 283-299.

Shinn-Cunningham, B. G., & Best, V. (2008). Selective attention in normal and impaired hearing. Trends Amplif, 12, 283-299.

Shosaku, A., and Sumitomo, I. (1983). Auditory neurons in the rat thalamic reticular nucleus. Exp. Brain Res., 49, 432-442.

Simson, R., Vaughn, H. G., Jr, & Ritter, W. (1977). The scalp topography of potentials in auditory and visual discrimination tasks. Electroencephalography and Clinical Neurophysiology, 42(4), 528-535.

Smith, R. L. (1979). Adaptation, saturation and physiological masking in single auditory-nerve fibers. J. Acoust Soc Am, 65, 166-178.

Snyder, J. S., & Alain, C. (2007). Toward a neurophysiological theory of auditory stream segregation. Psychological Bulletin, 133, 780-799.

Sommers, M.S. (1997). Stimulus variability and spoken word recognition II. The effects of age and hearing impairment. Journal of the Acoustical Society of America, 101, 2278-2288.

Sommers, M. S., & Danielson, S. M. (1999). Inhibitory processes and spoken word recognition in young and older adults: the interaction of lexical competition and semantic context. Psychology and Aging, 14(3), 458-472.

Sommers, N. S., & Humes, L. E. (1993). Auditory filter shapes in normal-hearing, noise-masked normal, and elderly listeners. The Journal of the Acoustical Society of America, 93, 2903-2914.

Soros, P., Teismann, I. K., Manemann, E., & Lutkenhoner, B. (2009). Auditory temporal processing in healthy aging: a magnetoencephalographic study. BMC Neurosci. 10, 34

Stapells, D. R., & Picton, T. W. (1981). Technical aspects of brainstem evoked potential audiometry using tones. Ear Hear, 2(1), 20-9.

Steinschneider, M. Volkov, I. O., & Noh, M. D. (1999). Temporal encoding of the voice-onset-time phonetic parameter by field potentials encoded directly from human auditory cortex. J Neurophysiol, 82(23), 46-57.

Stine, E. L., & Wingfield, A. (1987). Process and strategy in memory for speech among younger and older adults. Psychol Aging 2, 272-9.

Strauß, A., Henry, M. J., Scharinger, M., & Obleser, J. (2015). Alpha phase determines successful lexical decision in noise. J. Neurosci. 35, 3256-3262.

Sun, W., Lu, J., Stolzbeg, D., Gray, L., Deng, A., Lobarinas, E., et al. (2009). Salicylate increases the gain of the central auditory system. Neuroscience 159, 325-334.

Suneja, S. K., Benson, C. G., & Potashner, S. J. (1998a). Glycine receptors in adult guinea pig brain stem auditory nuclei: regulation after unilateral cochlear ablation. Exp. Neurol. 154, 473-488.

Suneja, S. K., Potashner, S. J., & Benson, C. G. (1998b). Plastic changes in glycine and GABA r elease and uptake in adult brain stem auditory nuclei after unilateral middle ear ossicle removal and cochlear ablation. Exp. Neurol. 151, 273-288.

Swink, S., & Stuart, A. (2012). Auditory long latency responses to tonal and speech stimuli. Journal of Speech, Language, and Hearing Research, 55, 447-459.

Syka, J., & Rybalko, N. (2000). Threshold shifts and enhancement of cortical evoked responses after noise exposure in rats. Hear. Res. 139, 59-68.

Syka, J., Rybalko, N., & Popelar J. (1994). Enhancement of the auditory cortex evoked responses in awake guinea pigs after noise exposure. Hear. Res. 78, 158-168.

Tabri, D. Abou Chacra, K.M.S., & Pring T. (2010). Speech perception in noise by monolingual, bilingual and trilingual listeners. Int J Lang Commun Disord, Early Online Article, 1-12.

Tallal, P., Miller, S., Fitch, R. H. (1993). Neurobiological basis of speech: a case for the preeminence of temporal processing. Annals of the New York Academy of Sciences 682(1), 27-47.

Tiesinga, P. H., Fellous, J. M., Salinas, E., Jose, J.V., & Sejnowski, T., J. (2004). Inhibitory synchrony as a mechanism for attentional gain modulation. J. Physiol Paris, 98, 296-314.

Tiitinen, H., Sivonen, P., Alku, P., Virtanen, J., & Naatanen, R. (1999). Electromagnetic recordings reveal latency differences in speech and tone processing in humans. Cognitive Brain Research, 8, 355-363.

Tombaugh, T. N., Kozak, J., & Rees, L. (1999). Normative data stratified by age and education for two measures of verbal fluency: FAS and animal naming. Archives of Clinical Neuropsychology, 14(2), 167-177.

Tomquist-Uhlen I. (1996). Topography of auditory evoked long-latency potentials in children with severe language impairment: the P2 and N2 components. Ear Hear, 17(4), 314-26.

Tong, Y., Melara, R. D., & Rao, A. (2009). P2 enhancement from auditory discrimination training is associated with improved reaction times. Brain Research, 1297, 80-88.

Tremblay, K., & Burkard, R. F. (2007). The aging auditory system. In: R. F. Burkard, M. Don, & J. J. Eggermont (Eds.): Auditory Evoked Potentials-Basic Principles and Clinical Application (pp. 403-425). Lippincott Williams & Wilkins

Tremblay, K. L., & Kraus, N. (2002). Auditory training induces asymmetrical changes in cortical neural activity. J Speech Lang Hear Res, 45, 564-572.

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, 1332-1343.

Tremblay, K. L., Billings, C. & Rohila, N. (2004). Speech evoked cortical potentials: effects of age and stimulus presentation rate. J Am Acd Audiol, 15, 226-237.

Tucker, D.A., Dietrich, S., Harris, S., & Pelletier, S. (2002). Effects of stimulus rate and gender on the auditory middle latency response. Journal of the American Academy of Audiology, 13(3), 146-153, quiz 171-172.

Tucker, D. A., Dietrich, S., McPherson, D.L., & Salamat, M.T. (2001). Effect of stimulus intensity level on auditory middle latency response brain maps in human adults. Journal of the American Academy of Audiology, 12(5), 223-232.

Tun, P. A., Wingfield, A., & Stine, E. A. (1991). Speech-processing capacity in young and older adults: A dual-task study. Psychology and Aging, 6, 3-9.

Tun, P., O'Kane, G., & Wingfield, A. (2002). Distraction by competing speech in young and older adult listeners. Psychol Aging, 17, 453-467.

Turrigiano, G. G. (1999). Homeostatic plasticity in neuronal networks: the more things change, the more they stay the same. Trends Neuroscience 22, 221-227.

Turrigiano, G. (2007). Homeostatic signaling: the positive side of negative feedback. Curr. Opin. Neurobiol. 17, 318-324.

Uhlmann, R. F., Larson, E. B., Rees, T. S., Koepsell, T. D., & Duckert, L. G. (1989). Relationship of hearing impairment to dementia and cognitive dysfunction in older adults. JAMA, 261; 1916-19.

Van Rooij, J. C., & Plomp, R. (1992). Auditive and cognitive factors in speech perception by elderly listeners. III. Additional data and final discussion. Journal of the Acoustical Society of America, 91, 1028-1033.

Vaughan Jr H. G. & Ritter W. (1970). The sources of auditory evoked responses recorded from the human scalp. Electroenceph clin Neurophysiol, 28(4), 360-7.

Vaughan Jr H. G., Ritter W. & Simson R. (1980). Topographic analysis of auditory event-related potentials. Prog Brain Res, 54, 279-85.

Vaughan, H. G. Jr., & Kurtzberg, D. (1992). Electrophysiologic indices of human brain maturation and cognitive development. In M. R. Gunnar, C. Nelson (Eds.), Minnesota Symposia on Child Psychology (Vol. 24, pp. 1-36). Hillsdale, NJ: Lawrence Erlbaum.

Verkindt C., Bertrand O., Thevenet M., & Pemier J. (1994). Two auditory components in the 130-230 ms range disclosed by their stimulus frequency dependence. Neuroreport, 5(10), 1189-92.

Vivion, M. C., Wolf, K. E., Goldstein, R. Hirsch, J. C., & McFarland, W. H. (1979). Toward objective analysis for electroencephalic audiometry. J. Speech Hear. Res.22: 88-102.

Wang, J., Ding, D., & Salvi, R. J. (2002). Functional reorganization in chinchilla inferior colliculus associated with chronic and acute cochlear damage. Hear Res, 168, 238-249.

White L., & Atcherson S. (2012). Cortical event-related potentials. In S. R. Atcherson, & T. M. Stoody (Eds.). Auditory Electrophysiology (pp137-160). New York: Thieme.

Whiting, K. A., Martin, B. A., & Stapells, D. R. (1998). The effects of broadband noise masking on cortical event-related potentials to speech sounds /ba/ and /da/. Ear Hear, 19(3), 218-231.

Williams, A. J., & Fuzessery, Z. M. (2011). Differential roles of GABAergic and glycinergic input on FM selectivity in the inferior colliculus of the pallid bat. J. Neurophysiol 106(5), 2523-2535.

Wolpaw J. R., & Penry J. K. (1975). A temporal component of the auditory evoked response. Electroenceph clin Neurophsyiol, 39(6), 609-20.

Woods D. L., Knight R. T., & Scabini D. (1993). Anatomical substrates of auditory selective attention: behavioral and electrophsiological effects of posterior association cortex lesions. Brain Res Cogn Brain Res, 1(4), 227-40.

Woods, D.R., Clayworth, C. C., Knight R. T., Simpson, G. V., & Naeser, M. A. (1987). Generators of middle- and long-latency auditory evoked potentials: implications from studies of patients with bitemporal lesions. Electroephalography and Clinical Neurophysiology, 68(2), 132-148.

Wang, X. (2007). Neural coding strategies in auditory cortex. Hear. Res. 229, 81-93.

Watson, C., Kelly, W., & Wroton, H. (1976). Factors in the discrimination of tonal patterns. II. Selective attention and learning under various levels of stimulus uncertainty. J. Acoust. Soc. Am. 60, 1176-1185.

Welford, A. T. (1985). Changes of performance with age: an overview. In: Charness N. (eds.) Aging and Human Performance. New York: John Wiley & Sons, 333-369.

Wever, E.G., & Bray, C. W. (1930). Auditory nerve impulses. Science, 17 (1834), 215.

Whittington M. A., Faulkner H. J., Doheny H. C., & Traub R. D. (2000). Neuronal fast oscillations as a target site for psychoactive drugs. Pharm Ther, 86, 171-190.

Whittington, M. A., Traub, R. D. (2003). Interneuron diversity series: inhibitory interneurons and network oscillations in vitro. Trends Neurosci, 26, 676-682.

Williams, H. L., Tepas, D. I., & Morlock, H. C., Jr (1962). Evoked responses to clicks and electroencephalographic stages of sleep in man. Science, 138, 685-686.

Willot, J. F. (1991). Aging and the auditory system. Singular, San Diego.

Willot, J. F. (1996). Anatomic and physiological aging: A behavioral neuroscience perspective. Journal of the American Academy of Audiology, 7, 141-151.

Willott, J. F., & Lu, S. M. (1982). Noise-induced hearing loss can alter neural coding and increase excitability in the central nervous system. Science, New series 216(4552), 1331-1332.

Wilson, R. H., McArdle R., Watts, K.L., & Smith, S.L. (2012). The revised speech perception in noise test (R-SPIN) in a multiple signal-to-noise ratio paradigm. J Am Acad Audiol, 23, 590-605.

Wingfield, A., Lombardi, L., & Sokol, S. (1984). Prosodic features and the intelligibility of accelerated speech: Syntactic versus periodic segmentation. J Speech Hear Res 27, 128-134.

Wingfield, A., & Stine, EA. (1992). Age differences in perceptual processing and memory for spoken language. In R. L. West & J.D. Sinnott (Eds.), Everyday memory and aging: Current research and methodology (pp. 101-123). New York: Springer-Verlag.

Wolpaw, J. R. & Penry, J. K. (1975). A temporal component of the auditory evoked response. Electroencephalography and Clinical Neurophysiology, 39(6), 609-620.

Wong, P. C. M., Jin, J. X., Gunasekera, G. M., et al. (2009). Aging and cortical mechanisms of speech perception in noise. Neuropsychologia, 47, 693-703.

Wood, C. C., Allison, T., Goff, W. R., Williamson, P. D., & Spencer, D. D. (1980). On the neural origin of P300 in Man. Progress in Brain Research 54, 51-56.

Wood, C. C., Spencer, D. D., Allsion, T., McCarthy G. (1988). Localization of human sensorimotor cortex during surgery by cortical surface recording of somatosensory evoked potentials. Journal of Neurosurgery 68(1), 99-111.

Woods, D. L., & Clayworth, C. C. (1986). Age-related changes in human middle latency auditory evoked potentials. Electroenceph. Clin. Enurophysiol. 65, 297-303.

Woodruff, D. S. (1983). A review of aging and cognitive processes. Res Aging 5, 139-153.

Working Group on Speech Understanding & Aging, National Research Council, Commission on Behavioral & Social Sciences & Education, Washignton, DC: 7 Committee on Hearing.

Wu, C. Y. & Stapells, D. R. (1994). Pure-tone masking profiles for human auditory brainstem and middle latency responses to 500 Hz tones. Hear Res, 78, 169-174.

Yamada, O., Kodera, K., & Yagi, T. (1979). Cochlear processes affecting wave V latency of the auditory evoked brainstem response. Scand. Audiol. 8, 67-70.

Yingling, C. D., & Hosobuchi, Y. (1984). A subcortical correlate of P300 in man. Electroencephalography and Clinical Neurophysiology, 59(1), 72-76.

Yingling, C. D., & Skinner, J. E. (1977). Gating of thalamic input to cerebral cortex by nucleus reticularis thalami. In J. E. Desmedt (Ed.), Progress in clinical neurophysiology: Attention, voluntary contraction, and event-related cerebral potentials (pp. 70-96). Basel: Karger.

Young, E. D., Sachs, M. B. (1979). Representation of steady-state vowels in the temporal aspects of the discharge patterns of populations of auditory-nerve fibers. The Journal of the Acoustical Society of America 66, 1381-1403

Yueh, B., Shapiro, N., MacLean, C. H., et al. (2003). Screening and management of adult hearing loss in primary care. Journal of the American Medical Association, 289 (15), 1976-1985.

Yvert, B., Crouzeix, A., Bertrand, O., Seither-Preisler, A., & Pantev, C. (2001). Multiple supratemporal sources of magnetic and electric auditory evoked middle latency components in humans. Cerebral Cortex, 11(5), 411-423.

Yvert, B., Fischer, C., Bertrand, O., & Pernier, J. (2005). Localization of human supratemporal auditory areas from intracerebral auditory evoked potentials using distributed source models. NeuroImage, 28(1), 140-153.

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. Heairng Research 309, 55-62.

Appendix A: Subjects' demographic data.

A-1. Young normal-hearing subjects (YS)

				Audiometric Thresholds						
	Gender	Age	Ear	250	500	1000	2000	4000	8000	LP-SPIN (%)
YS1	M	28	R	5	5	0	10	5	10	92
YS2	F	22	L	5	5	5	5	0	-10	92
YS3	M	22	L	5	5	0	10	10	0	88
YS4	M	19	L	10	5	10	0	0	0	100
YS5	F	22	L	0	0	0	-5	-5	-5	92
YS6	F	19	R	0	5	0	0	0	5	100
YS7	F	20	L	0	5	0	0	0	0	96
YS8	F	19	R	10	10	10	5	0	-5	96
YS9	M	19	R	10	10	5	10	10	-5	88
YS10	F	22	L	5	0	0	-5	0	0	88
YS11	F	22	L	5	5	5	5	5	0	96
YS12	F	18	R	10	10	10	10	15	10	92
YS13	F	20	R	10	10	5	5	5	-5	96
YS14	M	22	R	10	10	10	5	10	0	80
YS15	F	30	R	10	5	10	10	5	5	92
YS16	F	19	L	5	5	10	10	5	-5	96
YS17	F	23	L	5	0	5	-5	0	0	100
YS18	F	18	L	0	-5	-5	0	5	-10	92
YS19	M	18	L	5	5	5	5	10	0	80
YS20	F	22	L	0	-5	0	5	0	-10	92
YS21	M	19	R	5	15	10	15	5	5	88
YS22	M	19	L	10	10	10	10	0	-10	96
YS23	F	22	L	5	0	5	5	0	5	84
YS24	F	20	L	5	10	5	10	0	-10	88
YS25	F	18	L	5	5	0	5	5	0	88
YS26	M	19	R	5	5	5	5	0	-5	84
YS27	M	23	R	5	5	5	0	0	-5	88
YS28	F	20	R	5	10	5	10	5	-10	92
YS29	F	23	R	10	10	15	15	5	-5	84
YS30	F	26	L	5	5	5	0	0	-10	84
Average		**21**		**6**	**6**	**5**	**5**	**3**	**-2**	**91 %**
SD		**2.92**		**3.41**	**4.61**	**4.55**	**5.49**	**4.42**	**5.98**	**5.57 %**

Appendix A: Subjects' demographic data.

A-2. Older subjects with near-normal hearing (ONS)

				Audiometric Thresholds						
	Gender	Age	Ear	250	500	1000	2000	4000	8000	LP-SPIN (%)
ONS1	F	58	L	10	15	20	25	25	30	84
ONS2	F	60	L	15	20	20	15	15	10	92
ONS3	F	61	L	15	25	20	10	15	15	84
ONS4	F	60	R	5	10	5	15	20	15	88
ONS5	F	57	L	10	15	10	15	20	15	92
ONS6	F	60	L	10	5	5	5	30	35	88
ONS7	F	56	R	10	10	10	5	10	10	84
ONS8	M	61	L	20	15	15	20	25	25	92
ONS9	M	60	R	5	10	10	10	15	5	84
ONS10	M	70	R	0	5	10	15	25	25	92
ONS11	M	65	R	15	10	10	20	25	30	84
ONS12	F	75	R	10	10	15	20	20	30	92
ONS13	F	73	L	10	20	20	25	35	20	88
ONS14	F	71	R	20	-10	15	25	25	30	96
ONS15	F	62	L	5	-10	5	15	20	25	92
ONS16	F	65	R	5	0	5	10	25	25	96
ONS17	F	68	R	5	10	10	0	10	0	84
ONS18	F	57	R	5	10	5	10	10	5	88
ONS19	F	69	R	10	10	15	15	10	15	88
ONS20	F	66	L	10	10	5	15	15	5	80
ONS21	F	61	L	10	5	10	10	20	15	88
ONS22	M	68	R	10	10	10	10	25	30	80
ONS23	F	64	L	5	10	0	5	5	25	92
ONS24	F	59	L	20	20	25	25	20	15	72
ONS25	F	60	R	5	0	15	30	30	15	68
ONS26	F	71	L	5	5	15	20	30	30	80
Average		**63.7**		**9.62**	**9.23**	**11.73**	**15**	**20.19**	**19.42**	**86.46 %**
SD		**5.4**		**5.28**	**8.21**	**6.16**	**7.48**	**7.55**	**10.03**	**6.70 %**

Appendix A: Subjects' demographic data.

A-3. Older hearing-impaired subjects (OHS)

				Audiometric Thresholds						
	Gender	Age	Ear	250	500	1000	2000	4000	8000	LP-SPIN (%)
OHS1	M	68	L	20	10	30	65	70	60	52
OHS2	F	62	R	20	25	35	45	50	50	52
OHS3	F	61	L	10	15	10	10	0	60	76
OHS4	F	59	L	20	20	20	20	45	60	84
OHS5	F	64	L	25	30	20	25	25	65	96
OHS6	F	71	R	10	15	5	15	55	55	60
OHS7	F	82	R	35	35	35	35	50	60	68
OHS8	F	71	R	5	10	40	45	60	60	36
OHS9	F	75	L	25	30	50	50	60	65	84
OHS10	M	74	L	15	20	20	40	65	75	64
OHS11	F	70	L	30	40	40	50	50	50	56
OHS12	F	89	L	30	40	55	65	60	60	44
OHS13	F	76	R	15	20	20	40	50	55	60
OHS14	F	74	R	10	10	10	40	50	60	44
OHS15	F	81	R	25	20	30	35	55	60	80
OHS16	M	78	R	5	10	15	15	30	50	92
OHS17	F	66	L	10	15	15	30	45	65	84
OHS18	M	87	R	30	45	55	60	65	75	24
OHS19	F	62	L	30	35	35	40	30	55	76
OHS20	F	72	R	20	20	20	30	50	60	72
OHS21	M	73	L	15	15	15	20	35	55	80
OHS22	F	77	L	10	30	30	45	65	75	36
OHS23	F	77	L	10	10	10	10	45	75	68
OHS24	F	77	L	20	25	25	40	50	60	52
OHS25	M	80	L	10	15	15	15	40	50	76
OHS26	M	79	L	15	15	30	40	60	80	48
Average		**73.3**	**18.15**	**22.04**	**26.11**	**35.56**	**42.14**	**48.52**	**60.93**	**63.56 %**
SD		**7.7**	**8.45**	**10.31**	**3.54**	**13.68**	**15.65**	**14.92**	**9.10**	**18.54%**

Appendix B: Animal Naming Task

Name _____ **ID #** _____

Date _____

ANIMAL NAMING

Introduction: "I'd like to ask a question to check your memory."

Instruction: "Tell me the names of as many animals as you can think of, as quickly as possible."

Procedure: Time for 60 seconds and record all responses.
If the person stops before 60 seconds, say "Any more animals?"
If the person says nothing for 15 seconds, say "A dog is an animal.
"Can you tell me more animals?"

1. _____	12. _____
2. _____	13. _____
3. _____	14. _____
4. _____	15. _____
5. _____	16. _____
6. _____	17. _____
7. _____	18. _____
8. _____	19. _____
9. _____	20. _____
10. _____	21. _____
11. _____	22. _____

Scoring: Count the total number of animals (NOT including repetitions or non-animal words): _____

Next step: If the score is less than 14, further testing should be done.

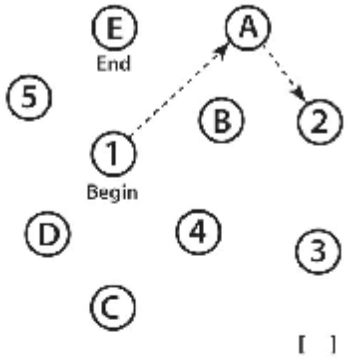
Sager MD, MA; Hermann PhD, BP; LaRue PhD, A; Woodard PhD, JL, Screening for Dementia in Community-based Memory Clinics. Wisconsin Medical Journal 2006.105(7)25-29

Appendix C: Montreal Cognitive Assessment (MoCA)

MONTREAL COGNITIVE ASSESSMENT (MOCA)
Version 7.1 Original Version

NAME :
Education : Date of birth :
Sex : DATE :

VISUOSPATIAL / EXECUTIVE — POINTS



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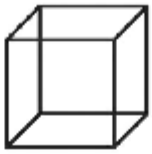


[ ] [ ]

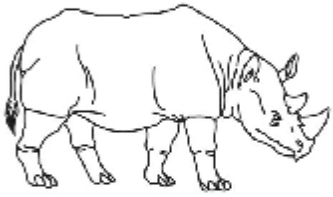
Draw CLOCK (Ten past eleven) (3 points)

[ ] Contour [ ] Numbers [ ] Hands

__/5

NAMING

[ ]



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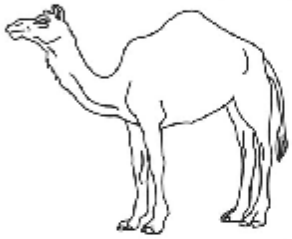

[ ]

__/3

MEMORY Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful. Do a recall after 5 minutes.

	FACE	VELVET	CHURCH	DAISY	RED
1st trial					
2nd trial					

No points

ATTENTION Read list of digits (1 digit/ sec.). Subject has to repeat them in the forward order [ ] 2 1 8 5 4

Subject has to repeat them in the backward order [ ] 7 4 2

__/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors

[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B

__/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65

4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt**

__/3

LANGUAGE Repeat : I only know that John is the one to help today. [ ]

The cat always hid under the couch when dogs were in the room. [ ]

__/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ] _____ (N ≥ 11 words)

__/1

ABSTRACTION Similarity between e.g. banana - orange – fruit [ ] train – bicycle [ ] watch – ruler

__/2

DELAYED RECALL

	Has to recall words WITH NO CUE	FACE [ ]	VELVET [ ]	CHURCH [ ]	DAISY [ ]	RED [ ]	Points for UNCUED recall only
Optional	Category cue						
	Multiple choice cue						

__/5

ORIENTATION [ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City

__/6

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TOTAL __/30

Add 1 point if ≤ 12 yr edu

Administered by: _____

Appendix D: An example of the Revised Speech Perception in Noise Test

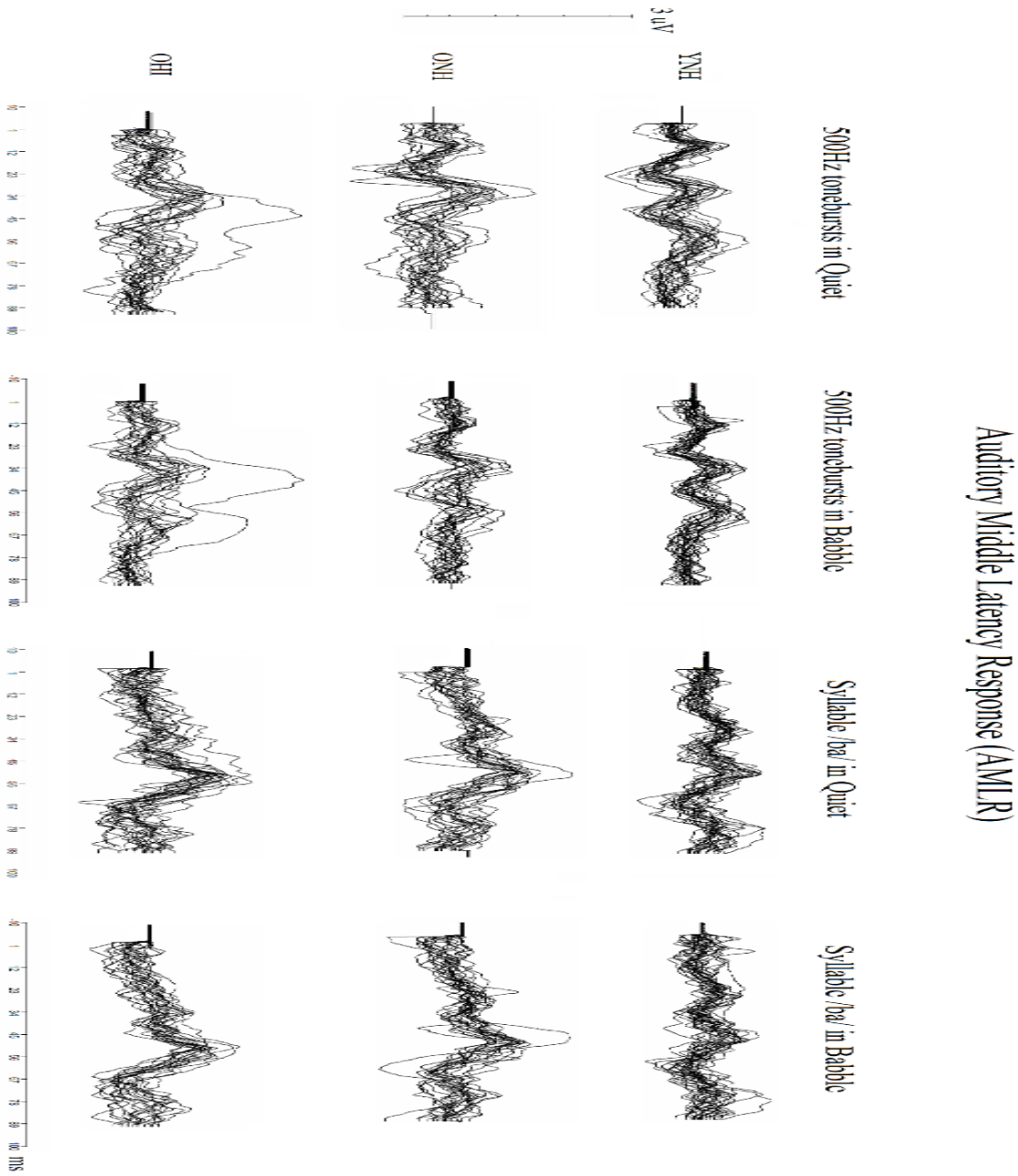
Form #-2 of the Revised SPIN Test (12/83)

Name _____ (# _____) Marker _____ Date _____

S/B +8 dB #C-HIGH _____ #C-LOW _____ ACCEPT? Y / N Percent Hrg. _____

1.	Miss Black thought about the LAP.		L	1
2.	The baby slept in his CRIB.	H		2
3.	The watchdog gave a warning GROWL.	H		3
4.	Miss Black would consider the BONE.		L	4
5.	The natives built a wooden HUT.	H		5
6.	Bob could have known about the SPOON.		L	6
7.	Unlock the door and turn the KNOB.	H		7
8.	He wants to talk about the RISK.		L	8
9.	He heard they called about the LANES.		L	9
10.	Wipe your greasy hands on the RAG.	H		10
11.	She has known about the DRUG.		L	11
12.	I want to speak about the CRASH.		L	12
13.	The wedding banquet was a FEAST.	H		13
14.	I should have considered the MAP.		L	14
15.	Paul hit the water with a SPLASH.	H		15
16.	The ducks swam around on the POND.	H		16
17.	Ruth must have known about the PIE.		L	17
18.	The man should discuss the OX.		L	18
19.	Bob stodd with his hands on his HIPS.	H		19
20.	The cigarette smoke filled his LUNGS.	H		20
21.	They heard I called about the PET.		L	21
22.	The cushion was filled with FOAM.	H		22
23.	Ruth poured the water down the DRAIN.	H		23
24.	Bill cannot consider the DEN.		L	24
25.	This nozzle sprays a fine MIST.	H		25
26.	The sport shirt has short SLEEVES.	H		26
27.	She hopes Jane called about the CALF.		L	27
28.	Jane has a problem with the COIN.		L	28
29.	She shortened the hem of her SKIRT.	H		29
30.	Paul hopes she called about the TANKS.		L	30
31.	The firl talked about the GIN.		L	31
32.	The guests were welcomed by the HOST.	H		32
33.	Mary should think abou the SWORD.		L	33
34.	Ruth could have discussed the WITS.		L	34
35.	The ship's Captain summoned his CREW.	H		35
36.	You had a problem with a BLUSH.		L	36
37.	The flood took a heavy TOLL.	H		37
38.	The car drove off the steep CLIFF.	H		38
39.	We have discussed the STEAM.		L	39
40.	The policemen captured the CROOK.	H		40
41.	The door was opened just a CRACK.	H		41
42.	Tom is considering the CLOCK.		L	42
43.	The sand was heaped in a PILE.	H		43
44.	You should not speak about the BRAIDS.		L	44
45.	Peter should speak about the MUGS.		L	45
46.	Household goods are moved in a VAN.	H		46
47.	He has a problem with the OATH.		L	47
48.	Follow this road around the BEND.	H		48
49.	Tom won't consider the SILK.		L	49
50.	The farmer baled the HAY.	H		50

Appendix E: Superimposed individual waveforms of AMLR recorded for each condition (stimulus X noise condition) in all subjects. The waveform was averaged over all recordings for each condition from each subject.



Appendix F: Superimposed individual waveforms of ALLR recorded for each condition (stimulus X noise condition) in all subjects. The waveform was averaged over all recordings for each condition from each subject.